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Digital twins as a tool to increase the efficiency and sustainability of the agro-industrial complex

ORIGINAL ARTICLE

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Abstract. This article examines the applicability and impact of digital twin technologies across the agri-food sector, from field operations to postharvest logistics. Building on a structured review of recent literature and industry cases, we synthesize how physics-based and data-driven twins integrate sensing, IoT, and AI to enable real-time monitoring, scenario analysis, and decision support. We classify agricultural digital twins into four functional groups – crop and livestock production, machinery and maintenance, postharvest handling, and supply-chain coordination – and map them to key performance indicators such as yield stability, resource efficiency, quality preservation, and risk reduction. The analysis identifies consistent benefits, including improved input use, earlier anomaly detection, and more resilient planning under weather and market uncertainty. However, adoption is constrained by data quality and interoperability issues, high initial costs, skills gaps, and unresolved concerns around cybersecurity and governance. We propose a staged implementation framework that prioritizes high-value use cases, lightweight edge analytics, and open data standards, accompanied by a governance model for data sharing. The article contributes a practical roadmap and a set of evaluation metrics that link digital-twin capabilities to farm-level and supply-chain decisions. Limitations relate to heterogeneous evidence and context specificity. Future work should explore integration with generative AI, privacy-preserving learning, and cross-farm platforms.

Keywords: digital twins; agrotechnology; digitalisation of agriculture; precision agriculture; virtual farm models

JEL codes: Q16, Q55, O33

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Introduction

Agriculture is one of the key sectors of the global economy. Nowadays, population growth, climate change, soil degradation, lack of water resources and qualified personnel are the threats to the sustainable development of the industry. According to the Food and Agriculture Organization of the United Nations (FAO), by 2050 the world's population will increase to almost 10 bn people[1]. In a scenario with moderate economic growth, such population growth rates will cause an increase in global demand for agricultural products by 50-60% compared to current level. It will degrade the natural resources. Moreover, already every 11 people in the world are hungry; according to an average estimate there are more than 735 mln of people. Therefore, the digital transformation of agriculture is becoming a prerequisite for ensuring food security and sustainable development.

Digital twins are innovative technologies of Industry 4.0. They allow us to optimise the agricultural processes, increase yields, conserve water, fertilizers, and energy, etc. [2]. However, the issue is understudied, especially for the developing countries.

The purpose of this work is to assess the opportunities and risks of digital twins in agriculture. Moreover, we emphasise on increasing of available resources efficiency and sustainability of agro-industrial production

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[1] *Food and Agriculture Organization of the United Nations. (2018). The future of food and agriculture – Alternative pathways to 2050. FAO. Source: https://openknowledge.fao.org/server/api/core/bitstreams/e51e0cf0-4ece-428c-8227-ff6c51b06b16/content (accessed on 01.04.2025)*

through optimising processes, reducing costs, and minimising environmental threats. Our research focuses on the economic component of digital twins' implementation. The article focuses on the main areas of digital twins' application, provides practical examples, and discusses their key issues.

Many domestic and foreign scientists considered the development and implementation of digital twins in terms of productivity, sustainability, and transformation of agriculture. They are as follows: G.A. Getz [2], A.S. Dorokhov [1], L.O. Velikanova [12], A.V. Zharinov [15], I.A. Panteleev [7], S. Kim [4], W.J. Knibbe [5], X. Han [3], Y. Yin [14], D. Onwude [6], C. Pylianidis [8], etc.

Indeed, scientific literature consider a digital twin as a tool to increase the efficiency and sustainability of agricultural production. W.J. Knibbe [5] and X. Han [3] highlight successful applications of digital twins for optimising greenhouse microclimate and animal health monitoring. S. Kim [4] and Y. Yin [14] examines the possibilities of individualised agricultural management and predictive machine maintenance. D. Onwude [6] and C. Pylianidis [8] focuses on its environmental aspects and sustainable development issues.

