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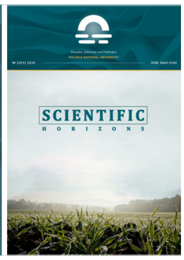

Economic models of smart farming integration into urban ecosystems

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Abstract. The aim of the study was to analyse the economic models of smart farming integration into urban ecosystems and their impact on the recovery of territorial communities in Ukraine and the European Union. In the process, a detailed review of modern smart farming technologies and models, such as hydroponics, aquaponics, vertical farms, as well as Internet of Things systems for agricultural management, rooftop farms and agro-industrial parks, was carried out. The main results included a comparative analysis of the productivity of traditional and vertical farming. It showed that vertical farms outperform traditional agriculture in terms of yield (150.23 kg/m^2 versus 4), water consumption (20 l/kg versus 250), and land use efficiency (0.0066 m^2/kg versus 0.25). In turn, the forecast for the IoT market in Europe showed a steady increase from USD 196.85 billion in 2025 to USD 284.26 billion in 2029, representing a compound annual growth rate of 9.62%. The results also indicated that investments in agricultural projects in the EU exceeded EUR 150 billion between 2015 and 2024, with Poland, the Czech Republic and Romania receiving the most funding, indicating a great potential for smart farming in these countries. Additionally, it was determined that regions in Ukraine with a high gross regional product (GRP), such as Kyiv (USD 9,268.5 million), Dnipro (USD 16,550.2 million) and Kharkiv (USD 10,494.4 million), have a greater potential for the introduction of smart farming technologies due to their high economic potential and infrastructure development. The practical significance of the study is to substantiate the effectiveness of the

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introduction of smart farming technologies to increase agricultural productivity, optimise resource use and promote the economic development of urban agro-systems

Keywords: agricultural innovation; sustainable development; digitalisation of agriculture; hydroponics and aquaponics; Internet of things

INTRODUCTION

The modern development of agriculture is increasingly focused on innovative solutions that allow for increased efficiency in the use of natural resources, a reduction in negative environmental impact, and the ensuring of food security in the face of growing urbanisation. One promising avenue is the implementation of smart farming, which involves the use of digital technologies, automated management systems, hydroponic and aquaponic setups, vertical farming, and other innovative solutions to boost the productivity of the agricultural sector. Despite the active development of this trend in developed countries, in Ukraine, its integration into urban ecosystems remains at an initial stage due to a number of economic, technological, and institutional barriers. The main problem is the insufficient development of economic models that justify the feasibility of implementing such technologies in urban environments and their impact on the socio-economic development of local communities (Malik *et al.*, 2023).

For example, a study by A. Berxolli *et al.* (2023) discusses the necessity of innovative approaches to enhance the efficiency of Ukraine's agricultural sector amidst the war. The authors emphasise the importance of innovation and a comprehensive approach in the agricultural sector, which is relevant when considering the integration of smart farming into urban ecosystems. The integration of artificial intelligence (AI) in land resource management allows for increased efficiency in agricultural production through automated data analysis, yield forecasting, and the optimisation of fertiliser and water use (Wrzecińska *et al.*, 2023; Shebanina *et al.*, 2025).

For their part, S.K. Sharma *et al.* (2024) investigated the economic aspects of implementing smart farming technologies, including the internet of things (IoT), AI, and data analysis, in urban agro-ecosystems. The authors highlighted that precision agriculture, vertical farms, and hydroponics contribute to resource optimisation, increased productivity, and the adaptation of agriculture to urbanisation and climate change. Researchers H. Shahab *et al.* (2025) considered the implementation of IoT in smart farming as a tool for achieving sustainable development goals. They demonstrated the effectiveness of an IoT system for monitoring soil parameters and using AI to optimise crop management, which contributes to increased productivity and the sustainability of agricultural production. Furthermore, M. Dhanaraju *et al.* (2022) explored the impact of smart farming on traditional agricultural practices through the use of IoT, wireless sensors, and cloud technologies. The authors highlighted the challenges of integrating new technologies into agriculture, particularly during the period from sowing to harvesting, as well as in packaging and transportation. Additionally, the findings of the work by H. Chawla *et al.* (2025) underscored the important role of IoT technologies in enhancing water efficiency and reducing carbon emissions in horticulture. Researchers N. Khan *et al.* (2023) analysed the role of social entrepreneurship and the factors influencing the adoption of smart farming technologies among older people. They determined that a positive attitude and social impact promote the implementation of smart farming, and also emphasised the importance of social entrepreneurs in improving older people's knowledge of these technologies.

In turn, O.B. Akintuyi (2024) emphasised that vertical farming is a promising solution for ensuring food security in the context of urbanisation. The author highlighted the importance of the architectural integration of vertical farms into the urban environment to optimise space utilisation, energy efficiency, and sustainable development, as well as the role of technologies in enhancing the efficiency and resilience of food systems. The results of the work by A. Mishra (2023) indicated the advantages of smart urban farming, including the possibility of growing nutritious crops in urban conditions using AI and IoT. The use of these technologies helps to reduce resource costs, improve product quality, and decrease environmental impact, which contributes to the creation of a clean and green urban environment. Additionally, G. Orbelyan (2024) developed a theoretical model, the "Comprehensive Model of Smart Tourism and Infrastructure", which focuses on the integration of engineering, transport, and tourism to create a sustainable urban ecosystem that promotes sustainable economic growth and inclusivity through intelligent technologies.

