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Agricultural Technologies as a Tool for Integrating Artificial Intelligence into the Agricultural Infrastructure of Ukraine

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Abstract

This study evaluates the potential of artificial intelligence (AI) and agritech solutions to drive sustainable development in Ukraine's agricultural sector during the post-war recovery period. Emphasizing high-potential technologies such as IoT-enabled precision farming and robotics, the research highlights their technical and commercial viability, as well as investment opportunities, in alignment with global trends. By employing systems analysis, formalization, and logical abstraction, the study identifies innovative solutions to enhance resource efficiency, minimize environmental impact, and promote economic growth. Key findings reveal that agritech serves as a critical enabler for rebuilding Ukraine's agricultural infrastructure, creating a post-war model that balances economic and environmental priorities. Strengthening the integration of AI and advanced technologies will enhance the efficiency and productivity of farms, bolster Ukraine's global competitiveness, and deliver positive social outcomes, including fostering digital adoption in rural communities. These insights provide a roadmap for leveraging agritech to align with sustainable development goals while addressing local challenges.

Keywords

Sustainable development; Innovative technologies; Agridrones; Smart farming; Automation

Introduction

The global climate crisis, population growth, and food security challenges demand modern and innovative management approaches. Globally, efforts are being made to develop and implement environmentally friendly technologies and products. In today’s agricultural landscape, the agrotechnology industry has become a key driver of sustainable development and a crucial factor in the economic growth of agricultural production (Shabatura, Nikoliuk and Gryshova, 2020). Digital technologies and AI are increasingly integrated into agribusiness, supporting agricultural production strategies, complementing traditional business models, and contributing to the evolution of production chains and value-creation processes. AI technologies are already widely used in agriculture, facilitating automation through machines and mechanisms equipped with GPS navigation and other advanced smart technologies, digitalization, and an ecologically balanced approach to farm management. The agricultural technology sector offers innovative solutions that redefine traditional farming methods, including process digitalization and farm automation. The agri-industrial sector is set to become an even more essential component of the global economy, as it will need to meet the demands of a population projected to reach 9.7 billion by 2050 (Neto, Brewer and Gray, 2023). This sector is poised to reduce costs, optimize time and resource use, and enhance crop yields and livestock quality. Simultaneously, the gradual transformation of the global agro-industrial sector and the adoption of new technologies are expected to increase global agricultural production by 69% from 2010 to 2050 (European Commission, n.d.).

There is an ongoing and lively discussion within the scientific community about the specific aspects of digital transformation in global agriculture. Klerkx, Jakku and Labarthe (2019) highlighted several key themes in the socio-scientific literature on agricultural digitalization. These include the adoption, use, and adaptation of digital technologies on farms; the influence of digitalization on farmers' identities, skillsets, and work processes; concerns surrounding power dynamics, ownership, privacy, and ethical considerations in digitalized agricultural production and value chains; the role of digitalization within Agricultural Knowledge and Innovation Systems (AKIS); and the economic and managerial dimensions of digital systems in agricultural production and value chains. The authors emphasize that managing the digital transformation of agriculture should carefully consider social factors and work to minimize potential negative impacts. Although studies emphasize the need for social aspects of the introduction of digital technologies, there is insufficient information on how exactly to adapt global technological solutions to the local conditions of Ukraine, especially in the context of post-war reconstruction.

Ingram *et al*. (2022) argue that digital agriculture policies require a broader evidence base. Khaustova *et al.* (2021) highlight issues within state policy on technology transfer in the agribusiness sector, particularly in the context of its legal support. Tielkiniena *et al.* (2020) emphasize the advancement of agricultural lobbying at the legislative level, enabling a more responsive approach to global market dynamics. MacPherson *et al*. (2022) examine high-level policy and legislation in Germany and Europe, identifying the key institutional, social, and legal prerequisites for implementing digital agriculture, which supports various sustainable development goals. They propose specific measures, such as financial support, training, and advisory services, to help small farmers overcome barriers to implementing these initiatives effectively.

In their study, Garske, Bau and Ekardt (2021) present a somewhat contrasting perspective to that of MacPherson *et al*. (2022). They argue that digital innovation and artificial intelligence can significantly contribute to the sustainable advancement of agriculture and the achievement of climate and environmental goals. Garske, Bau and Ekardt (2021) highlight that precision farming technologies can reduce nutrient surpluses and water pollution, while digital technologies can monitor emissions and support environmental protection efforts. Additionally, MacPherson *et al.* (2022) examine digital transformation processes that facilitate the transition to renewable energy sources. Garske, Bau and Ekardt (2021) emphasize that key prerequisites for agricultural digitalization include the advancement of power grids, data transmission infrastructure, and public investment. Although studies consider the potential of digital innovations for the sustainable advancement of agriculture, they do not take into account the specifics of the economic challenges of the post-war period.

The study by Neto, Brewer and Gray (2023) on data collection and usage across the agricultural supply chain reveals significant heterogeneity in data collection and analysis practices. Increased customer satisfaction and improved decision-making were identified as the primary benefits of data utilization. However, the anticipated benefits and challenges of implementing these efforts vary, with companies at the initial stages of the supply chain often differing in their views on the perceived advantages and obstacles. Ehlers *et al*. (2022) suggest that digitalization scenarios in the agricultural infrastructure should incorporate diverse perspectives, particularly focusing on transparency, data management, efficiency, workflow automation, privacy, and control. The authors highlight the need to consider uncertainties and the variety of long-term policy strategies, as well as to define the roles of governments, agribusinesses, non-governmental organizations, and other stakeholders in shaping effective strategies. They conclude that successful digitalization in agriculture requires accessible digital infrastructure, flexible strategies, and the integration of responsible research and innovation into agricultural policy. The digitalization processes in the agricultural infrastructure vary significantly based on the specific circumstances and context of each country. Countries may be Internet of Things (IoT) in various phases of development and show varying levels of efficiency based on available resources, infrastructure, and technological maturity.