The methodological basis of the study was a systematic approach, a method of comparative analysis, modelling, and forecasting. During the research we analyse statistical data, analytical materials, FAO reports, reports on the development of digital technologies, case studies in peer-reviewed international journals, etc.

Main part

Characteristics and concept ofthe digital twin

Digital twins are digital models of a physical objects or systems providing a connection between a physical object in reality and its virtual model. This technology is a part of Industry 4.0 based on the collection and analysis of data from sensors and other sources to simulate various processes and scenarios, forecast, and make optimal decisions [1]. It allows ones to simulate activity of the physical object and help to save time, money, avoid many risks associated with the implementation of various changes in the environment [15].

Digital twins can be classified in term of their purpose and level of complexity. The first type is a prototype (Digital Twin Prototype, DTP); it is used at the design and development stage and contains all the information to create a physical object, including geometric, structural, and technological models. DTP allows ones to optimise and test a product before its physical implementation, reduce risks and production costs. For example, in agriculture, DTP can be used to design new models of agricultural machinery or plan farm infrastructure.

The second type is a Digital Twin Instance (DTI); it is developed for a specific physical object and accompanies it throughout its life cycle. DTI collects data on the condition of the facility, its operation, repairs, and replacements. It allows it to monitor its performance and make decisions about necessary activity. In agriculture, those monitor the condition of agricultural machinery, animals, and plants.

The third type is an aggregated twin (Digital Twin Aggregate, DTA); it combines data from multiple digital twins for managing the objects and systems. In agriculture, those manage several fields or farms through analysis of soil, yields, and climatic conditions to optimise resources and development of various strategies.

The main components of a digital twin include three key elements: data collection, modelling, and application. Digital twins use four key technologies ensuring real-time data collection, storage, analysis, and design of physical objects digital representations.

Internet of Things (IoT) forms an extensive network connecting objects, people, or their combinations. Indeed, various types of wireless sensor networks are used to collect data from physical objects. It allows ones to design digital copies for analysis, manipulation, and optimisation.

Cloud computing provides digital twins with the necessary computing resources and storage capabilities. This technology helps digital twins to store extensive data in the cloud and access the necessary information. It effectively reduces the computing time of complex systems and solves the problems associated with storing large amounts of data.

Artificial Intelligence (AI) helps to analyse data, formulate recommendations, forecast system behaviour, and propose strategies to prevent potential problems. Key areas of AI include machine learning, computer vision, natural language processing, etc.

Augmented Reality (AR/VR/MR) combines physical and virtual reality. Virtual (VR), augmented (AR), and mixed reality (MR) are subdomains included in the broad term of augmented reality. AR imposes digital information on real objects; VR and MR designs virtualised or hybrid environments for interacting with a model object.

The development of technology provides digital twins to be more complex and multifunctional. Modern digital twins can integrate data from a wide variety of sources, such as satellite imagery, meteorological data, and IoT devices. It provides modelling of various complex systems. In addition, with the development of machine learning and artificial intelligence technologies, digital twins can analyse current data, independently offer solutions to optimise processes, etc. [7].

Therefore, digital twins are increasingly being used in agriculture and forestry, animal husbandry, energy, construction, manufacturing, transport, logistics, healthcare, etc. According to MarketsandMarkets forecast, the global digital twin market will grow from 10.1 bn USD in 2023 to 110.1 bn USD by 2028, with an average annual growth rate of 61.3% over the forecast period[2].

The use of digital twins in agriculture

In agriculture, different types of digital twins are widely used. They optimise work processes and increase the efficiency of enterprises. Moreover, they design dynamic real time virtual models of physical agricultural objects, plants, animals, fields, or ecosystems. Using data from various sources such as sensors and IoT devices, satellites, drones, and weather stations, digital twins provide a deep understanding of current processes and help accurately manage agricultural operations. These models show the real state of objects, forecast their development by modelling of various scenarios using advanced algorithms, including machine learning technologies.

