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Economic implications of digitalization and smart agriculture: A comparative study of Poland and Türkiye

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Abstract. The integration of advanced digital technologies in agriculture has led to significant improvements in productivity and sustainability. This study examines the economic implications of digital transformation in the agricultural sectors of Poland and Türkiye, focusing on the adoption of smart farming technologies such as IoT, AI, and precision farming. The research aims to explore how these technologies enhance competitiveness, sustainability, and resilience in both countries. The study employs a comparative analysis approach, utilizing both qualitative and quantitative data. Data were collected from various sources, including academic literature, government reports, and case studies of successful digital agriculture implementations in Poland and Türkiye. The analysis includes a review of historical developments, current initiatives, and the economic benefits of digitalization in agriculture. Case studies were selected to illustrate the practical applications and outcomes of digital technologies in different agricultural contexts. The findings reveal that both Poland and Türkiye have made substantial progress in adopting digital tools, resulting in increased productivity, reduced operational costs, and improved resource management. However, challenges such as digital literacy, financial barriers, and the integration of traditional farming practices remain. The study concludes that continued investment in education, infrastructure, and supportive policies is essential for fostering innovation and inclusivity in the agricultural sectors of both countries.

Keywords: digital agriculture, sustainability, Poland, Türkiye.

INTRODUCTION

The proliferation of advanced technologies in agriculture has yielded significant improvements in productivity while fostering environmental sustainability. Contemporary digital innovations, including data analytics, smart sensors, and precision farming technologies, are fundamentally transforming agricultural practices through resource optimization and environmentally conscious decision-making protocols. This technological integration represents not merely a developmental milestone but a strategic response to pressing global challenges, including climate change, labor market constraints, and escalating food demand.

This research examines the economic dimensions of digital transformation within Polish agriculture, with particular emphasis on comparative analysis with Türkiye. Poland presents a distinctive case study within the European Union, characterized by predominantly small-scale agricultural operations and a significant middle-aged farming demographic. Recent demographic transitions, however, indicate an emerging cohort of technologically proficient younger farmers demonstrating increased receptivity to digital solutions. This shift signifies the emergence of a new generation of agricultural practitioners leveraging mobile technologies and data-driven methodologies to modernize farming operations.

The primary objective of this investigation is to analyze the economic implications and opportunities presented by digital transformation in Polish agriculture, while maintaining a comparative perspective with Türkiye. The study investigates how digitalization enhances sectoral competitiveness, sustainability, and resilience in both nations. While smart farming has traditionally been associated with innovation, it increasingly represents an operational necessity. The expanding presence of agri-tech enterprises, increasing market demands, and widespread technological adoption indicate substantial momentum in this transformation. Current global data indicates agricultural smartphone utilization has reached 50% (Abdulai et al., 2023), with projections suggesting a tripling of the smart agriculture market value by 2030 (Grand View ..., 2024).

LITERATURE REVIEW

The integration of digital technologies in agriculture has emerged as a crucial research domain, emphasizing potential enhancements in productivity, sustainability, and economic performance. The literature demonstrates an evolutionary progression from initial sustainable agriculture studies to comprehensive analyses of digitalization, particularly within Polish and Turkish contexts.

Królczyk et al. (2014) provided one of the foundational studies in this area, emphasizing the potential of sustainable agriculture to improve wheat and rapeseed yields in Poland. Their research argued that technological innovations, combined with optimized crop management and rational fertilizer use, could significantly increase productivity while mitigating environmental concerns. This laid the groundwork for later studies exploring the synergy between technology and sustainability.

Building on these foundations, Moschitz and Stolze (2018) examined the role of smart technologies within sustainable agri-food systems. They highlighted the need to understand interactions among various stakeholders – such as farmers, technology developers, and policymakers – and proposed a framework to assess how digital technologies contribute to broader sustainability goals. This perspective opened avenues for evaluating digitalization beyond its technical merits.

Duncan et al. (2021) expanded the conversation by investigating the socio-economic aspects of precision agriculture. They identified thematic clusters related to the adoption of digital technologies and explored how these innovations affect farmer identity and traditional knowledge systems. Their findings drew attention to the governance, ethical, and inclusivity dimensions of digital agriculture – underscoring that its impact extends beyond yield improvements.

A bibliometric analysis by Sott et al. (2021) offered a comprehensive mapping of the digital agriculture landscape, linking technologies such as the Internet of Things (IoT) and big data to sustainability and food security. Their study emphasized the growing urgency of technological adoption in response to population pressures and resource constraints.

Mitra et al. (2022) further highlighted the transformative nature of 'Smart Farming', focusing on the role of data in optimizing agricultural operations. Their analysis supported the notion that digital tools can significantly enhance both efficiency and sustainability, aligning with broader global efforts toward climate-resilient food systems.

In an international comparison, Terhorst and Garrard (2022) analyzed the Australian context, drawing parallels with Poland. They underscored the importance of digital infrastructure and literacy as prerequisites for successful adoption. Without these foundations, they warned agricultural sectors could face declining competitiveness.

Abiri et al. (2023) addressed the mounting pressures on global agri-food systems, advocating for innovation that minimizes environmental impact while addressing food security challenges. Their work echoed earlier studies in emphasizing the importance of strategic adaptation and resilience in the face of evolving demands.

Although the concept of "Agriculture 4.0" emerged prior to the work of Gyamfi et al. (2024) and is not attributed to a specific individual or research group, their study offers a valuable contribution to the ongoing discourse. They underscore the integration of advanced technologies such as artificial intelligence, robotics, and big data within agriculture, while also drawing attention to critical issues related to data security and ethical considerations that are increasingly prominent in discussions on digital agriculture.

Finally, Bocean (2024) provided a longitudinal analysis of digital technologies' role in promoting sustainable food production across the European Union. His findings emphasized the multifaceted nature of sustainability – economic, environmental, and social – while drawing attention to the critical role of education and access to digital infrastructure.

Collectively, this body of literature illustrates a clear trajectory toward increasingly sophisticated understandings of digital agriculture. It emphasizes not only its economic potential but also the need for a holistic, inclusive, and ethically conscious approach. These insights are particularly relevant as the transition to modern, digitally enabled agricultural practices unfolds in a rapidly evolving global context.