The aim of this research was to identify economic models for the integration of smart farming into the urban ecosystems of Ukraine and the EU, as well as their impact on the recovery of local communities, which has not been detailed in previous works. The research objectives included analysing existing smart farming technologies, their effectiveness and economic potential in the context of urbanisation, and comparing smart farming models in Ukraine and the EU to identify opportunities for their implementation.

MATERIALS AND METHODS

To achieve the research objective, the economic models of smart farming integration into urban ecosystems were analysed and their impact on the recovery of territorial communities in Ukraine and the EU countries was considered. Initially, the study considered such models and technologies as hydroponics and aquaponics, vertical farms, IoT systems for agricultural management, rooftop farms, and agro-industrial parks. This made it possible to trace the main stages of their implementation and interaction with other elements of the urban environment. Reference productivity indicators for traditional and vertical farming were also considered, which allowed to assess the competitiveness of smart farming technologies compared to traditional agricultural production methods (Moghimi & Asiabanpour, 2021). These indicators included the following parameters: benchmark production per year; the number of hours one person spends producing 1 kg of product; energy and water consumption, yield, and land ratio for producing 1 kg per year.

An example is the Green Future company, which is one of the largest vertical farms in Ukraine (One of the largest vertical farms in Ukraine…, 2024). On the other hand, to determine the prospects for the use of digital technologies in the agricultural sector, an analysis of the projected development of the IoT market in European countries in US dollars for 2025-2029 was carried out (Statista, n.d.). The data obtained on the main models of smart farming were systematised in the form of a comparative analysis covering their advantages and limitations. For this purpose, the expert evaluation method was used to identify the key success factors for each model. Further, to assess the effectiveness of the introduction of smart farming technologies, the economic effect assessment formula (Kosinska, 2019) was applied, which took into account changes in production levels, investment costs, and resource savings (1):

$$E = \frac{(Y_s - Y_b) \times (C + I + T)}{C} \times 100\%, \quad (1)$$

where E – efficiency of technology adoption, %; Y_s – production level after technology adoption; Y_b – production level before technology adoption; C – costs of technology adoption; I – investments in staff training and technical support; T – savings from reduced use of resources (water, fertilisers, etc.).

Based on this formula, the efficiency of smart farming implementation was calculated, which allowed to estimate the potential increase in productivity and profitability of public initiatives. Additionally, the schedule of regional production and international trade of Ukraine in 2019 was considered, which allowed to analyse the economic preconditions for the development of smart farming in different regions of the country (National Bank of Ukraine, n.d.). For this purpose, the gross regional product (GRP), exports and imports, as well as the level of economic activity of the regions were estimated, which made it possible to identify opportunities for the integration of smart farming technologies. Moreover, the total amount of funding for projects in EU countries for 2015-2024 was studied, which made it possible to identify possible mechanisms for financial support for such initiatives (European Commission, 2025). The analysis considers the specifics of the distribution of funds from the EU Cohesion Fund, as well as the level of investment in the development of smart farming technologies in different countries.

RESULTS

Analysis of economic models for integrating smart farming into urban ecosystems. Smart farming is an emerging trend in the agricultural sector that uses innovative technologies to increase the efficiency and sustainability of agronomic activities. In the context of urban ecosystems, smart farming is particularly important as it can meet the needs of urban areas for the production of environmentally friendly products, reducing dependence on agricultural products supplied from rural areas. In the context of urban ecosystems, smart farming can be represented by several economic models that are adapted to the specific conditions of the urban environment and can meet the food security needs of urban communities. For example, hydroponics and aquaponics are soilless methods of growing plants that use aqueous solutions for nutrition. Hydroponics involves growing plants in special systems where the roots of the plants are in water with dissolved nutrients. Aquaponics combines hydroponics with fish farming, creating a closed ecosystem where fish waste is used as fertiliser for plants and plants filter water for fish. Consider integrating hydroponics and aquaponics in urban ecosystems (Fig. 1).

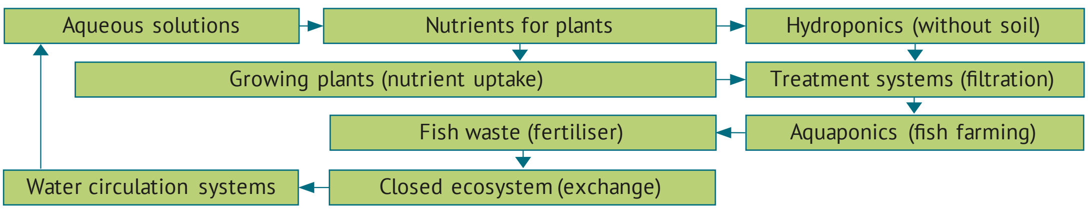

Figure 1*. Integrating hydroponics and aquaponics in urban ecosystems*
Source: *created by the authors*

This diagram shows the relationships between the different components of hydroponic and aquaponic systems, emphasising their integration into a closed ecosystem for efficient plant and fish production in urban environments. Generally speaking, hydroponics is a system of growing leafy vegetables such as lettuce and spinach in special pipes or containers where the roots of the plants are immersed in a water solution with the necessary nutrients. Such systems typically use networked solution flow technologies or a grid system. Aquaponics is implemented, for example, in urban greenhouses, where fish, such as tilapia, are grown in containers and their waste is used to fertilise plants, such as tomatoes or cucumbers, grown in the same conditions. The water in such systems circulates between the fish and plants, creating an efficient closed ecosystem that reduces water and fertiliser consumption.