In Ukraine, the potential for digitalization in the agricultural infrastructure is expanding even during wartime, as highlighted in scientific studies focused on rapid agricultural innovations and the use of artificial intelligence (Balian *et al.*, 2023). Agriculture in Ukraine is increasingly adopting "smart" characteristics, driven by the strong motivation of domestic farmers for post-war recovery and restoration of land resources, particularly in heavily impacted areas. These studies provide valuable insights into the opportunities and challenges of Ukraine’s agricultural digital transformation and help identify strategic directions for further development. The purpose of this study was to establish agricultural technologies as key enablers of AI in Ukraine's agricultural sector. Consequently, this research highlights the potential of AI to support the sustainable development of Ukraine’s agricultural industry in the post-war period.

According to research by ICL Group (2024), modern agrotechnologies play a key role in enhancing the efficiency and sustainability of agriculture. The primary technologies highlighted in this study include precision agriculture, the Internet of Things (IoT), artificial intelligence and machine learning, robotics and automation (e.g., the use of robots to perform various agricultural tasks, from sowing to harvesting), vertical farming, and biotechnology. These technologies have significant potential for application in the post-war reconstruction of Ukraine's agricultural sector. For example, precision agriculture and IoT can help optimize resource use on restored agricultural lands, while robotics can mitigate labour shortages in rural areas. The ICL Group study emphasizes that implementing these technologies requires not only technical knowledge but also changes in farm management approaches and farmer training. This aligns with Klerkx, Jakku and Labarthe (2019), who highlighted the importance of social factors in adopting digital technologies in agriculture.

This research aims to analyze the potential and prospects of integrating artificial intelligence technologies into Ukraine's agricultural sector, specifically to: Identify the key areas of application for AI technologies in agriculture. Assess the impact of implementing innovative technologies on the efficiency and productivity of agricultural production in Ukraine. Explore current trends in the advancement of the Internet of Things (IoT) and other AI solutions in the global agricultural infrastructure and their relevance to Ukraine. Identify opportunities, obstacles, and challenges on the path to digital transformation of Ukrainian agriculture. Develop recommendations for the effective integration of artificial intelligence technologies into Ukraine's agricultural sector, taking into account local specifics.

Materials and Methods

This study was conducted as a comprehensive analytical review focused on examining the role of agrotechnologies as tools for integrating artificial intelligence (AI) into Ukraine's agricultural sector. It was based on secondary data analysis and the application of various analytical methods. The selection of methods was adapted to the multifaceted nature of the research problem, prioritizing approaches that ensure a holistic and detailed understanding. This study was conducted as a comprehensive analytical review to explore the role of agricultural technologies as tools for integrating artificial intelligence (AI) into Ukraine's agricultural sector. A combination of qualitative and analytical approaches was employed to address the multifaceted nature of the research problem, ensuring both a holistic and detailed understanding of the subject matter.

To examine the interconnections among various components of agricultural technology implementation, a systems analysis approach was adopted. This method allowed for the identification of systemic links between technology adoption and its impact on productivity, sustainability, and economic outcomes. Frameworks such as SWOT were utilized to evaluate the strengths, weaknesses, opportunities, and threats associated with AI-driven agricultural innovations. The holistic perspective offered by systems analysis was critical for understanding the complex dynamics of technology integration in the context of post-war reconstruction.

Formalization was another key methodological tool, used to systematically structure and categorize data. This approach provided a clear representation of the current state and future potential of agricultural technologies in Ukraine. The use of formalization ensured that the analysis remained focused and precise, allowing the study to distill actionable insights from a diverse range of data sources. To generalize trends and conceptualize key aspects of Ukraine’s agricultural development, abstract analysis was employed. This method facilitated the identification of patterns critical for the successful implementation of agricultural technologies. Complementing this, logical analysis was used to establish connections between technological adoption and environmental sustainability, supporting the study's argument regarding the role of agricultural technologies as drivers of AI integration and post-war agricultural recovery. These methods were chosen for their ability to effectively interpret secondary data while addressing the complexity of the problem.

The study relied heavily on secondary data sources, including reports from Data Bridge and Mordor Intelligence, as well as statistical data from the Ministry of Agrarian Policy and Food of Ukraine. Reports by Data Bridge and Mordor Intelligence provided valuable insights into global market trends and technological advancements, known for their rigour and relevance. These reports were critically evaluated to mitigate potential biases and ensure their applicability to the Ukrainian agricultural context. Statistical data from the Ministry encompassed key indicators such as production volumes, cultivated areas, and labour productivity, which were essential for assessing the current state of the sector. These data were collected and processed using standardized international methodologies, ensuring reliability and relevance. However, it is important to acknowledge that the exclusive use of secondary data may limit the study's originality and depth. Commercial reports and industry forecasts, while valuable, may carry inherent biases due to their market-oriented perspectives. Although efforts were made to critically assess these sources and cross-reference findings with other datasets, the absence of primary data collection restricts the ability to directly validate conclusions. Incorporating primary data, such as interviews, surveys, or field studies, in future research would provide richer insights and strengthen the empirical foundation of the analysis. To assess the investment potential and integration opportunities for agricultural technologies in Ukraine, the study applied a systematic evaluation framework. Key indicators such as market size, growth projections, and adoption rates were analyzed to determine the feasibility and attractiveness of agritech investments. The analysis incorporated comparative benchmarking, where Ukraine's performance was measured against leading agritech markets, and scenario analysis to project the long-term impact of integrating advanced technologies. These methods provided a structured evaluation of both the economic viability and scalability of innovations, addressing specific challenges such as labour shortages and resource optimization.

By integrating these approaches and acknowledging the study's limitations, the research ensured a comprehensive yet transparent analysis of how agricultural technologies can drive sustainable development and economic recovery in Ukraine. This methodology provided a robust foundation for understanding the interplay between technology and sustainability, while also offering actionable insights to guide future strategies.