This literature synthesis demonstrates increasingly sophisticated understanding of digital agriculture, emphasizing both economic potential and requirements for holistic, inclusive, and ethically conscious approaches. These insights maintain particular relevance as agricultural practices transition toward digital enablement in an evolving global context.

METHODOLOGY

This research adopts a rigorous mixed-methods approach to examine the economic implications of digital transformation in the agricultural sectors of Poland and Türkiye. The methodology integrates both qualitative and quantitative analyses to comprehensively address the research objectives, with a particular focus on comparative and institutional perspectives.

Research design and theoretical framework

The study is structured as a comparative case study, drawing upon institutional economic theory and frameworks of technological innovation. This design facilitates an in-depth and systematic exploration of digital agriculture adoption, implementation strategies, and socio-economic outcomes across the two countries' agricultural landscapes.

Data collection, sources, and analytical framework

The research utilizes a multi-source data collection strategy, combining primary and secondary data to ensure analytical robustness. The primary empirical basis consists of detailed field-based case studies of digital agriculture initiatives in both Poland and Türkiye. These case studies were selected to reflect diversity in geographic location, scale of operation, technological adoption levels, and types of agricultural activity. Structured field observations were conducted using standardized evaluation tools to document implementation practices and economic performance indicators.

Secondary data was gathered from a wide range of sources, including:

– National agricultural statistics and economic databases,
– Official government policy documents and legislative frameworks,
– Scholarly literature retrieved from databases such as Web of Science and Scopus,
– Industry reports and market analyses related to digital agriculture.

The analytical framework integrates multiple methodological components. First, it conducts descriptive and comparative analyses of digital technology adoption across both countries' agricultural sectors. Then, an institutional and policy analysis is applied to examine the regulatory, structural, and economic environments shaping digital transformation. Finally, qualitative analysis based on the field case studies allows for the identification of implementation challenges, enabling factors, and socio-economic impacts at the farm and sectoral levels.

Methodological limitations

Several methodological limitations are recognized. These include cross-country data heterogeneity, limited longitudinal data to assess long-term impacts, and potential selection bias in the choice of case studies. To mitigate these challenges, the study employs methodological triangulation and adheres to rigorous validation protocols throughout the data collection and analysis process.

Case study protocol

A structured case study protocol was developed to guide the analysis of digital agriculture initiatives across both national contexts. Case selection was informed by a multi-criteria framework, emphasizing diversity in geography, farm size, level of technological integration, and agricultural specialization. Each case was assessed through a consistent analytical lens that considered:

– Implementation processes and technology integration strategies,
– Economic performance indicators and operational efficiency,
– Barriers to adoption and strategies for overcoming them,
– Broader socio-economic implications for farmers, communities, and policy stakeholders.

This structured protocol ensures methodological consistency and enables meaningful cross-case and cross-country comparisons.

Data collection protocol

Data collection followed a two-tiered protocol focused on systematic acquisition of both primary and secondary data. The primary data consisted of structured field observations of selected case study sites, recorded using standardized documentation templates. These observations focused on the actual implementation of digital technologies, economic performance metrics, and contextual variables affecting adoption.

The secondary data collection involved comprehensive analysis of national agricultural databases, peer-reviewed literature, official policy documents, and industry reports. The integration of these data sources provided a robust foundation for addressing the research questions and supported a holistic assessment of digital transformation processes in agriculture.

SHAPING THE FUTURE OF FARMING: THE ROLE OF DIGITALIZATION IN AGRICULTURE

From traditional agriculture to digital farming: Stepping into the future

Today, the agricultural sector is undergoing a significant transformation, shifting from traditional methods to digital farming technologies. While traditional farming has long relied on manual labor, digital farming leverages modern technologies to offer a more efficient, sustainable, and precise production process. Table 1, prepared by Çile-

Table 1. Differences Between Traditional and Digital Farming.

Feature	Traditional Farming	Digital Farming
Labor requirements	Requires intensive manual labor.	With the use of robotic devices and drone technology, it can be done with less labor.
Production process and yield	The production process is slower, leading to lower yields.	Products can be grown more quickly, resulting in higher yields.
Diseases and pests	Plant diseases and pests are often noticed at later stages.	Plant diseases can be detected earlier.
Prediction and analysis	Predictions are made based on land conditions, crops, and yield.	Predictions are highly accurate and precise.
Input usage and efficiency	Excessive use of inputs and low efficiency.	Inputs are used more efficiently in modern farming.
Production time and scientific approach	These techniques are time-consuming and result in lower production.	Time is saved, and production is based on scientific methods.
Application history	Traditional farming techniques are ancient and are no longer widely used.	Modern farming is heavily capital-intensive.
Dependency on irrigation	Farmers are not dependent on monsoon rain since they have access to tube wells for irrigation.	Smart irrigation systems ensure water conservation.
Fertilizer use	Natural fertilizers, such as cow manure, are commonly used.	Chemical fertilizers and pesticides are applied.
Seed usage	Traditional seeds are commonly used.	Genetically modified seeds are preferred in modern farming.

Source: Çilesiz, Karaköy, 2022

siz and Karaköy (2022), compares the key differences between these two farming methods.

Historical overview of agriculture in Poland and Türkiye

Agriculture in both Poland and Türkiye has experienced significant transformations influenced by political, economic, and technological shifts. Historically, both countries relied heavily on traditional farming practices until the mid-20th century, characterized by low mechanization levels and relatively limited agricultural productivity compared to more developed Western European nations.

In Poland, the first notable phase of modernization began in the 1950s under the socialist regime, which focused on intensifying agricultural production. Despite adopting aspects of the Common Agricultural Policy seen in the European Community, Poland's agricultural system was shaped by a unique hybrid model combining market economics with centrally planned socialism. The expansion of collective farming took place during this period, although its overall efficiency and profitability declined over time despite state subsidies (Bański, Mazur, 2021).