Vertical farms, on the other hand, are another innovative model of smart farming that is being actively integrated into urban ecosystems (Kunakh *et al.*, 2021). They involve the use of vertical structures on which multi-tiered systems for growing plants are placed. This allows for significant space savings, which is an important factor in urban environments where land is limited. Such farms use effective growing methods such as aeroponics (a soilless method of growing plants in which the roots of plants are suspended in the air and regularly moistened with a water solution containing nutrients), ensuring maximum productivity in a minimum area. Vertical farms are capable of producing a wide range of crops, from vegetables to fruits, and help reduce the cost of transporting products by localising production. For a better understanding, it is worth comparing productivity indicators for traditional and vertical farming (Table 1).

***Table 1**. Reference productivity indicators for traditional and vertical farming*

Option	Traditional farming (field cultivation)	Vertical farming
Reference production per year (kg)	907,184.7	907,184.74
Labour per kg (man-hours/kg)	0.014	0.066666667
Energy consumption per kg (kWh/kg)	0.575	5.75
Water consumption per kg (l/kg)	250	20
Yield (kg/m^2/year)	4	150.23
Land ratio for production of 1 kg per year (m^2/kg)	0.25	0.006656307

***Note:** man-hours – the number of hours that one person spends on the production of one kilogram of product*
***Source:** F. Moghimi and B. Asiabanpour (2021)*

In other words, vertical farms outperform conventional agriculture in terms of yields, water consumption and land use efficiency. However, they require more energy, which is also an important factor in their economic and environmental assessment. For example, entrepreneur Viktor Shuleshko, founder of Green Future, created one of the largest vertical farms in a bomb shelter in the city of Dnipro (One of the largest vertical farms in Ukraine..., 2024). After losing his previous farm to a rocket attack, he built a new one, 7 times larger, which enables to grow up to 3 kg of greenery per m^2.

In turn, IoT systems for agricultural management are becoming an important element for optimising and automating processes in smart farming. IoT helps to integrate various devices and sensors that collect data on environmental conditions (temperature, humidity, light, soil pH and other parameters), as well as on the condition of plants and animals. This data is used to monitor, forecast and manage agricultural processes in real time, which helps to increase production efficiency and reduce the cost of resources such as water, energy and fertilisers. An important factor in the development of such technologies is the overall growth of the IoT market, which reflects the level of investment and innovation in various industries. In this context, it is useful to consider the projected growth of the IoT market in Europe, as it directly affects the implementation of such solutions in the agricultural sector (Fig. 2).

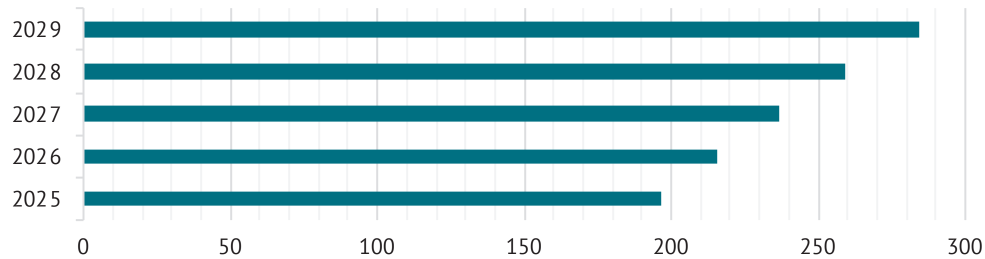

***Figure 2**. Forecasted size of the IoT market in Europe for 2025-2029*

***Source:** Statista (n.d.)*

The forecast shows a steady growth of the IoT market in Europe. It is expected to increase from USD 196.85 billion in 2025 to USD 284.26 billion in 2029, representing a compound annual growth rate of approximately 9.62%. This indicates the active integration of IoT into various industries, including the agricultural sector, where these technologies contribute to increased production efficiency. In general, in urban ecosystems, the use of IoT in smart farming allows for maximum adaptation of agricultural systems to the limited conditions of urban space. IoT can be used to automate watering, temperature and light control in vertical farms or hydroponic systems, making the process of growing plants much more efficient. For example, IoT-based technologies can automatically adjust water and energy consumption depending on environmental conditions, reducing the environmental footprint of agricultural production. The integration of IoT into agricultural management also opens up new opportunities for processing large amounts of data, allowing for crop forecasting, optimising logistics and reducing risks. With the help of IoT systems, farmers can receive analytical reports that allow them to respond quickly to changing conditions and make informed decisions aimed at improving production results and the sustainability of agricultural systems. One of the most promising models is the use of rooftop farms, which allow for the most efficient use of urban spaces. Such farms can be located on the roofs of residential and commercial buildings, as well as on industrial facilities. Not only do they provide access to fresh local produce, but they also help to improve the microclimate, reduce the heat load on buildings, reduce noise and increase air humidity. They can also be integrated with rainwater harvesting systems and solar panels, making them more energy efficient.