Results and Discussion

Overview of Modern Agricultural Technologies

One of the key areas of modern agricultural technology is precision farming, which implements the Internet of Things (IoT), computer vision, and artificial intelligence (AI). Technologies such as drones and robots are actively used to automate agricultural processes, reducing the need for physical labour. For example, the global IoT market in

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agriculture, according to Data Bridge Market Research (2024), reached $6.95 billion in 2023 and is projected to grow to $22.45 billion by 2031 (Figure 1).

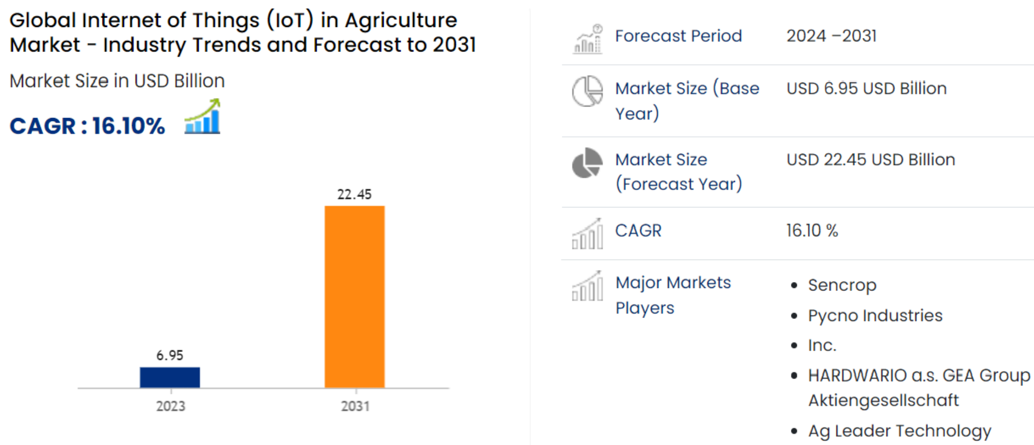

Figure 1: Global Internet of Things (IoT) Trends and Forecast in the Agriculture Market to 2031

This forecast highlights the growing interest in IoT technologies; however, the report primarily focuses on global market trends, which may only be partially relevant for Ukraine due to its specific context. The implementation of these technologies in Ukraine requires adaptation to local conditions, including limited infrastructure and a lack of financial resources for farmers. The report "Global IoT in Agriculture Market – Industry Trends and Forecast to 2031"[1] states that IoT enables precise monitoring of soil and crop conditions, optimizes resource usage, and automates processes. For Ukraine, this holds particular value in restoring agricultural lands damaged during the war. However, the report does not account for the challenges related to the low technological readiness of farmers in post-conflict regions, which may hinder the adoption of even proven solutions.

Introduction of Agricultural Technologies in Ukraine

The introduction of IoT sensors in Ukrainian farms could reduce water and fertilizer usage by 20–30% and increase yields by 15–20% (Shabatura, Nikoliuk and Gryshova, 2020). However, as Garske, Bau and Ekardt (2021) point out, the high costs of installing and maintaining IoT infrastructure remain a significant barrier, especially for smallholder farms. According to forecasts, the AI market in the agricultural sector is expected to grow from $1.7 billion in 2023 to $4.7 billion by 2028, with a compound annual growth rate (CAGR) of 22.5% (AI in Agriculture Market Size).[2] While these figures demonstrate the potential of AI for global agriculture, they do not account for Ukraine's local challenges, such as the lack of infrastructure and skilled specialists. Companies like Microsoft Corporation and Prospera Technologies Ltd. are investing in partnerships and innovations to secure competitive advantages. For Ukraine, this

[1] Global Internet of Things (IoT) in Agriculture Market – Industry Trends and Forecast to 2031. (2024). Available online at: https://shorturl.at/gnDD6 [Accessed on 23 October 2024].

[2] AI in Agriculture Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029) (2024). Available online at: Source: https://www.mordorintelligence.com/industry-reports/ai-in-agriculture-market [Accessed on 23 October 2024].

presents an opportunity to attract foreign investments, but only if global solutions are adapted to local needs. For example, AI can be effectively used to monitor soil conditions in regions that have undergone significant anthropogenic impact, particularly due to military actions.

This underscores the potential for leveraging advanced technologies to address both environmental and economic challenges. Global examples, such as the use of drones for crop monitoring by John Deere, show a 25% reduction in field treatment costs and a 20% increase in efficiency. In Ukraine, a similar approach is being applied by "Astra-Kyiv," which introduced drones for crop monitoring in 2023, enabling timely detection of diseases and optimization of field treatment costs. However, as noted by Neto, Brewer and Gray (2023), the effectiveness of technology implementation depends not only on its technical feasibility but also on social and economic conditions, such as access to financing and farmer training. Ukraine faces the challenge of a low level of farmer readiness for digital transformations, which may hinder the pace of AI and IoT adoption.

Economic Impact of Agricultural Technologies

The agricultural technology sector has several advantages, including increased efficiency and productivity, water conservation, cost reduction, improved safety, and enhanced sustainability. It is important to note the following growth factors: labour shortages, high labour costs, advancements in artificial intelligence and the Internet of Things, limited supply, and global dependence on advanced technologies. In this direction sources such as Data Bridge Market Research (2024) and Agriteka (2023) highlight the key benefits of agricultural technologies, including increased efficiency, resource savings, and cost reduction. However, many of these reports have a global focus and may insufficiently address the specific market conditions of countries like Ukraine. For instance, while the integration of IoT is noted to enhance water conservation and resource management, its implementation in Ukraine may be constrained by the limited availability of infrastructure and the high cost of equipment.

Despite these challenges, there are agricultural enterprises in Ukraine actively adopting IoT technologies, computer vision, and artificial intelligence (AI) to improve efficiency and automate processes. Notable examples include agricultural holdings such as "Ukrlandfarming," "Industrial Milk Company" (IMC), "Astra-Kyiv," and "Myronivsky Hliboproduct" (MHP). For instance, "Ukrlandfarming" employs a telemetry system consisting of external sensors to automatically collect data on irrigation, fertilizer application, and harvesting. This system optimizes resource use and improves production efficiency. The company "Astra-Kyiv" has introduced drones for monitoring crop conditions, enabling timely adjustments to growing conditions and reducing processing costs.