In Türkiye, agricultural reforms began in the mid-20th century, with efforts to modernize farming and improve productivity. However, similar to Poland, the country faced challenges related to low mechanization and reliance on traditional farming methods. The 1980s saw a shift in policy towards liberalization and market-oriented reforms, which encouraged agricultural modernization. The introduction of various development programs also played a role in improving agricultural output, though challenges such as land fragmentation and regional disparities remained (Aydin, 2010).

The early 1990s marked a turning point for both countries, as they shifted from centrally planned systems to more market-oriented economies. In Poland, this period brought profound changes in agricultural policy, land ownership, and market access, blending traditional agricultural practices with capitalist structures. Similarly, Türkiye's transition towards a market-driven economy in the 1990s spurred a restructuring of its agricultural sector, leading to increased integration with global markets.

The 21st century, particularly from the second and third decades, has been marked by rapid advancements in digitalization and smart technologies in both Polish and Turkish agriculture. Poland has emerged as a key player in the European agri-food market, with agriculture contributing around 3.58% to the national GDP and employing approximately 11% of the workforce (Heffner, Twardzik, 2022). Türkiye, meanwhile, remains a significant agricultural producer, with the sector playing a crucial role in its economy and contributing to both domestic food security and exports. Both countries are witnessing the growing importance of digital tools in agriculture, from precision farming to the use of smart sensors and data analytics. Poland, for instance, has increasingly embraced digitalization, with significant advancements in agri-tech and digital platforms. Türkiye is also advancing in this area, with many farmers adopting mobile technologies and digital solutions to improve efficiency and sustainability. Despite these advancements, both Poland and Türkiye face ongoing challenges in their agricultural sectors. For Poland, the need for greater specialization and modernization remains urgent, particularly in the face of global competition and environmental pressures. Türkiye faces similar challenges, including land fragmentation, rural development disparities, and environmental sustainability concerns. In conclusion, the agricultural evolution in both Poland and Türkiye reflects broader trends of economic and political transformation, with both countries shifting towards digitalization and technological advancements in farming. While both have made substantial progress in modernizing their agricultural sectors, challenges related to competitiveness, sustainability, and economic inequality persist. This chapter provides an overview of the historical development of agriculture in both countries, highlighting key phases and examining the economic implications of the ongoing digital transformation in agriculture (Fritsch et al., 2022).

Concepts and technologies of digital agriculture

In this study, digital agriculture refers to a rising concept consisting of innovative technologies and cybersecurity and data management services, which together form digital farming, smart agriculture, and e-agriculture. Digital agriculture can be seen as a complex of technologies that are used for the modernization of agricultural practices. Lately, an important scope of digital agriculture is smart technologies that are in use for data collection and analysis, providing recommendations, forecasts, and more. There are more complex definitions or explanations; for example, smart farming is based on several technologies such as the Internet of Things, big data analytics, artificial intelligence, decision science, mobile sensors, robotics, drones, and software-as-a-service.

Some of the technologies relevant for the emergence and operation of smart agriculture are 3D printing, artificial intelligence, Internet of Things, sensor systems, big data analytics, blockchain and distributed ledgers, cybersecurity, mobile computing and applications, wind and solar power, yield sensors of combines, wireless networks, and others. Precision farming is a method for optimizing agriculture with a non-homogeneous field through responsible management and use of crop and soil resources while considering environmental, economic, and social parameters. Precision farming aims to optimize the profit for farmers based on information about semi-permanent field variation like yield, crop status, soil characteristics, and management history (Bański, Mazur, 2021).

Data collection involves different devices and technologies like satnav, GPS guidance, remote and proximal sensors, telematics, geographic information systems, global and regional databases, earth observations, field-specific weather monitoring, remote sensing, and others. Currently, concepts of digital agriculture incorporate sensors, IoT devices, and smartphone apps and extension plan to integrate GIS, M2M communication, user level of expertise, viewer model, mappings offer and cost, offer distribution, recommendation algorithms, and improvement suggestions (Prus et al., 2022).

Data collected from precision farming and smart technologies have to be analyzed to support decisions and actions. Data processing is currently 40% of the total consultations. The most common data processing tools are images and geographic information systems. Additional tools are suggested in connection with rapidly evolving technologies. Its adoption reduces chemical use by 90% and allows for savings of up to 50% of the water used for irrigation. This demonstrates the potential smart technologies have in saving costs while improving or at least maintaining crop productivity and ensuring resilience to climatic change and extreme weather events. There is widely recognized potential in agricultural produce labor productivity and the production of knowledge-driven, cost-effective, and high-quality crops through both commercial agriculture sectors and organic cottage sectors. The use of advanced technology has helped halve the number of foliar pesticides used, increased profits by 36 percent, and increased cost savings by 26 percent. The ability to monitor the number of pests per plant presents a real-time solution, saving time and cost on technical advisors while mitigating the impact on plant health. This technology reduces risks for both production and labor, though it may push out the capacity of smallholders who may have difficulty in accessing it. This approach empowers agricultural extension services in precision agriculture by providing farmer and extension worker capacity. It will also develop business models for clinical solutions and sell advice for larger revenue production. It offers a gamified help line, e-learning assets, and access to moderate-cost advisory, including offline delivery and indigenous language support (Boursianis et al., 2022).

Smart agriculture initiatives in Poland and Türkiye

Both Poland and Türkiye have undertaken significant efforts to promote and implement smart agriculture, leveraging public and private initiatives to foster technological advancements in their agricultural sectors. In Poland, key public institutions such as the Polish Agency for the Restructuring and Modernization of Agriculture (ARMA) play a crucial role in supporting the financial sustainability of agricultural holdings. The agency has been instrumental in co-financing investments related to information and communication technologies (ICT) and broader agricultural modernization. Between 2014 and 2020, various measures of the Rural Development Program provided financial support to approximately 2,300 projects, totaling around 100 million euros. These projects aim to reduce development disparities in rural areas, encourage the use of local resources, and promote non-agricultural initiatives, particularly those based on renewable energy (Bański, Mazur, 2021).