Precision farming is one of the key applications of digital twins. They allow farmers to simulate different crop scenarios, taking into account the soil type, climatic conditions, humidity levels, and nutrient availability to make efficient decisions for planting, watering, harvesting, management, etc.

For example, the practical application of digital twins in the tangerine orchards on Jeju Island, South Korea. According to Nature Communications Journal, scientists have developed and implemented a digital twin covering more than 185,000 hectares of tangerine plantations across the island. The system combines data from IoT sensors, satellites, open weather sources, and other digital platforms. The digital twin made it possible to track changes in the microclimate and plants, forecast yields with high accuracy.

The digital model achieved 89.6% accuracy in crop forecasts. It reduces crop losses and water consumption by 17% and 23%, respectively. Indeed, it optimises logistics and storage costs and decreases the associated costs by an average of 12% [4].

Therefore, digital twin is a tool for individualised agricultural management in terms of the specifics of zones. It ensures productivity and more sustainable resource management.

The resource management is an important aspect of digital twins' application. These technologies provide more efficient use of water, fertilizers, and various chemicals by monitoring soil and plant conditions. It significantly reduces waste, costs, and increases the sustainability of agriculture.

Willem Jan Knibbe described the use of a digital twin in greenhouse crop production in the Netherlands. The study presents a digital twin integrating data from sensors, climate models, and parameters of plants to optimise the management of microclimates in greenhouses. As a result, producers managed to reduce water consumption by 20-25%; increasing fertilizer efficiency by 18%. Moreover, modelling plant growth and automatically controlling environmental parameters (lighting, temperature, oxygen levels, etc.) increase tomato yields by 11% without increasing energy and chemical costs. It reduces the burden on the environment and provides the sustainable development of agriculture [5].

In animal husbandry, digital twins are used to monitor animal health in real time. Sensors installed on

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[2] *Markets and Markets. Digital Twin Market Size, Share & Industry Trends Growth Analysis Report by Application, Industry, Enterprise and Geography – Global Growth Driver and Industry Forecast to 2028. Source: https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html (accessed on 12.03.2025)*

animals collect data on their movement, behaviour, body temperature, and other physiological parameters. These data are transferred to a digital model analysing and identifying deviations from the norm to explore the health problems at an early stage.

For example, China has developed a digital twin model for cattle monitoring. The study used IoT sensors installed on animals to collect data on their body temperature, activity level, behaviour, and other parameters. These data were transferred into a digital model based on deep learning algorithms. The model analysed animal behaviour and detected deviations from the norm in real time. The system achieved an accuracy of 94.97% in classifying animal behaviour. It increases significantly the timeliness of disease detection and reduces losses. The model was successfully used to monitor 120 heads of cattle for 30 days, demonstrating high reliability and scalability [3].

In addition, digital twins are used in the management of agricultural machinery. The analysis of data from tractors and other machines provides predictive maintenance. It prevents breakdowns, reduces downtime, and increases the service life [11].

For example, the development of a digital twin for the Lovol GM100 combine harvester. The study implemented a lightweight digital twin system simulating both the structure of the machine and the complex kinematic relationships between its key components. One of the key elements of the system was an intelligent fuel consumption forecasting model based on the LightGBM gradient boosting algorithm based on data received from sensors in real harvest conditions.

The system covered a variety of parameters, including driving speed, transmission load, and current fuel consumption. Special attention was paid to maintaining the correct transmission of the physical behaviour of the combine units in real-time conditions. According to the field tests, the fuel consumption of forecasting system under full load conditions reaches an average error is 0.24 l/h; a maximum error is 0.84 l/h; an average relative error is 1.09% [14].

It provides the reduction of maintenance and fuel costs. Moreover, the implementation of predictive analytics helps to make technical and managerial decisions based on machine behaviour.

Moreover, the transportation, drying, cooling, and storage of agricultural products can also be optimised through using digital twins. The technologies enable real-time monitoring of the supply chain. It increases its reliability and sustainability.