These examples demonstrate the potential of advanced technologies to transform agricultural practices in Ukraine. However, scaling such solutions to a national level requires addressing systemic challenges. Global estimates of the IoT and AI markets indicate significant growth potential, but their adaptation to local conditions remains a key challenge. For instance, the cost savings of up to 30% and the profitability increase of 15–20% mentioned in Table 1 from IoT implementation can only be achieved if proper infrastructure is established and access to financing is provided for small and medium-sized farms (Table 1).

Table 1: Successful projects of integration of AI and agricultural technologies into agricultural sectors of Ukraine

Project/ Technology	*Application Area*	*Impact*	*Increase in Profitability (%)*	*Cost Savings (%)*
IoT for Soil Monitoring	Precision farming	Improved resource allocation	15–20	30
AI for Yield Prediction	Forecasting crop yields	Enhanced decision-making accuracy	10–15	20
Robotics in Harvesting	Automation of harvesting	Reduced labour costs and efficiency	25-30	40
Drones for Crop Scouting	Monitoring crop health	Early detection of diseases	12-18	25
Smart Irrigation Systems	Water management	Optimized water usage	8-12	35

This gap highlights the importance of localized strategies for technology adoption, which are often overlooked in global analyses. Many sources, such as Drach (2024) and Garske, Bau and Ekardt (2021), pay insufficient attention to the methodology of technology implementation in the context of individual countries. For example, while cases of drone and robot deployment in the U.S. and EU countries are described, there is a lack of detailed information on adapting these practices to Ukraine's conditions, where farmers often face challenges such as limited access to training, resource constraints, and underdeveloped digital infrastructure. A more accurate analysis would require consideration of factors such as farm size, farmers' readiness for digitalization, and state support. Specifically, the metrics mentioned in the table, such as water savings or reductions in labour costs, may vary significantly depending on the type of farming operation and regional specifics.

For medium and small agricultural enterprises, the implementation of agrotechnologies requires significant capital investments. The introduction of IoT technologies in agriculture is associated with certain financial challenges. Initial costs for purchasing modern devices, sensors, and infrastructure can be quite high, especially for small farms or those located in regions with limited resources. Additionally, ongoing costs for maintenance, storage, and equipment connectivity further increase the overall expense of implementing IoT solutions. To overcome financial barriers, small and medium-sized enterprises in Ukraine's agricultural infrastructure need to utilize various financial models and actively engage with government support. Successful strategies for collaboration, cooperation, and training can significantly enhance the chances of successfully integrating new technologies and ensuring the sustainable development of agribusiness in Ukraine.

Social and Environmental Impacts

However, the implementation of innovative farming technologies is hindered by farmers' low technological readiness, limited awareness, restricted learning opportunities, and distrust of innovations. Problems with internet connectivity and inadequate digital infrastructure further constrain farmers' capabilities. Moreover, many modern technological solutions are not adapted for small farms, creating challenges in integrating innovations with traditional practices.

The reduced demand for physical labour may lead to population migration from rural areas to cities in search of work. This trend can cause demographic shifts and an ageing population in rural communities.

1. Social inequality. Farmers with greater resources may implement new technologies more quickly, potentially exacerbating social inequality between large agricultural companies and small farmers. Small farmers may struggle to access financing and training.
2. Changing the role of farmers. Farmers are evolving from being mere producers to becoming managers of technological processes. This transformation alters their role in society and imposes new educational and professional training requirements.

Research on farmers' readiness for digitalization is critical for understanding their training needs. Many farmers may be insufficiently prepared to use new technologies as a result of a lack of access to education or resources. It is necessary to develop specialized training programs for farmers that cover the basics of digital technologies, data management, and the use of modern agricultural practices. This will help farmers adapt to changes and enhance their competitiveness. Government support programs and funding can assist small farmers in implementing new technologies and receiving training. Collaboration between agribusiness and educational institutions can also contribute to fostering essential skill development in rural communities. Thus, the digitalization of the farming infrastructure holds the capacity to reshape employment and the social structure of rural communities in Ukraine. However, for the successful integration of new technologies, it is essential to increase farmers' readiness for change and address their training needs. Developing effective support and training strategies is key to ensuring the sustainable development of the agricultural infrastructure and improving living conditions in rural communities.

Building on this, the practical application of digital technologies by Ukrainian agricultural enterprises offers valuable insights into the potential benefits of innovation. The examples of Ukrainian companies, such as "Ukrlandfarming" and "Astra-Kyiv," demonstrate positive outcomes from implementing innovations; however, their impact on the sector requires further quantitative evaluation. For instance, while "Ukrlandfarming" successfully uses a telemetry system for irrigation monitoring, there is a lack of information regarding the long-term effectiveness of these innovations and their impact on the sustainability of farming enterprises. The studies by Ingram *et al.* (2022) and MacPherson *et al.* (2022) emphasize the importance of the social aspects of digitalization, such as its effects on employment and the evolving requirements for qualifications. In the Ukrainian context, these challenges become even more significant due to rural population migration and inequalities between small-scale farmers and large agricultural holdings. While global trends in agrotechnologies show significant potential, their implementation in Ukraine requires adaptation to local conditions. Most studies focus on the technical aspects of innovations but insufficiently address the social, economic, and infrastructural challenges. Future research should concentrate on developing localized strategies that integrate successful global practices while accounting for the realities of Ukraine.