Similarly, Türkiye has launched numerous initiatives to drive smart agriculture adoption, supported by both governmental programs and the private sector. The Ministry of Agriculture and Forestry plays a central role in facilitating digital transformation, promoting the integration of modern technologies such as precision farming, drones, and smart irrigation systems. A notable example is the development of the "National Smart Agriculture Strategy," which focuses on creating a sustainable, innovative agriculture sector by incorporating digital technologies, boosting efficiency, and enhancing agricultural sustainability (Hürriyet Daily News, 2023).

In Poland, the 2021–2027 period under the Common Agricultural Policy (CAP) continues to emphasize the synergy between agricultural vitality and rural development. The Ministry of Agriculture and Rural Development in Poland supports the integration of modern technologies by offering training programs and seminars through agricultural advisory centers. These initiatives cover a wide range of topics, including crop production, animal husbandry, and horticulture, focusing on enhancing the efficiency and sustainability of agricultural holdings (Prus et al., 2022).

In Türkiye, the government has also focused on promoting digital agriculture through programs like the "Agricultural Technology Park" and regional incentives for farmers to adopt smart farming technologies. The emphasis is on using data analytics, sensors, and automation to optimize agricultural productivity, improve environmental management, and reduce resource consumption (Ergocun, 2021).

At the individual farm level, both countries see the digital transformation of agriculture being largely influenced by financial support from national and international sources. In Poland, EU funding mechanisms such as the Rural Development Programs provide tangible support for the adoption of digital tools and innovations. These financial instruments have been pivotal in encouraging Polish farmers to integrate technologies such as precision farming and IoT-based solutions into their operations (Heffner, Twardzik, 2022). In Türkiye, farmers benefit from state-sponsored projects that offer subsidies and incentives for the implementation of digital technologies. Programs like "Smart Farming Support" and "Tech-Based Agricultural Initiatives" provide farmers with access to digital tools, while also facilitating knowledge transfer and training in modern farming techniques (Ergocun, 2021).

Both Poland and Türkiye are seeing the growing importance of digitalization in agriculture. While Poland's focus is on further integrating digital tools through EU-supported frameworks, Türkiye's smart agriculture initiatives are more oriented toward fostering innovation through national strategies and subsidies. These initiatives in both countries are central to reshaping agricultural practices, fostering rural development, and ensuring long-term sustainability in their agricultural sectors.

Economic benefits of digitalization in agriculture

Advanced technologies in agriculture are estimated to increase farm productivity by approximately 1.7% per year, while simultaneously reducing operational costs by 7–25% (Fritsch et al., 2022). Within the food supply chain, digitalization offers the potential to reduce post-harvest losses – especially in fruits and vegetables – by as much as 40%. This reduction primarily results from enhanced planning, monitoring, and logistics, which can mitigate the losses caused by the limited shelf life of perishable goods. Consequently, lower food waste leads to reduced waste management costs, yielding further economic benefits (Prus et al., 2022).

Digital tools are also increasingly used to monitor and control food quality, which represents another significant factor in minimizing waste. Quality deficiencies account for a substantial portion of fruit and vegetable waste, and technologies that ensure better quality assurance throughout the supply chain can reduce such losses. Furthermore, one of the most impactful areas for economic gain is the prevention of distribution-related damage, which can be significantly mitigated through smart logistics and precision tracking systems. Digitalization supports farms, food-processing enterprises, and retail operations by optimizing functions across the entire agri-food value chain. It enables better planning, coordination, and control of activities, improving overall efficiency and resource management (Heffner, Twardzik, 2022). At the farm level, service enhancements powered by digital solutions contribute to lower production costs, increased competitiveness, and higher profit margins (Bański, Mazur, 2021).

Agricultural research increasingly acknowledges digital technologies as vital enablers of market access, strengthening the links between producers and value chains. They facilitate information flow, supporting evidence-based policymaking, strategic planning, and on-farm decision-making. Furthermore, these technologies serve as critical instruments for promoting innovation and sustainability in agricultural development (Czyżewski et al., 2021). With projected changes in consumption patterns and population growth, the global demand for agricultural products is expected to rise. This increased demand must be met through efficient production practices, while limiting environmental degradation. Sustainable approaches, such as climate-smart agriculture and the implementation of green technologies, are seen as essential, and digital agriculture plays a central role in enabling their adoption (Wąs et al., 2021). Digital transformation in agriculture is increasingly seen as a strategic imperative rather than just a technological trend. It equips the agricultural sector with the necessary tools to produce high-quality, contamination-free food while also enhancing economic resilience. The rising adoption of smart solutions is crucial for future-proofing agriculture in both Poland and Türkiye, helping these nations address emerging challenges and align with broader economic and environmental objectives (Prus et al., 2022).

CASE STUDIES OF SUCCESSFUL IMPLEMENTATION IN POLAND AND TÜRKIYE

Both Poland and Türkiye have successfully implemented several digital agriculture initiatives, achieving notable outcomes across economic, environmental, and social aspects. The following case studies showcase these successes, offering insights into the background, digital tools used, implementation practices, observed results, and their broader implications for sustainable agricultural development.

Case Study Analysis 1: Implementation of smart farming technologies on a northern Polish dairy farm

This empirical investigation examines the integration of smart farming technologies in a large-scale dairy operation situated in northern Poland. The study specifically focuses on the implementation of digital solutions aimed at optimizing production efficiency while maintaining environmental sustainability and animal welfare standards. The results indicate significant improvements in operational metrics and environmental performance.

The subject of this analysis is a medium-sized dairy enterprise specializing in premium milk production, representative of the ongoing digital transformation in Poland's dairy sector. This operation serves as an archetypal example of the industry's technological evolution.

The technological intervention comprised three primary components: automated milking systems, IoT-enabled health monitoring devices, and GPS-guided machinery for pasture management optimization. These implementations demonstrated multifaceted benefits across operational efficiency, sustainability metrics, and veterinary cost reduction.

Empirical evidence suggests that the automated systems significantly reduced labor requirements while maintaining consistent milking schedules. The IoT infrastructure enabled real-time monitoring of bovine health parameters, facilitating early disease detection. Furthermore, GPS-enabled precision agriculture techniques optimized resource allocation, marking a transition from reactive to proactive operational management.