In addition, there are urban models of innovative agricultural clusters, such as agro-industrial parks. These are special agricultural parks that combine high-tech greenhouses, agricultural processing centres, crop research laboratories, educational parks and sales markets. Such clusters help to create new jobs, reduce logistics costs, develop small and medium-sized enterprises, and intensify cooperation between the agricultural sector, research institutions and municipal authorities. Thus, the considered smart farming models have their advantages and limitations (Table 2). Each of them adapts to the urban environment in different ways, taking into account factors such as spatial constraints, resource consumption and cost-effectiveness. The choice of the appropriate model depends on specific conditions, including resource availability, local community needs, environmental requirements and economic opportunities.

***Table 2**. Benefits and limitations of smart farming models in urban ecosystems*

Model	Benefits	Limitations
Hydroponics and aquaponics	Reduced water consumption	High cost of system installation
	Fast cultivation	The need for energy resources
	High space efficiency	Difficulty in balancing the ecosystem
	Sustainable process with minimal environmental footprint	
Vertical farms	High yields on small areas	High initial cost
	Reduced transport costs	High energy costs
	Conservation of resources (water, land)	
IoT systems for agricultural management	Increased efficiency through monitoring and automation	Data security issues
	Reduced resource costs	High cost of implementation
	Precise management of agricultural processes in real time	
Rooftop farms	Efficient use of urban space	Limitation of space for placement
	Improving the microclimate	Dependence on building design features
	Access to fresh products	
Agro-industrial parks	Creation of new jobs	High initial investment
	Development of high technologies	Need for government support
	Reduction of logistics costs	Difficulty in coordination between different actors
	Stimulation of the local economy	

***Source:** created by the authors*

Thus, the optimal choice of model depends on the specific conditions of the urban environment. Hydroponics and aquaponics models are best suited for confined spaces where production speed and efficient water use are important. Vertical farms are effective in tall cities with limited land space, particularly for growing vegetables and herbs. IoT systems are useful in the context of large farms or innovative agri-parks, where automation and monitoring are required. Rooftop farms are most appropriate for use in highly urbanised cities, where it is important to maximise the use of available space and ensure sustainable development. In addition, agro-industrial parks are promising for regions with a high level of technological development, where it is necessary to create jobs and reduce logistics costs.

The impact of smart farming models on the restoration of territorial communities in Ukraine and the EU. In the modern world, there is an active implementation of smart farming technologies aimed at addressing the problems of growing demand for food, climate change, lack of natural resources and the need to ensure the sustainability of agriculture. The use of technologies such as vertical farms, hydroponics and aquaponics allows crops to be grown in limited space and with minimal water use. Moreover, smart farming plays a key role in increasing the efficiency of the agricultural sector by automating processes, reducing resource use and improving product quality. In particular, IoT technologies allow for precise monitoring of soil conditions, moisture, temperature and other parameters, which contributes to more efficient management of agricultural processes. Another important aspect is the use of AI for crop forecasting and production management, which helps to reduce losses and increase the profitability of agricultural enterprises (Yerzhanova *et al.*, 2021).

In other words, the introduction of smart farming technologies in the agricultural sector is a key factor in increasing production efficiency. To quantify the impact of such technologies on agricultural productivity, an extended model can be used that takes into account various aspects of innovation (Kosinska, 2019). For example, before the introduction of smart farming technologies, the level of production was 100 units. After the introduction of the technology, production increased to 120 units. Implementation costs amounted to 50 units, investment in training – 10 units, and savings from reduced resource use - 5 units. The efficiency is then calculated as follows (1):

$$\mathrm{E} = \frac{(120-100)\times(50+10+5)}{50} \times 100\% = 260\%. \quad (2)$$

Thus, the effectiveness of the introduction of smart farming technologies can be assessed by increasing productivity per unit of inputs. In the example above, each unit of inputs brought an additional 2.6 units of output, which indicates the high efficiency of such technologies in the agricultural sector. This means that the introduction of smart farming technologies has a significant potential to increase agricultural productivity and also has the potential to have a significant impact on the recovery of local communities. By reducing inputs, improving product quality and creating new jobs, these technologies contribute to economic growth and infrastructure rehabilitation in regions affected by conflict or economic hardship. As a result, smart farming is not only a factor in increasing productivity, but also in stabilising local economies in various countries and regions, such as Ukraine and the EU.

Ukraine has significant potential for the development of smart farming, but the pace of adoption of new technologies can vary significantly depending on the region and level of economic development. In recent years (2020-2025), there has been a trend towards more active adoption of innovations such as vertical farms, hydroponics, aquaponics and rooftop agriculture, especially in economically developed regions. At the same time, a number of regions face low levels of investment, limited resources and a lack of infrastructure, which slows down the pace of smart farming adoption. To better understand the spread of innovations in different regions of Ukraine and their impact on economic development, it is worth considering data on regional economic activity, such as GRP, exports and imports (Fig. 3). This helps to determine which regions have the greatest potential for the development of smart farming technologies and where additional efforts should be focused to improve the efficiency of innovation.