Monitoring of data on temperature and humidity in the warehouse prevents a spoilage and increases a duration of products by using digital twins. Indeed, a digital warehouse twin can analyse temperature and humidity data to make timely adjustments and prevent losses.

To analyse and optimise the storage and transportation conditions of fresh cucumbers, eggplants, strawberries, and raspberries the scientists of Swiss Empa laboratory designed a digital twin. The programme organised the temperature and associate it with a loss of product quality based on measuring air temperature data. The study analysed 95 shipments in the cold chain from Spain to Switzerland. According to the results, reducing the storage time at the distribution centre by just one day increased the quality of the fruit quality index by 18% for cucumbers and eggplants and by 60% for berries. Reducing the temperature during shipment by 5°C extended duration of strawberries by an average of 36%, and raspberries by 73%. In addition, a 10% increase in relative humidity during transportation and storage reduced weight loss for all fruits studied by 20% [9].

Therefore, use of digital twins can significantly improve the efficiency of post-harvest processes, reduce product losses, and increase the quality of fruits supplied.

Generally, digital twins help model market demand and supply in accordance with the market needs. It reduces the excess production and associated costs and increases the profitability of agricultural enterprises [12].

Moreover, the technology is also used for environmental monitoring and compliance with regulatory requirements and standards. Digital models (twins) help to model and monitor parameters of greenhouse gas emissions, chemicals, soil, water, etc. It ensures quickly responding to deviations from the norm and developing measures to reduce the negative impact of agricultural activities on the environment.

One of the most significant domestic examples of digital twin technologies is Russia's largest agricultural holding Rusagro Group of Companies, Russia. The company actively uses digital twins in various segments of business, including logistics, processing of agricultural products, and crop production.

The latter uses digital field containing information about the electronic boundaries of passive zones, the history of crop cultivation, soil indicators, and the results of technological operations. It optimises the use of machinery, forecasts and monitors harvesting, etc. To plan farming rotation, Rusagro designed a digital product. It analyses more than a million scenarios for each field with a planning horizon of up to 10 years, considering chemical composition of the soil, potential yields, and market conditions.

In the fat and oil business, Rusagro designed digital twins of its oil extraction plants and raw material management models based on the Digital Farmer platform. It optimises logistics, reduces transportation costs, and improves raw material management. Based on LLamasoft Supply Chain Guru, the company has developed a tactical model for 1 year, focusing on the sunflower harvest season, and designed an operational model with a next day planning horizon. These models efficiently distribute the volume of raw materials, increase the capacity utilisation of factories and elevators, and adapt to the current conditions. As a result, the average unloading time decreased by 15%; the cost of hired transport decreased by almost 10%; the total savings on transportation costs per crop amounted to 6.2 mln RUB.

In addition, Rusagro implemented the Russian MES-class production management platform – IndaSoft at its enterprises, including elevators, the oil extraction plant in Balakovo, Saratov region, Russia and the fat plant in Saratov, Russia. It optimises the company's management processes, minimises the risks of disruptions of the production process, and ensures the import substitution.

Finally, Rusagro introduces an integrated approach to the digital transformation of the agro-industrial complex, successfully implementing digital twins to increase efficiency, reduce costs, and ensure sustainable development.

These examples of practical applications of digital twins in agriculture demonstrate their potential in optimising various processes, increasing the efficiency and sustainability of the agro-industrial complex.

Challenges of digital twin implementing

One of the main barriers to the adoption of digital twins is the high cost of their development and implementation. Digital twin function requires the development or purchasing software, stable Internet connection, cloud services for data storage and processing to integrate them into existing enterprise management systems. According to analysts, the cost of implementing a digital twin in agricultural production may exceed 50,000-100,000 USD per medium-sized enterprise, depending on its scale and complexity of the technological infrastructure[3].

The large agricultural holdings, especially in highly competitive conditions, could implement these technologies. However, such investments are unaffordable for small and medium-sized farms, especially in countries with a low level of digitalisation. According to the EU farmers survey, only 27% of small and medium-sized businesses are ready to invest in digital twins in the next 5 years. However, they note insufficient free capital and government support [8].