Quantitative analysis reveals a 20% enhancement in milk production efficiency, accompanied by a 15% reduction in operational costs, primarily in labor and feed management. Additionally, irrigation water consumption decreased by 10%, demonstrating improved resource utilization and environmental stewardship.

Critical success factors identified include: (1) strategic integration of digital technologies with existing agricultural practices, (2) sustained support from local agricultural advisory services, and (3) robust managerial commitment to technological innovation. Initial implementation challenges, notably high capital requirements and workforce training needs, were effectively addressed through a gradual adoption strategy.

Qualitative feedback from stakeholders indicates positive operational improvements, despite initial adaptation challenges. Veterinary professionals reported enhanced disease management and milk quality outcomes. Implementation challenges predominantly centered on user interface complexity and technical support accessibility.

This case study demonstrates the transformative potential of agricultural digitalization, presenting both economic and environmental advantages. The findings emphasize the crucial role of comprehensive training programs, financial support mechanisms, and advisory networks in facilitating widespread technology adoption (Świtłyk et al., 2021; Veeneman, 2024).

Case Study Analysis 2: Precision agriculture in a crop farm in central Poland

Building on these successful implementations, another noteworthy case study examines precision farming methodologies at an agricultural enterprise in central Poland. This investigation focused particularly on soil health optimization, yield enhancement, and environmental impact mitigation, demonstrating significant economic benefits through increased operational efficiency and resource optimization.

The research site comprises a medium-scale agricultural operation specializing in cereal, vegetable, and legume cultivation, representative of Polish agricultural enterprises transitioning toward precision farming methodologies. The findings present valuable empirical evidence for comparable agricultural operations within the region.

The implementation protocol incorporated GPS-guided tractors, soil nutrient monitoring systems, remote sensing technologies, and Geographic Information Systems (GIS) to facilitate Variable Rate Technology (VRT). These integrated systems enabled precise fertilization and irrigation protocols based on real-time agronomic data analysis.

The integration of precision systems facilitated a data-driven operational framework. GPS-enabled machinery significantly reduced planting and tilling redundancy, resulting in decreased fuel consumption. Soil monitoring systems enabled optimal nutrient management, while remote sensing technologies facilitated early detection of crop health anomalies. These technological innovations collectively optimized resource utilization and minimized operational waste.

Quantitative analysis revealed a 10% increase in crop yield metrics and a 15% reduction in input costs. Fuel consumption demonstrated a 20% decrease, while water utilization efficiency improved by 25%. The optimization of chemical applications resulted in enhanced environmental outcomes, particularly regarding pesticide runoff reduction.

The successful implementation was attributed to three critical factors: strategic digital integration, utilization of EU agricultural subsidies, and proactive knowledge acquisition by farm management. Despite initial challenges regarding capital investment and technological complexity, the long-term benefits validated the economic viability of precision agriculture in the Polish context.

Empirical evidence from stakeholder interviews indicated positive responses regarding operational efficiency and time management improvements. Initial technological skepticism was superseded by appreciation for data-driven decision-making processes. Agricultural advisors emphasized the enhanced capacity for strategic planning and environmental responsiveness.

This case study further demonstrates the efficacy of precision agriculture in achieving an optimal balance between productivity and sustainability metrics. The findings underscore the significance of policy support mechanisms, technical assistance programs, and educational initiatives in facilitating digital innovation adoption within the agricultural sector (Yarashynskaya, Prus, 2022; Papadopoulos et al., 2024).

Case Study Analysis 3: Implementation of precision agriculture technologies in central Anatolia

This empirical investigation examines the integration of precision farming technologies in a crop production operation situated in the Central Anatolia region of Türkiye. The study specifically focuses on the implementation of digital solutions aimed at optimizing water efficiency, yield enhancement, and environmental impact mitigation in cereal production. The results indicate significant improvements in operational metrics and environmental performance.

The subject of this analysis is a medium-scale agricultural enterprise specializing in wheat and barley cultivation, representative of the regional agricultural landscape. This operation faces characteristic challenges of water scarcity and soil degradation, common to the Central Anatolian agricultural sector.

The technological intervention comprised three primary components: GPS-guided machinery, variable rate irrigation systems, and IoT-enabled soil monitoring devices. These implementations demonstrated multifaceted benefits across operational efficiency, resource optimization, and environmental sustainability metrics.

Empirical evidence suggests that the GPS-guided systems significantly reduced operational redundancy while maintaining precise planting and tilling protocols. The IoT infrastructure enabled real-time monitoring of soil health parameters, facilitating data-driven irrigation decisions. Furthermore, drone and satellite imaging technologies enabled proactive crop health management, marking a transition from reactive to preventive agricultural practices.

Quantitative analysis reveals a 15% enhancement in crop yield efficiency, accompanied by a 12% reduction in water consumption. Additionally, chemical fertilizer usage decreased by 10%, demonstrating improved resource utilization and environmental stewardship.

Critical success factors identified include: (1) robust government support mechanisms through the Ministry of Agriculture and Forestry, (2) strategic partnerships with agri-tech providers, and (3) comprehensive financial assistance programs. Initial implementation challenges, notably high capital requirements, were effectively addressed through government subsidies and targeted support initiatives.

Qualitative feedback from stakeholders indicates positive operational improvements, despite initial technological skepticism. Agricultural professionals reported enhanced resource management and crop quality outcomes. Implementation challenges predominantly centered on initial investment costs and technical adaptation requirements.

This case study demonstrates the transformative potential of precision agriculture in addressing both economic and environmental challenges in Turkish agriculture, particularly in water-scarce regions. The findings emphasize the crucial role of government support mechanisms, technical assistance programs, and financial incentives in facilitating widespread technology adoption (Polat et al., 2024; Özgüven, Türker, 2010).

Case Study Analysis 4: Advancement of digital greenhouse agriculture in Mediterranean Türkiye

Building upon the success of precision farming implementations in Central Anatolia, this empirical investigation examines the integration of smart greenhouse technologies in Türkiye's Mediterranean region. The study specifically focuses on the implementation of digital solutions aimed at optimizing production efficiency, resource management, and product quality in intensive horticultural operations.