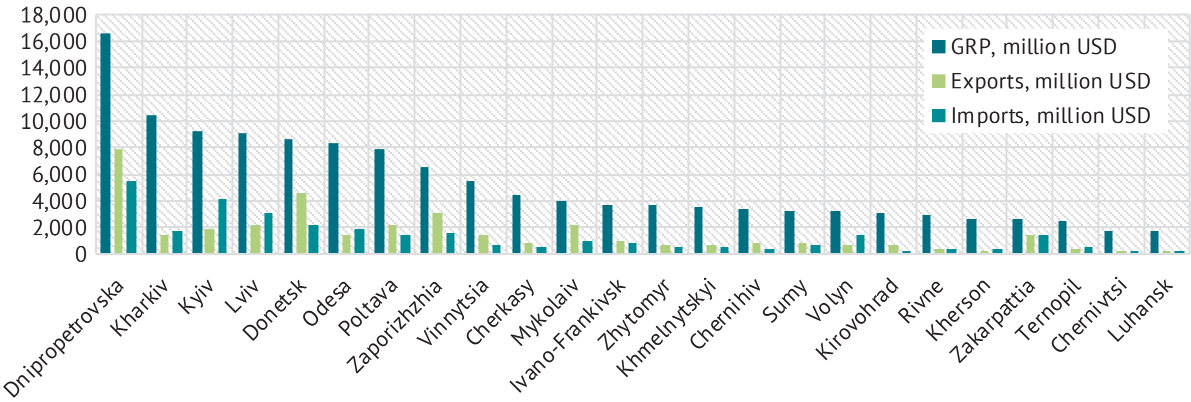

Figure 3*. Regional production and international trade in Ukraine in 2019*
Source: *National Bank of Ukraine (n.d.)*

According to the data provided, the highest GRP values are observed in Kyiv (USD 9,268.5 million), Dnipro (USD 16,550.2 million) and Kharkiv (USD 10,494.4 million) regions. This indicates the high economic potential of these regions, which have developed infrastructure and significant production. Higher GRP also indicates a greater potential for the integration of smart farming technologies, as these regions have more resources for innovation and the development of new agricultural models. At the same time, the highest exports are observed in Dnipropetrovska region (USD 7,907.2 million), which may indicate the importance of this region for foreign trade. In terms of smart farming, high exports in these regions may provide an additional opportunity for the development of agricultural technologies, as the demand for innovative agricultural products abroad may stimulate the development of new technologies.

In addition, in the most economically developed regions, such as Kyiv and Dnipro, imports are much higher (USD 4,112.3 million and USD 5,522.2 million accordingly), which may indicate a dependence on external suppliers to meet the needs for technology, equipment and raw materials. For smart farming, it is important to understand these flows, as imports of technology and innovations can be a key factor for their adoption in Ukraine. Thus, regions with high GRP and exports, such as Kyiv, Dnipro and Kharkiv, have a greater potential for integrating smart farming models, as their economic activity and foreign trade support the development of new technologies. In contrast, less developed regions, such as Chernivtsi or Luhansk regions, may face challenges in adopting such technologies due to limited resources. This also highlights the need to concentrate resources on supporting innovation in less economically developed regions to ensure sustainable development and recovery of communities throughout Ukraine.

On the other hand, the EU is witnessing an active adoption of smart farming technologies, including hydroponics, vertical farms, integration of IoT into agriculture, and the use of drones and AI to optimise agricultural production. Countries such as the Netherlands, Germany and France are leading the way in introducing innovative technologies that can significantly increase production efficiency and reduce the environmental impact of the agricultural sector. The importance of understanding the financing of smart farming technologies in the EU is that it enables to assess the extent to which countries are actively investing in the development and implementation of innovative agricultural practices. The financing system that supports such projects is a key factor for the development of smart farming, particularly in countries that are leading the way. Therefore, the total amount of investment allocated to various areas of agro-innovation, including hydroponics, vertical farms and IoT technologies, should be demonstrated (Fig. 4).

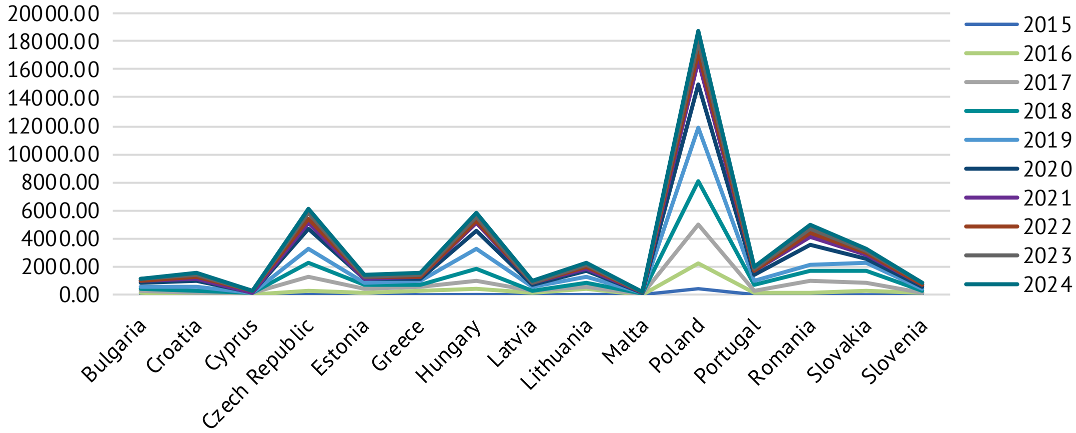

Figure 4*. Total funding from the EU Cohesion Fund for projects in EU countries (2015-2024)*
Source: *European Commission (2025)*