Investment Opportunities and International Cooperation

At the same time, Ukraine's vast agricultural land areas and the significant role of agriculture in the national economy present substantial investment opportunities. Among the most promising areas is the development of land demining technologies, which are essential for restoring agricultural productivity in regions affected by military activities. Modern agricultural technologies, like autonomous aerial vehicles (drones) and artificial intelligence systems, can be used for effective monitoring of contaminated areas. For instance, the combination of drone reconnaissance with mechanized demining tools allows for faster and safer clearing of large agricultural fields from mines and shells. This accelerates the return of land to agricultural use, which is critical for food security. For example, the Ukrainian UAV SKIF, developed by Culver Aviation, is used for field measurements and crop monitoring. With high image accuracy (up to 1 cm per pixel), SKIF helps farmers obtain detailed outlines of their plots, enabling optimized planting and disease prevention. Mordor Intelligence (2024) highlights that global trends, such as the development of data analytics and the accessibility of precision agriculture technologies, are key drivers of investment. However, these reports focus on general global trends and often fail to account for the specific conditions of the Ukrainian market, including limited infrastructure and unequal access to technologies for smallholder farms.

The agreement between Ukraine's Ministry of Economy and Palantir for implementing technologies for humanitarian demining serves as a successful example of collaboration with international partners. The use of data analysis platforms like Palantir enhances the efficiency of demining processes, but the practical application of such technologies is constrained by their high cost and the need for specialized training. This underscores the necessity of developing programs that provide local companies with access to similar solutions. On the other hand, the use of SKIF drones and THEMIS ground robots for demining agricultural lands is a significant achievement in the development of agricultural technologies. However, further research is needed to understand the long-term impact of these technologies on productivity and land restoration. These factors collectively create a favourable environment for investments in agricultural technologies, stimulating innovation and contributing to the growth of the Ukrainian economy. Thus, investors can consider Ukraine's agricultural technologies as a promising sector, especially amid the ongoing development of technologies and the increasing global demand for agricultural products. The creation of such collaborative platforms indicates a readiness to invest in agricultural technologies in Ukraine. Foreign investors' interest in agricultural technologies is explained by the fact that Ukraine is a powerful agricultural player. Given the significant potential of Ukrainian agriculture, investors can expect substantial opportunities for development and innovation in the agritech sector. This underscores the importance of collaboration between local developers and international investors, fostering further technology development and improving the efficiency of Ukraine's agro-industrial complex. It is also worth noting that Ukrainian agritech startups have opportunities to attract investments and receive support through various forms of funding, including grants from public or private funds, as well as through accelerators, incubators, and ecosystems. AgTech Ukraine, a company founded in 2015 to promote the development of a high-tech market for Ukraine's agricultural sector and advance Ukrainian technologies on the international stage, has already invested over $1 million in promoting agritech in Ukraine. Tielkiniena *et al*. (2020) indicate that the scalability of agricultural technologies for small farms remains a critical barrier. This is also true for Ukraine, where small farmers face challenges in accessing financing and digital infrastructure. Despite support from organizations like AgTech Ukraine, which has invested over $1 million in agritech development, these efforts need to be expanded to address systemic issues.

The Global Innovation Mission for Ukraine until 2030 identifies agritech as one of its priorities, providing a positive signal for investors (Ministry of Digital Transformation of Ukraine, n.d.). MacPherson *et al*. (2022) highlight that the creation of subsidies and financial incentives is key to overcoming barriers to technology adoption. For Ukraine, this necessitates the development of targeted support programs aimed at infrastructure development and farmer training. However, while these high-level initiatives provide a roadmap for progress, many sources, such as Wang (2024) and Mordor Intelligence (2024), focus on macroeconomic data and global trends, often overlooking the unique challenges faced at the local level. For instance, market estimates for IoT and agritech often do not account for specific conditions faced by small farmers in Ukraine, such as limited financing or access to specialized training. This creates gaps in understanding how these technologies can be adapted to the Ukrainian context. The investment potential of agritech in Ukraine remains high, but its realization requires overcoming several barriers, including limited infrastructure, high technology costs, and unequal access to innovations for small farmers. A critical analysis of the sources highlights the need to localize global solutions and develop targeted government support programs. Successful collaboration between international and local partners, such as the agreement with Palantir, demonstrates the potential of investments in the agritech sector while emphasizing the importance of institutional support and adapting innovations to local conditions.

Advancing Agricultural Robotics in Ukraine

Building on this foundation, agricultural technologies are increasingly recognized as essential tools for addressing global challenges related to sustainable development and employment in agriculture. Rising labour costs and declining availability, exacerbated by border closures, economic instability following the COVID-19 pandemic, and Russia's military aggression against Ukraine, have placed significant strain on farmer incomes. Over the past decade, the implementation of agricultural technologies in Ukraine has been vital not only for reviving its economy after the war but also for contributing to global food security. To effectively address these challenges, Ukraine must prioritize investments in innovative agricultural solutions that ensure a stable level of production and sustainable practices. Automation can help alleviate these problems. Advancements in robotics and artificial intelligence have made the use of agricultural robots a more realistic option. Around the world, many startups and established companies have developed ready-made solutions for various agricultural tasks such as weeding, planting, and harvesting.

Agricultural robotics is rapidly evolving due to modern technologies. Everyday tasks on the farm are often repetitive, time-consuming, and dangerous, making them ideal for automation using robotic systems. In Ukraine, robotic systems are actively being implemented in agricultural enterprises, significantly improving the effectiveness of agricultural production. Companies like Ecorobotix have developed robots that can automatically detect weeds and spray them with a small dose of herbicides. This reduces the use of chemicals by 2-3 times, representing an environmentally safe approach. John Deere has introduced the electric tractor robot Sesam 2, which can perform tasks such as soil cultivation and harvesting. This tractor can work in synergy with other robots, ensuring overall productivity. The use of drones for the early identification of diseases in fields allows agronomists to conduct timely treatments. Drones are equipped with high-definition cameras and GPS, providing detailed images of crops. The Aquarius robot is used for automated irrigation of plants in greenhouses. It can operate in two modes: a fixed mode, where the agronomist sets the irrigation rate, and a proportional mode, where the robot independently determines the necessary amount of water using sensors. Robots are also used in automated livestock management systems, enabling farmers to effectively monitor the health of livestock and provide proper care. Robots for tillage can perform various tasks, such as soil cultivation and planting. They free farmers from hard labour and enhance the efficiency of crop production. However, regulatory restrictions still hinder the widespread adoption of agricultural robotics, and the level of autonomy of these systems remains relatively limited. Despite this, the market for agricultural drones is expected to continue to grow actively for the foreseeable future. Other areas of robotic applications in agriculture are still developing. Field robots that perform tasks such as weeding and planting are in the early stages of commercialization. Unlike milking robots, which are stationary and typically operate indoors, the advancement of autonomous field robots faces several technical challenges that have historically restricted progress in this area.