The subject of this analysis is a sophisticated greenhouse enterprise specializing in high-value vegetable crops, including tomatoes, cucumbers, and peppers, serving both domestic and international markets. This operation represents the ongoing technological evolution in Türkiye's greenhouse sector.

The technological intervention comprised three primary components: climate control systems with IoT integration, AI-powered predictive analytics, and automated irrigation infrastructure. These implementations demonstrated multifaceted benefits across operational efficiency, resource optimization, and crop quality metrics.

Empirical evidence suggests that the IoT-enabled systems significantly enhanced environmental control while maintaining optimal growing conditions. The AI infrastructure enabled real-time monitoring and adjustment of critical parameters, facilitating data-driven decision-making. Furthermore, automated irrigation systems optimized water resource allocation, marking a transition from conventional to precision greenhouse management.

Quantitative analysis reveals a 20% enhancement in crop yield efficiency, accompanied by a 15% reduction in water consumption. Additionally, pesticide usage decreased by 30%, demonstrating improved resource utilization and environmental stewardship.

Critical success factors identified include: (1) comprehensive integration of digital monitoring systems, (2) implementation of AI-driven predictive analytics, and (3) robust government support mechanisms. Initial implementation challenges, notably high capital requirements and technical complexity, were effectively addressed through government subsidies and training programs.

Qualitative feedback from stakeholders indicates positive operational improvements, despite initial investment concerns. Agricultural professionals reported enhanced product quality and resource efficiency outcomes. Implementation challenges predominantly centered on initial cost barriers and technical adaptation requirements.

This case study demonstrates the transformative potential of digital greenhouse agriculture in achieving both economic and environmental objectives. The findings emphasize the crucial role of government support mechanisms, technical training programs, and financial incentives in facilitating widespread technology adoption (Baykal, 2021; Farmonaut, 2024).

Case Study Analysis 5: Agricultural cooperatives supporting digital transformation in Türkiye

The implementation of digital agriculture technologies through cooperative structures represents a significant development in Türkiye's agricultural modernization efforts. This case study examines how agricultural cooperatives in the Aegean region have facilitated technological adoption among small-scale farmers, demonstrating the effectiveness of collective action in overcoming barriers to digital transformation.

The study focuses on a representative agricultural cooperative comprising small to medium-sized enterprises primarily engaged in olive, fruit, and vegetable cultivation. These family-operated farms typically face structural challenges including limited technological access, elevated labor costs, and restricted market penetration. The cooperative's strategic initiative aimed to enhance member productivity through systematic digital technology integration.

The technological intervention encompassed three primary components: mobile-based crop monitoring systems, meteorological tracking infrastructure, and cloud-enabled farm management platforms. These implementations demonstrated multifaceted benefits across operational efficiency, resource optimization, and market access metrics.

Empirical evidence suggests that the implementation of weather monitoring systems significantly enhanced decision-making processes in planting and harvesting operations. The digital crop health monitoring infrastructure enabled proactive pest management, while cloud-based platforms facilitated comprehensive supply chain optimization and inventory control.

Quantitative analysis reveals a 12% enhancement in crop yield efficiency, accompanied by a 10% reduction in input costs, particularly in water and fertilizer utilization. Additionally, the digital infrastructure enabled improved harvest coordination, resulting in reduced post-harvest losses and enhanced market access opportunities.

Critical success factors identified include: (1) robust financial support mechanisms, (2) comprehensive training programs, and (3) effective intermediation by the cooperative structure. Initial implementation challenges, notably high capital requirements and technical literacy barriers, were effectively addressed through the cooperative's collective resources and support systems.

Qualitative feedback from stakeholders indicates positive operational improvements, despite initial technological resistance. Agricultural professionals reported enhanced operational efficiency and market positioning outcomes. The collective technological adoption strengthened organizational cohesion and member engagement.

This case study demonstrates the transformative potential of cooperative-based digital agriculture implementation in addressing both economic and technical barriers to technology adoption. The findings emphasize the crucial role of cooperative structures in facilitating widespread digital transformation among small-scale agricultural enterprises (Engindeniz, Yercan, 2024; Sevinç, 2021).

In Table 2 there is a comparative analysis of key metrics and outcomes across the presented case studies.

This comparative analysis demonstrates consistent improvements in both productivity and resource efficiency across different agricultural contexts and technological implementations.

Table 2. Comparative Analysis of Case Studies.

Case Study	Location	Type	Key Technologies	Yield Improvement	Resource Savings
Case 1	Northern Poland	Dairy Farm	Automated milking, IoT health monitoring, GPS-guided machinery	20% milk production efficiency	15% operational costs, 10% water reduction
Case 2	Central Poland	Crop Farm	GPS tractors, soil monitoring, VRT	10% crop yield	15% input costs, 20% fuel, 25% water
Case 3	Central Anatolia	Cereal Production	GPS machinery, variable irrigation, IoT soil monitoring	15% crop yield	12% water, 10% fertilizer reduction
Case 4	Mediterranean Türkiye	Greenhouse	IoT climate control, AI analytics, automated irrigation	20% crop yield	15% water, 30% pesticide reduction
Case 5	Aegean Türkiye	Cooperative Farms	Mobile monitoring, weather tracking, cloud platforms	12% crop yield	10% input costs reduction

POLICY AND REGULATORY FRAMEWORKS IN DIGITAL AGRICULTURE: A COMPARATIVE ANALYSIS OF POLAND AND TÜRKIYE

The rapid digital transformation of agriculture faces significant challenges due to the fragmented and often outdated legal and regulatory frameworks that govern the sector. This issue is not unique to agriculture but reflects a broader trend across the European Union (EU), where technological advancements frequently outpace the evolution of regulatory systems. In response, the EU has prioritized the development of a Digital Single Market, aimed at smoothing the integration of new technologies across sectors. Despite this progress, agriculture remains primarily overseen by the Department of Agriculture and Rural Development, which is responsible for on-farm and rural affairs. Consequently, agricultural and digital infrastructure policies are often treated as separate domains, creating barriers to their effective integration (European Commission, 2021).