Although these data cover different types of projects, they are important for the introduction of innovative technologies, including smart farming, in the agricultural sector. For example, Cohesion Fund funding grew between 2015 and 2024, exceeding EUR 150 billion in 2024. This indicates sustainable funding for infrastructure and technology development, including smart farming initiatives. It is important to note that it was in the period from 2015 to 2024 that many EU countries increased their investments in innovation, particularly in the agricultural sector. Poland, the Czech Republic, and Romania received the most funding. This may indicate that these countries have significant potential for the development of smart farming projects, as the funding received can be used for innovations in the agricultural sector. For Poland, for example, a significant increase in funding for agricultural projects could facilitate the widespread adoption of smart farming.

Countries such as Malta or Cyprus received much less funding, which may indicate their limited economic potential for large-scale adoption of smart farming technologies. However, even these countries can use the funds to develop small and medium-sized projects in the agricultural sector. Overall, funding from the EU Cohesion Fund plays an important role in the development of innovations, including smart farming technologies. Given the large sums allocated to projects in Poland and the Czech Republic, it can be noted that these countries are actively integrating the latest technologies, including agricultural ones, to support sustainable development. This contributes to the restoration of regional communities and improves economic stability in rural areas, and the inclusion of EU funding can be important for the recovery of local communities.

It is worth noting that smart farm technologies are being actively implemented not only in Ukraine and the EU, but also in many other regions of the world, contributing to the recovery and development of local communities. For example, in Africa, there is a growing interest in implementing innovative agricultural practices. Due to limited water resources and the need to improve food security, the continent is actively developing hydroponics and vertical farms. These technologies make it possible to use limited resources efficiently and provide the population with the necessary products. In turn, Asia, in particular in countries such as Japan, South Korea and Singapore, is witnessing rapid adoption of smart farming technologies. High population density and limited land resources encourage the use of vertical farms and hydroponics. These methods allow for efficient food production in urbanised areas, reducing dependence on imports and improving food security. For their part, South American countries such as Brazil and Argentina are seeing the integration of IoT and drones into agriculture. These technologies help farmers monitor the condition of crops, optimise the use of resources and increase yields. As a result, there is an increase in productivity and an improvement in the economic situation of rural communities.

Overall, the adoption of smart farming technologies has the potential to significantly improve the agricultural sector in various regions of the world, contributing to economic development and the recovery of communities. However, successful implementation depends on access to finance, technological infrastructure and training of local farmers.

DISCUSSION

The results obtained confirm that the integration of IoT into smart farming helps to increase crop yields, reduce water consumption, and optimise the use of land resources, making agriculture more sustainable and efficient. The study by M.K. Pasupuleti (2024) considered the overall impact of IoT on precision agriculture, urban infrastructure, and digital security, with a focus on real-time monitoring and the cybersecurity of IoT ecosystems. That is to say, the results are consistent, as both studies confirm the importance of IoT in the development of the agricultural sector, but the research conducted here specifically focuses on the economic efficiency of smart farming models in urban ecosystems. Similarly, the study by K. Bakirov *et al.* (2024) examined the implementation of IoT in hydroponic vertical farming, demonstrating the effectiveness of dynamic management of water and energy resources based on sensor data, which led to a 50% increase in yield thanks to the integration of smart irrigation and solar photovoltaic panels. In this regard, the current results confirm that IoT is a key factor in increasing the productivity of smart farming, reducing water consumption, and improving energy efficiency. Consequently, the current work emphasises a comprehensive economic analysis of the implementation of technologies in urban ecosystems, whereas the reviewed work focused on the mathematical modelling of resource optimisation.

This research focuses on the economic efficiency of implementing smart farming technologies in urban ecosystems, such as vertical farms and agro-industrial parks, which allows for increased productivity and reduced resource costs. At the same time, the study by A.A. Zhahir *et al.* (2024), in developing a conceptual model for the adoption of technologies in smart urban farming, focuses on the social and economic factors influencing the implementation of innovations in urban agriculture, without considering the technological aspects in detail. In turn, the results of the work by M. Abbas *et al.* (2025) are focused on the application of IoT and cloud technologies to optimise dairy farm management, which shows the effectiveness of sensor technologies in reducing costs and increasing productivity. This aligns with the current results, as in both studies, IoT plays an important role in enhancing the efficiency of agricultural processes, although the research conducted here emphasises the application of technologies in urban agro-systems, while the mentioned study focuses on dairy farming.