In Ukraine, the implementation of field robots that perform tasks such as weeding and planting is still in the early stages of commercialization. However, unlike stationary milking robots that operate indoors, autonomous field robots face several technical challenges that limit their development. Some agricultural companies in Ukraine are testing robots for automated weed removal. These machines utilize machine vision and AI-based technologies to accurately identify and remove weeds without harming the crops. Ukrainian farmers are beginning to implement automated planting robots capable of precisely placing seeds in the fields. This helps reduce resource usage and increases planting efficiency. The use of drones for monitoring fields and applying fertilizers is becoming increasingly popular. Drones can quickly cover large areas, providing agronomists with crucial information about plant conditions. Companies like John Deere are developing electric robotic tractors capable of executing tasks related to soil cultivation and harvesting. These robots help reduce the physical burden on farmers and enhance productivity. Some agricultural enterprises are implementing automated irrigation systems that can autonomously determine the water needs of plants and supply them according to environmental conditions. Thus, while field robots in Ukraine may not achieve widespread commercialization yet, their implementation can significantly improve the effectiveness of agricultural production in the country.

The agricultural environment has its unique challenges, such as unpredictable terrain, unknown obstacles, and changing weather conditions, which can complicate autonomous navigation and operation, as well as reduce the reliability of these systems. Furthermore, many agricultural regions are located in rural areas where access to communications, as well as repair and maintenance services, may be limited. Despite these challenges, significant progress has been made in computer vision and AI technologies, bringing field robotics closer to commercial use. Startups like Naïo Technologies, ecoRobotix, and TerraClear are actively commercializing robots for various agricultural tasks. Meanwhile, major equipment manufacturers like John Deere, AGCO, and Kubota are working on developing autonomous tractors. The Fendt MARS project offers a glimpse into the future of agricultural robotics by utilizing small autonomous robots to perform tasks traditionally carried out by piloted tractors. The results of this project have laid the groundwork to further the development of the Xaver agricultural robot lineup. Companies such as Octinion, Harvest CROO, and FF Robotics are investing in the progression of robotics for harvesting fresh fruits, as this is an important agricultural activity that remains a significant challenge for automation. This work requires a precise balance of using computer vision to determine fruit ripeness, accurate positioning for precise harvesting, and soft-grasp technology to avoid damaging the fruit during collection. These companies are developing innovative solutions aimed at improving the efficiency and quality of the fruit harvesting process, which can positively impact overall agricultural production, as the progression of agricultural robotics leads to the emergence of new value-added chains (Figure 2).

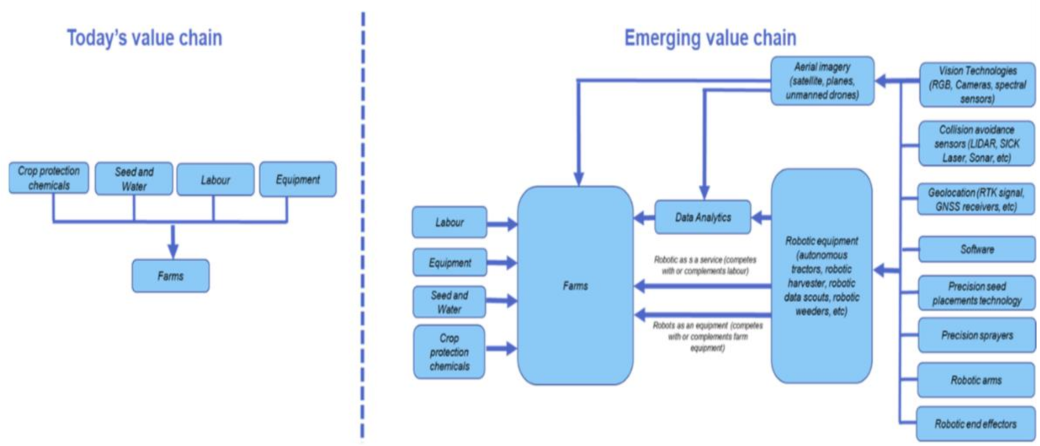

Figure 2: The advancement of agricultural robotics leads to the emergence of new value chains

Wang (2024) highlights the growing use of agricultural robots and their potential to automate complex processes, such as fruit harvesting. However, challenges related to adapting these technologies to the conditions of Ukrainian farms remain underexplored. For instance, field robots face technical obstacles, such as uneven terrain and unstable weather, which can limit their applicability. Moreover, startups like Naïo Technologies and ecoRobotix focus on developing environmentally friendly solutions, such as robots for weed control. However, these solutions require significant initial investments, which can pose challenges for Ukrainian farmers who lack access to subsidies or grants. Therefore, while global advancements in agricultural robotics offer promising solutions, their successful implementation in Ukraine necessitates tailored approaches that consider local challenges and provide adequate financial and infrastructural support to farmers. Building on this, smart farming in Ukraine is indeed becoming an increasingly important area of agricultural development. The application of modern technologies, such as sensors and data collection systems. Automation in growing various crops helps optimize production processes, reducing labour and resource costs.