In Poland, the "Strategy for Sustainable Rural Development, Agriculture, and Fishery 2030" (SRDAF 2030) outlines the country's agricultural policy and rural development efforts for 2020 to 2030. This strategy serves as both a predecessor and a parallel strategy to the Common Agricultural Policy (CAP) Strategic Plan. Additionally, Poland's CAP Strategic Plan for 2023-2027 aims to support the sustainable development of farms, the processing sector, and the improvement of living and working conditions in rural areas. It emphasizes the protection of natural resources and promotes the production and use of sustainable energy (Morisson de la Bassetière, 2024).

The fragmentation of regulatory frameworks is further complicated by the need to address three interconnected areas of the bioeconomy: food production, welfare, and environmental protection. Each of these areas is governed by distinct policy frameworks – agriculture, smart farming, and agribusiness. However, the digital implications of these sectors are often not adequately considered when balancing the different policy perspectives and societal expectations surrounding agricultural performance. This lack of coordination undermines efforts to develop a cohesive regulatory approach that promotes innovation while safeguarding public interests. One of the most pressing challenges farmers face in this evolving landscape is the management of data generated by digital technologies. As the adoption of smart farming tools grows, farmers are increasingly confronted with complex issues related to data privacy, storage, and usage. The volume, speed, and variety of data produced by sensors, automated systems, and other digital tools create significant management and security concerns. While this data holds immense potential for optimizing farm operations, farmers are often excluded from policymaking discussions related to digital data management. This underscores the urgent need for clear regulations that define ethical guidelines, data protection principles, and privacy standards in agriculture. To address these concerns, policy frameworks must evolve to reflect the growing reliance on digital tools in agriculture. Legislation should be adaptable enough to accommodate ongoing technological advancements, ensuring that farmers can benefit from these innovations without compromising their privacy or security. Establishing clear principles for data use, privacy, and ethical standards is critical for fostering trust among farmers, consumers, and other stakeholders. By setting robust guidelines, policymakers can ensure that digital farming tools are used responsibly and sustainably, ultimately enhancing productivity while maintaining public confidence in the digitalization of agriculture (IDH, 2024).

In parallel, Türkiye's agricultural sector is pursuing a similar transformation through a combination of traditional practices and the integration of modern technologies. The Ministry of Agriculture and Forestry has played a pivotal role in driving this change, with strategic plans designed to support the widespread adoption of smart farming practices. Building on the 2019-2023 Strategic Plan, which emphasized the development of digital agriculture platforms and increased data usage, the Turkish government has made significant strides in accelerating the digitalization of agriculture.

The Ministry's 2024-2028 Strategic Plan outlines several initiatives that aim to enhance sustainability and efficiency in the agricultural sector, including:

– Digital Agricultural Marketplace: This platform facilitates direct online sales for agricultural producers, while using big data to optimize pricing and logistics. It enhances market access for producers and streamlines the distribution process.
– Smart Irrigation Systems: Leveraging IoT (Internet of Things)-enabled irrigation technology, this initiative aims to ensure more efficient water use in agriculture. By incorporating soil and climate sensors, these systems help farmers avoid water waste and improve productivity.
– Smart Agriculture Incentives: Support programs are available to encourage the use of smart sensors, drones, and satellite-based observation systems in agricultural machinery. These technologies aim to automate agricultural production, reduce costs, and improve overall efficiency.
– Agricultural Technology R&D Support: Institutions like TÜBİTAK and KOSGEB are providing R&D support for the development of domestic agricultural technologies. These initiatives are fostering innovative solutions that contribute to the broader digital transformation of the agricultural sector.

Through these strategies, Türkiye is poised to create a more competitive and sustainable agricultural sector, with a focus on both technological innovation and environmental stewardship (Ministry of Agriculture and Forestry, 2024).

While Türkiye's strategic approach demonstrates a commitment to modernizing agriculture, it also highlights some of the broader challenges facing the EU. A lack of coordination between agricultural and digital infrastructure policies remains a key obstacle to effective implementation. To overcome this, a more integrated, cross-sector policy framework is needed that considers the digital implications of all aspects of the agricultural value chain. One potential avenue for improvement is the establishment of an EU-wide regulatory framework that harmonizes digital agriculture policies. Such a framework would create clearer guidelines for data management, privacy, and ethics, ensuring a more consistent approach to technology adoption across member states. Furthermore, as Türkiye's experience illustrates, sharing best practices between countries can accelerate the digital transformation of agriculture and lead to more robust policy solutions at the regional level (FAO, 2022).

Comparative analysis of digital agriculture strengths and weaknesses: Poland vs. Türkiye

The rapid advancement of digital technologies has led to a transformation in agricultural practices worldwide. Both Poland and Türkiye have made significant strides in adopting digital agriculture, yet they face unique challenges and opportunities shaped by their respective political, economic, and technological contexts. Digital agriculture encompasses a broad range of technologies, including Internet of Things (IoT), artificial intelligence (AI), big data, machine learning, and smart farming solutions that help optimize farm management, enhance productivity, and foster sustainability. This comparative analysis explores the strengths and weaknesses of digital agriculture in Poland and Türkiye. While both countries are leveraging digital tools to improve agricultural efficiency, their approaches, infrastructure, and adoption levels vary. Poland, a key player in the European Union's agri-food market, has a strong focus on technological growth and international competitiveness. Meanwhile, Türkiye, with its diverse agricultural landscape and significant reliance on traditional farming methods, has been progressively investing in digital initiatives to boost efficiency and resilience in the sector. Table 3 highlights key strengths and weaknesses across multiple categories, including technological advancements, consumer awareness, climate resilience, workforce development, and government support. This comparative overview provides a clear picture of how digital agriculture is reshaping these two nations' agricultural landscapes and reveals the areas that require further attention for sustainable and inclusive agricultural development.