This research focuses on the economic models of smart farming, such as hydroponics, aquaponics, vertical farms, and IoT for agricultural management, and has revealed the high efficiency of these technologies compared to traditional agriculture in terms of yield, water consumption, and land use efficiency. The study by A.M. Rosário and A.C. Boechat (2024) confirms the significance of smart technologies for the sustainable development of urban ecosystems, particularly the use of IoT and AI to optimise resources, which corresponds to the main aspects of the current research. On the other hand, the work by J. Procházka and A. Kubacova (2024) analyses the implementation of IoT solutions in the Czech Republic through Smart Post Boxes, which also highlights the effectiveness of technologies for sustainable development, but the research conducted here examines smart farming in the context of various EU countries, and not just the Czech Republic.

The analysis carried out showed that vertical farms demonstrate a yield of 150.23 kg/m^2 compared to 4 kg/m^2 in traditional farming, and water consumption was reduced to 20 litres/kg compared to 250 litres/kg in conventional agricultural production. In contrast to the study by C. Pereira de Sá *et al.* (2025), which considers organic farming and strategies for product certification through transparent governance and public procurement, the current research focuses on comparing smart farming models in agro-systems, where the main goal is to increase efficiency and reduce resource costs, rather than certification strategies. Furthermore, according to the results of the current analysis, the integration of smart farming technologies into urban agro-systems contributes to a significant reduction in energy and water consumption, which are key aspects of the sustainable development of urban ecosystems. Whereas the study by G.M. Ostanaqulova (2025) uses regression models and the analytic hierarchy process to assess technological innovations in smart cities, the research conducted here applies economic models to assess the effectiveness of technologies in the agriculture of urban ecosystems, specifically to compare different smart farming models and determine their economic feasibility in the context of different regions of the EU and Ukraine.

The research conducted has shown that the integration of smart farming into urban ecosystems contributes to increased resource efficiency, optimised food security, and the recovery of local communities, particularly through the implementation of IoT technologies and vertical farms. In turn, G.R. Pradyumna and R. Hegde (2024) emphasise the role of smart sensors and devices in improving the monitoring of urban ecosystems within blue-green infrastructures, while also drawing attention to cybersecurity risks and the need to use digital twins for real-time optimisation of urban processes. While the current work focuses on the integration of smart farming into urban ecosystems, the study by X. Kuai *et al.* (2024) highlighted the importance of combining urban data through the development of a Smart City Ontology Framework. This framework provides semantic compatibility for IoT, Building Information Modeling, and Geographic Information Systems in urban management. In this regard, the current research considers the need for data standardisation for the effective implementation of smart farming models, which contributes to increasing the productivity of urban agriculture and the sustainable use of resources.

The results obtained also showed that vertical farms significantly outperform traditional agriculture in terms of land use efficiency – 0.0066 m^2/kg compared to 0.25 m^2/kg, which confirms their competitiveness in urban conditions. This is consistent with the study by M.T. Abdelfatah (2025), which demonstrates that the Vertical Urban Oasis model helps to optimise land resources, ensure sustainable food supply, and promote economic development, although high initial costs and social barriers remain the main challenges. Additionally, the analysis of hydroponics in the current research showed its advantages in urban agricultural production due to minimal water use, automated parameter control, and increased yields. This is confirmed by the work of K. Kueh Yung Shin *et al.* (2023), which presented Smart Grow – an IoT-oriented hydroponic system that provides efficient management of plant water balance. However, unlike the mentioned work, the current research focuses on the economic analysis of the large-scale implementation of hydroponics in urban ecosystems.

The efficiency of using smart farming technologies significantly exceeds traditional agricultural methods; in particular, yields in hydroponic and aquaponic models reach 120 kg/m^2, which is several times higher than under traditional conditions (Poloviy *et al.*, 2024). This indicates the high productivity and economic benefit of such technologies. However, compared to the study by S. Raj *et al.* (2023), which focuses on data integration for smart cities and the optimisation of agricultural services, it should be noted that while these technologies contribute to sustainable development, the issues of efficient use of digital resources and ensuring confidentiality are important for further development. The research conducted also showed that investments in agricultural projects in the EU exceeded EUR 150 billion between 2015 and 2024, with Poland, the Czech Republic, and Romania receiving the most funding. This indicates a significant potential for the development of smart farming in these countries. At the same time, the study by P.-A. Langendahl (2021) noted that in Sweden, the implementation of smart farming promises to reduce costs and increase food security. However, its real effect is often limited, and in the EU, despite large investments, the effectiveness of agricultural initiatives often remains limited and in many cases does not lead to radical changes in traditional production methods (Shahini *et al.*, 2023).

Overall, this research compared the economic indicators of traditional agriculture and smart farming technologies, and the results showed significant advantages of such technologies, particularly in increasing yields, reducing water consumption, and improving land use efficiency. At the same time, the study by N. Khan *et al.* (2024) obtained similar results regarding the high efficiency of smart farming in conditions of urbanisation and limited resources. However, unlike the provided research, the current results analyse in more detail the economic prerequisites for the implementation of such technologies in different regions, particularly in Ukraine. The study by M. Bakhar and E. Evanita (2021) also confirms the benefits of agricultural innovations, particularly in the context of reducing the use of natural resources and increasing productivity. However, unlike their analysis, the current results emphasise the importance of factors such as infrastructure support and the level of investment for the effective implementation of smart farming at the level of urban ecosystems.