The incorporation of diverse technological solutions opens new opportunities for farmers, helping to enhance their productivity and profitability. The advancement of this direction in agriculture is a key factor in supporting sustainable and efficient food production. Ehlers *et al*. (2022) and Neto, Brewer and Gray (2023) highlight the significant potential of precision farming technologies to reduce resource losses, lower emissions, and improve biodiversity. These findings are particularly relevant for Ukraine, where environmental issues have become increasingly critical due to the consequences of war. However, these studies primarily focus on developed countries with advanced infrastructure. Adapting these practices to Ukraine's realities requires additional analysis, especially considering the country's limited digital infrastructure and insufficient funding for small-scale farms. Projections from sources like "TOP-5 Reasons..."[3] indicate significant growth in the IoT market in agriculture by 2029. However, most studies, including these, fail to account for regional differences, such as the lack of internet access and infrastructure in rural Ukraine. To adapt these technologies in Ukraine, targeted funding programs and technical support initiatives are necessary. Moreover, while sensor technologies promise resource conservation and efficiency gains, the costs of installation and maintenance remain substantial barriers for Ukrainian farmers. This underscores the need for financial instruments, such as government subsidies and grants, to support farmers in adopting these innovations. In parallel, the projected growth of the AI market in agriculture by 2028 highlights a growing interest in the integration of advanced technologies into farming practices. Artificial intelligence offers significant benefits over traditional farming methods, including precision farming, drone analytics, and the use of agro robots. These advantages include increased efficiency, accuracy, and reduced resource costs.

The Ukrainian context underscores the importance of adapting global technologies. For example, Borrero and Mariscal (2022) highlight that the use of IoT and drones enhances water resource and nutrient management. However, their study does not address the economic barriers, such as the high cost of implementing these technologies, which may hinder their adoption among Ukrainian farmers. The high cost of IoT and drone technologies presents a significant challenge, particularly for small-scale farmers who comprise a large portion of Ukraine's agricultural sector. Artificial intelligence, as noted by Agriteka (2023) and Ehlers *et al*. (2022), holds great potential for optimizing production processes, such as monitoring plant and livestock health. However,

[3] TOP-5 reasons why you need to use touch agtech technology in 2023 (2023). Available online at: https://agriteka.com/2405-top-5-prichin-chomu-potrbno-vikoristovuvati-sensorn-agtech-tehnologyi-u-2023-roc.html (Accessed on 1 February 2024).

implementing these technologies in Ukraine faces challenges related to a lack of specialists and limited access to high-tech equipment. Addressing these challenges requires comprehensive training programs tailored to farmers and agronomists. Additionally, Borisova *et al*. (2020) emphasize the importance of engaging young specialists in managing technological systems but fail to consider the issues of workforce migration and demographic challenges in rural areas. Successful implementation of these solutions necessitates accounting for social factors, including worker motivation and the development of educational programs. While global studies emphasize the potential of agricultural technologies, their implementation in Ukraine faces various challenges, including technical, financial, and social barriers. Adapting global solutions to local conditions requires a comprehensive approach that includes infrastructure development, educational programs, and financial support mechanisms. Combining global innovations with local adaptations will be key to the sustainable development of Ukraine's agricultural sector.

Innovative Agrotech Solutions for Ukraine

Building on this foundation, the post-war recovery of Ukraine's agricultural infrastructure should be underpinned by smart Agrotech models that dynamically enhance resilience and facilitate the restoration of devastated areas. The strengthening of the integration process of advanced farming technologies into Ukraine's agriculture can significantly modernize the agricultural infrastructure with innovative solutions, increase the investment attractiveness of the industry and the efficiency of agricultural businesses, and reduce risks associated with the extreme conditions of restoring land resources. This includes the following key aspects:

1. Water Quality Monitoring via Semtech Long-Range Wide-Area Network (LoRaWAN) Standard: This will allow for effective and reliable large-scale water quality monitoring, which is particularly important for agriculture in dispersed and expansive areas. The information obtained from such monitoring will enable farmers to make informed decisions about water resource management and reduce environmental impact.
2. Use of ExactRate Technology for Optimizing Fertilizer Use: This will enhance the efficiency of fertilizer application and reduce costs, which may lead to increased yields and minimize negative effects on soil resources and the environment.
3. Application of IoT for Managing Weather-Related Risks: Through IoT-based weather monitoring and forecasting systems, farmers can receive early warnings about potentially hazardous weather conditions, such as droughts or floods, and take timely measures to protect their crops and property.
4. Increasing Awareness and Investment in Europe for IoT in Agriculture: Encouraging farmers to adopt IoT technologies in agriculture is a crucial step toward creating a sustainable and efficient agricultural system. European experience can serve as a model for Ukraine in implementing cutting-edge solutions in this area.

All these measures improve risk management, enhance the efficiency and resilience of Ukrainian agriculture, and rejuvenate the environment.

The Ukrainian agricultural infrastructure is indeed one of the key industries in the economy, and its significance is increasing in the context of the war. The development and implementation of modern agrotechnologies can play a significant role in ensuring the resilience and productivity of this sector. The adoption of agrotechnologies, such as process automation and precision agriculture, can substantially increase crop yields. For instance, technologies that use data to optimize production enable farmers to reduce resource costs and enhance land use efficiency. This is especially important in wartime conditions, where resources may be limited. The agricultural infrastructure in Ukraine is facing significant losses due to negative impacts such as weather conditions and economic difficulties. The use of agrotechnologies can help mitigate the effects of these factors. For example, monitoring and forecasting systems can assist farmers in adapting their strategies to changing climate and market conditions. This ensures greater resilience of agricultural enterprises to risks, which is critical under the current circumstances. Ukraine has significant potential in utilizing water resources and land. Modern technologies can contribute to their rational use. For example, precision agriculture systems can optimize water and fertilizer usage, achieving not only productivity but also reducing detrimental effects on the environment. The advancement of agricultural technologies also stimulates innovative activities in agriculture. This can involve the creation of innovative plant varieties and the implementation of drones for field monitoring. Investments in agrotechnologies facilitate the attraction of both domestic and foreign investments, modernizing the infrastructure of the agricultural infrastructure and achieving competitiveness in the global market. Thus, modern agrotechnologies possess the capability to significantly enhance the resilience and productivity of Ukraine's agricultural infrastructure in wartime. They not only help reduce vulnerability to external factors but also promote rational resource use and the advancement of innovative activities.