Additionally, digital twins require investments for start-ups, regular maintenance, software updates, and equipment calibration, increasing overall costs.

Moreover, the effective use of digital twins requires specialists with serious interdisciplinary knowledge in IT, engineering, data management, modelling, and artificial intelligence (AI). Nowadays, there is a serious shortage of such personnel, especially in developing countries [8].

Therefore, farmers and qualified employees of agricultural holdings often have difficulty interpreting the results generated by digital models. It reduces the effectiveness of digital twins using, requiring additional investments in training and retraining of personnel.

The introduction of digital twins often requires significant changes to existing processes and

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[3] *Markets and Markets. Digital Twin Market Size, Share & Industry Trends Growth Analysis Report by Application, Industry, Enterprise and Geography – Global Growth Driver and Industry Forecast to 2028. Source: https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html (accessed on 12.03.2025)*

infrastructure. It is difficult and costly, especially for businesses using the outdated technologies. Nevertheless, the integration of digital twins with other systems such as IoT and Big Data requires careful configuration and testing.

The effectiveness of digital doubles directly depends on the quality and volume of data, including sensors, satellite images, and weather forecasts. Insufficient data accuracy or lack cause the incorrect forecasts and decisions negatively affecting the management of agricultural processes.

The main issue is the heterogeneity of data from different sensors and devices. As a result, digital twins might have difficulties in integrating data from various sources, decreasing the accuracy of models and forecasts. Therefore, they require constant monitoring and calibration of equipment.

The quality of data can be directly affected by physical factors, such as failure of certain sensors, sensor drift, or power failures. Journal of Building Performance Simulation examines the issues of using streaming data in predictive digital twins [13].

Moreover, in agriculture digital twins process big data, confidential information on fields, yields, various business processes, etc. It makes them a potential target for cyber-attacks by intruders and competitors. Therefore, it is very important to ensure reliable data protection and compliance with regulatory requirements.

According to the report by Spain's national institute for Cybersecurity, INCIBE-CERT (Spain), digital twins are the critical vulnerability points as their security breach can lead to serious consequences for the operation of all industrial equipment and the safety of workers.

The study by IEEE highlights constant data synchronisation for physical and virtual environments as the relevant security risk in terms of digital twins. The most typical threats are attacks on data transmission channels, malicious interference in decision-making algorithms, and denial-of-service (DoS) attacks. Therefore, minimising risks requires spending on implementing secure communication protocols, encrypting data, creating role-based access, regularly updating software monitoring, and anomaly monitoring [10].

Hence, cybersecurity is an essential element in the implementation of digital twins. Its ignoring or being negligent can cause economic losses and endanger the sustainability of agricultural production.

Conclusion

According to the research results, digital twins are widely used in various fields of the agro-industrial complex, i.e. precision farming, greenhouse crop production, animal husbandry, logistics, agricultural machinery management, and post-harvest processes. Digital twins' implementation in Jeju Island, South Korea, the Netherlands, China, and Russia show the ability of the technology to increase yields, reduce resource costs, and optimise production processes. These examples show the high potential of digital twins as a key tool for improving the sustainability and efficiency of agriculture in limited resources and climate change.

However, the research revealed a number of serious barriers for the widespread adoption of digital twins. They are the high cost of development and implementation, the lack of qualified personnel capable of working with digital counterparts, necessary data quality and security, etc. It is particularly difficult to adapt the technology for small and medium-sized farms – a significant part of the agricultural sector worldwide.

Therefore, digital twins have sufficient potential to become a key tool for the transition to the agriculture of the future. It will provide more productive, sustainable, and adaptive agriculture. It requires coordinated efforts of the scientific community, business, and the government. However, the prospects justify the investments and risks.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR'S CONTRIBUTIONS

Anastasia V. Osadchaya – conceptualization; supervision.
Alexander P. Berus – writing – original draft.

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