Thus, the research results confirm that the implementation of smart farming technologies and models, such as hydroponics, aquaponics, vertical farms, and IoT, significantly increases the efficiency of agricultural production, reduces resource costs, particularly water consumption, and optimises the use of land resources, which are key to the sustainable development of urban ecosystems. Moreover, smart farming is capable of significantly enhancing food security and supporting the recovery of local communities through the integration of modern technologies into the urban environment.

CONCLUSIONS

An analysis of economic models for integrating smart farming into urban ecosystems has confirmed the high efficiency of technologies such as hydroponics, aquaponics, vertical farms, IoT systems, rooftop farms and agro-industrial parks. Vertical farms have shown yields of up to 150.23 kg/m^2, which is higher than traditional farming, where yields are only 4 kg/m^2. Water consumption in vertical farms is 20 litres/kg of production, which is significantly less than the 250 litres/kg in conventional farming. In addition, they occupy only 0.0066 m^2 per 1 kg of produce, which is more efficient than conventional methods that use 0.25 m^2 per 1 kg. Hydroponics and aquaponics also contribute to a significant reduction in water consumption compared to traditional agriculture, ensuring more efficient use of water resources. In addition, IoT systems that optimise agricultural management can reduce energy and water costs, providing better control and efficiency. Rooftop farms make use of limited urban land resources, reducing the need for additional land for agricultural production, and agro-industrial parks provide an opportunity to integrate different agricultural technologies and enterprises in an urban environment. These technologies help to increase productivity, reduce water and energy costs, which are important factors for urban agricultural systems.

The results of the implementation of smart farming technologies in the agricultural systems of Ukraine and the EU have highlighted that this contributes to a significant recovery of local economies, as such technologies reduce resource costs and increase agricultural production. In particular, the comparative analysis showed that in developed regions such as Kyiv, Dnipro and Kharkiv, the introduction of smart farming models such as vertical farms and IoT systems can significantly increase the efficiency of agricultural production. In EU countries such as the Netherlands and Germany, innovative agricultural technologies are being actively used to increase not only productivity but also reduce environmental impact. Investments in smart farming projects in the EU, including through the Cohesion Fund, exceeded 150 billion euros in 2024, which demonstrates support for innovation in the agricultural sector. This demonstrates the high potential for the development of smart farming, which is an important element for ensuring food security and sustainable development of urban agricultural systems in Ukraine and the EU.

The main constraints to the introduction of smart farming technologies and models are high initial costs for infrastructure and equipment, as well as the lack of sufficient technical training among farmers, which can slow down the process of adopting innovations. In addition, the legal and regulatory frameworks to support such technologies need to be modernised, especially in Ukraine. To overcome these barriers, it is recommended to develop state support programmes and subsidies for farmers, increase investments in education and training, and strengthen cooperation between the government, research institutions and business to stimulate innovation in the agricultural sector.

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CONFLICT OF INTEREST

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Економічні моделі інтеграції смарт-фермерства у міські екосистеми

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Анотація. Метою дослідження був аналіз економічних моделей інтеграції розумного землеробства в міські екосистеми та їх вплив на відновлення територіальних громад в Україні та Європейському Союзі. У процесі було проведено детальний огляд сучасних технологій та моделей розумного землеробства, таких як гідропоніка, аквапоніка, вертикальні ферми, а також системи Інтернету речей для управління сільським господарством, дахові ферми та агропромислові парки. Основні результати включали порівняльний аналіз продуктивності традиційного та вертикального землеробства. Він показав, що вертикальні ферми перевершують традиційне сільське господарство за врожайністю (150,23 кг/м^2 проти 4), споживанням води (20 л/кг проти 250) та ефективністю використання землі (0,0066 кг/м^2 проти 0,25). У свою чергу, прогноз ринку IoT в Європі показав стабільне зростання з 196,85 млрд доларів США у 2025 році до 284,26 млрд доларів США у 2029 році, що становить сукупний річний темп зростання 9,62 %. Результати також показали, що інвестиції в сільськогосподарські проекти в ЄС перевищили 150 мільярдів євро між 2015 і 2024 роками, причому Польща, Чехія та Румунія отримали найбільше фінансування, що свідчить про великий потенціал для розумного землеробства в цих країнах. Крім того, визначено, що регіони України з високим валовим регіональним продуктом (ВРП), такі як Київ (9,268,5 млн доларів США), Дніпро (16,550,2 млн доларів США) та Харків (10,494,4 млн доларів США), мають більший потенціал для впровадження технологій розумного землеробства завдяки своєму високому економічному потенціалу та розвитку інфраструктури. Практичне значення дослідження полягає в обґрунтуванні ефективності впровадження технологій розумного землеробства для підвищення продуктивності сільського господарства, оптимізації використання ресурсів та сприяння економічному розвитку міських агросистем

Ключові слова: аграрні інновації; сталий розвиток; цифровізація сільського господарства; гідропоніка та аквапоніка; Інтернет речей