The combination of technical innovations with social aspects creates a comprehensive approach to the advancement of the agricultural sector, which can significantly improve farmers' lives through increased production efficiency, improved decision-making, social adaptation, and environmental sustainability.

The study by Klerkx, Jakku and Labarthe (2019) emphasizes the social aspects of digitalizing agriculture, highlighting that the adaptation of technologies must take local conditions into account. This is particularly relevant for Ukraine, where the implementation of innovative solutions faces challenges such as a lack of skilled personnel and limited financial resources. While global trends showcase the advantages of agrotechnologies, such as reducing resource use and increasing yields, their effectiveness in Ukraine depends on adapting to the country’s specific conditions. Findings of Garske, Bau and Ekardt (2021) confirms that artificial intelligence and precision farming can contribute to achieving environmental goals. However, in the Ukrainian context, these technologies must account for local climatic conditions and the types of crops being cultivated. For example, the experience of companies like "Ukrlandfarming" demonstrates that telemetry systems can significantly optimize the use of water and fertilizers, but their implementation requires substantial investments and staff training.

The adaptation of technologies also involves educating farmers and raising their awareness of new tools. Successful projects demonstrate that without proper training and support, farmers may encounter difficulties in adopting new technologies. For example, companies implement training programs for their employees, which promote better understanding and utilization of AI. The adoption of AI demands substantial capital investments, posing challenges for small and medium-sized enterprises. Local market characteristics, such as the availability of financing and investments, affect the pace of technology adoption. For example, projects may be adapted according to the financial capabilities of farmers, allowing for the avoidance of excessive financial burdens. Specific examples of successful projects in Ukraine, such as the telemetry collection system for the agroholding "Ukrlandfarming," demonstrate how AI can be integrated into existing processes. This system not only automates processes but also enables farmers to obtain data for task execution in real time, which is critical for enhancing productivity. Water quality monitoring technologies, particularly the use of the LoRaWAN standard, can play a crucial role in restoring lands contaminated as a result of the war. Research by Ingram *et al*. (2022) highlights the effectiveness of such technologies in reducing the environmental impact of agriculture. However, large-scale implementation in Ukraine faces challenges, such as insufficient infrastructure and the high cost of equipment.

The implementation of ExactRate for fertilizer optimization represents a critical step toward cost reduction and yield improvement. However, research by MacPherson *et al*. (2022) emphasizes that the successful adoption of such technologies requires financial support for small-scale farms. For Ukraine's agricultural sector, this underscores the necessity of subsidy and grant programs. Research by Borrero and Mariscal (2022) underlines the importance of IoT in mitigating risks associated with weather conditions. However, in Ukraine, limited internet access in rural areas may hinder IoT adoption in agriculture. Addressing this barrier requires government initiatives to improve infrastructure. The experience of companies such as "Ukrlandfarming" demonstrates the significant potential of AI solutions to enhance agricultural efficiency. However, Ingram *et al*. (2022) note that without government support and educational programs, farmers may struggle to adapt to these technologies. For instance, the development of tailored training programs is a vital prerequisite for the successful integration of AI into the agricultural sector. Research by Borisova *et al*. (2020) emphasizes the importance of engaging young specialists in the agricultural sector through the development of modern educational programs. This is particularly relevant for Ukraine, where a significant portion of rural youth migrates to cities in search of employment. Creating modern working conditions in the agricultural sector can encourage the return of young specialists and drive the modernization of the industry. European experiences with IoT in agriculture, as noted by Klerkx, Jakku and Labarthe (2019), could be adapted for Ukraine. However, it is crucial to consider that most European solutions are designed for high-tech farms and require modification to suit Ukraine's less developed infrastructure.

Thus, modern agricultural technologies hold significant potential for restoring Ukraine's agricultural sector. However, their implementation requires adaptation to local conditions, including financial barriers, limited infrastructure, and the need for farmer education. Global examples, such as the use of IoT and AI, can serve as models for creating innovative solutions that contribute to the sustainable development of Ukraine's agricultural sector.

Achieving success will necessitate the development of a national strategy to support farmers, incorporating funding, education, and infrastructure development.

Conclusions

This study highlights the significant potential of agricultural technologies in transforming Ukraine's agricultural sector by improving efficiency, sustainability, and resilience. Key findings include:

- Main Benefits of Agricultural Technology: Technologies such as IoT, AI, and robotics can reduce resource use by up to 30% and increase yields by 15–20%. Crop monitoring drones improve processing efficiency by 20% and reduce costs by 25%.
- Barriers to Adoption: Limited infrastructure, high upfront costs, and low digital readiness among farmers, especially smallholders, remain critical concerns. For example, IoT adoption costs can exceed $10,000 per farm, posing a significant financial barrier for small businesses.
- Role of Education and Support: More than 70% of farmers lack sufficient training in digital technologies, highlighting the need for tailored programs to equip them with the necessary skills to adopt these technologies. Public-private partnerships and international collaborations are critical for addressing these gaps.
- Investment Opportunities: The global IoT market for agriculture is projected to grow from $6.95 billion in 2023 to $22.45 billion by 2031. Ukraine's agritech sector, supported by 41.5 million hectares of arable land, is well-positioned to attract significant investment, particularly in precision agriculture and robotics. Strategic Recommendations: Adapting global technologies to local conditions, expanding subsidy programs, and improving digital infrastructure can promote adoption. For example, government-supported initiatives could enable small farms to achieve a 15–20% increase in profitability through precision farming.

By addressing these challenges and harnessing its agricultural potential, Ukraine can unlock the transformative power of agricultural technologies, contributing not only to its economic recovery but also to global food security.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*	*Author 6*
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes	Yes
Collected the data	No	No	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	No	Yes	Yes	Yes	Yes
Wrote the article/paper	No	No	Yes	Yes	No	No
Critical revision of the article/paper	Yes	Yes	No	No	Yes	Yes
Editing of the article/paper	No	Yes	Yes	No	No	No
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Research involving human bodies or organs or tissues (Helsinki Declaration)
The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of

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