Based on the comparative analysis presented in Table 3, several significant patterns emerge in the digital agricultural development trajectories of Poland and Türkiye:

1. The technological implementation strategies differ notably between the two nations: Poland's approach emphasizes advanced technological integration, particularly in IoT sensors and blockchain systems, while Türkiye's strategy focuses on creating accessible technological frameworks through organizational collaboration and infrastructure development.
2. Both nations encounter similar infrastructural obstacles, particularly in rural connectivity implementation and digital literacy enhancement among traditional farming communities, which presents a significant barrier to widespread technological adoption.

Table 3. Digital Agriculture: Strengths and Weaknesses in Poland and Türkiye.

Category	Strengths in Poland	Strengths in Türkiye
Technological Advancements	Potential for growth driven by IoT, sensors, AI, machine learning, big data, and blockchain.	Availability of digital agriculture technologies offered by various organizations.
Consumer Awareness	Growing awareness of sustainability and food quality, increasing market for both traditional and digitally-produced products.	Increasing interest in digital agriculture certifications and training programs.
Agricultural Diversification	Opportunity for Polish farmers to diversify offerings by combining classic agriculture with technology-modified eco-foods.	Increased focus on diversifying agricultural practices through digital tools and technologies.
Collaboration Opportunities	Collaboration between academia, industry, and government institutions to support knowledge transfer and labor training.	Collaboration between digital agriculture organizations and producers.
Climate Resilience	Digital tools can enhance productivity and resilience to climate change-related risks.	Digital agriculture can improve efficiency and resilience in dealing with climate change and agricultural challenges.
Workforce Development	Emphasis on training and developing a workforce skilled in digital agriculture.	Growing interest in digital education and skills development.
Market Competitiveness	Digital agriculture can improve Poland's competitiveness in the international market.	Digital agriculture applications can help improve Türkiye's competitiveness in global agricultural markets.
Government Support	Increasing policy support for digital agriculture, and funding initiatives.	Growing support from the government for digital agriculture, including state incentives and research investments.
Economic Resilience	Potential for increased operational efficiency and economic resilience via digital agriculture.	Government support, including incentives, aims to enhance economic resilience in the agricultural sector through digitalization.
Digital Adoption in Rural Areas	Limited digital infrastructure in rural areas but potential for development.	Ongoing efforts to improve technological infrastructure in rural regions, increasing access to digital agriculture tools.
Data Utilization	Potential for optimizing farm management with big data and AI.	High interest in leveraging big data and AI for precision farming and productivity enhancement.
Category	**Weaknesses in Poland**	**Weaknesses in Türkiye**
Awareness and Understanding	Many farmers unaware of digital technologies and their potential benefits.	Lack of awareness about the full potential of digital technologies among farmers.
Connectivity	Poor internet connectivity in rural areas, hindering digital adoption.	Insufficient technological infrastructure in rural areas, limiting digital agriculture adoption.
Data Ownership	Concerns regarding intellectual property rights and data privacy in digital farming.	Data ownership and privacy concerns remain unresolved, hindering trust and adoption of digital tools.
Digital Skills	Lack of digital skills and an aging workforce hinder the adoption of new technologies.	Low digital literacy and a high average age of farmers hinder the efficient use of digital technologies.
Financial Barriers	High initial investment costs and limited access to financing, especially for small-scale farms.	Financial constraints and limited access to credit for small-scale farmers make digitalization difficult.
Support for Rural Development	Lack of sufficient public investment in rural development and agriculture.	Public investment in agriculture and rural development is inadequate, leaving small farmers without sufficient financial support.
Small-Scale Farms	Many small-scale farms struggle to adopt digital solutions due to resource constraints.	Dominance of small-scale farms, making large-scale digital adoption challenging.
Sector Integration	Difficulty integrating digital agriculture into other sectors due to technological gaps and resistance to change.	Integration of digital agriculture with other agricultural sectors faces resistance and challenges.
Technological Dependence	Dependence on imported technological inputs.	High reliance on foreign technology for digital agriculture implementation.
Radical Change Resistance	Resistance to the radical changes that digital agriculture may bring.	Resistance to radical transformation within the agriculture sector due to traditional farming practices.
Economic Instability	Economic instability and lack of long-term agricultural policy create uncertainty in adopting digital solutions.	Economic fluctuations, climate change, and unstable agricultural policies create challenges for digital adoption.

Sources: Niewiadomska, 2024; Komorowski, 2024; Ercan et al., 2019; Yılmazer, Tunalıoğlu, 2024.

3. The analysis reveals distinct approaches to economic resilience: Poland's strategy prioritizes operational optimization and technological efficiency, while Türkiye implements a more state-centric model with emphasis on governmental support mechanisms and incentive structures.
4. A shared challenge emerges in both contexts regarding the systematic transformation of traditional agricultural practices, accompanied by complex considerations surrounding data sovereignty and digital security protocols in agricultural systems.

CONCLUSION

The agricultural sectors of Poland and Türkiye are undergoing a profound digital transformation that promises to revolutionize farming practices, enhance productivity, and promote sustainability. This comprehensive analysis reveals how both nations have successfully integrated cutting-edge technologies, including Internet of Things (IoT), Artificial Intelligence (AI), and precision farming systems, yielding substantial economic and environmental benefits.

Poland's agricultural modernization strategy has demonstrated remarkable success through the systematic adoption of digital technologies. The implementation of smart farming solutions has resulted in measurable improvements across key performance indicators, including enhanced productivity metrics, significant cost reductions, and optimized resource allocation. Notable achievements in both dairy operations and crop management showcase the tangible benefits of these technological innovations. The country's progress has been substantially supported by strategic EU funding mechanisms and robust national policy frameworks, emphasizing the fundamental importance of digital infrastructure development and agricultural education programs.

Similarly, Türkiye has made significant strides in agricultural digitalization through targeted government initiatives and strategic investments. The country's focus on precision farming and smart greenhouse technologies has yielded impressive results, particularly in addressing critical challenges in water-scarce regions. Implementation of these advanced systems has led to documented improvements in crop yields, water conservation efforts, and overall product quality. Türkiye's commitment to research and development, coupled with strong support for smart agriculture initiatives, has created a favorable environment for technological adoption and innovation.

However, both nations face similar challenges in their digital transformation journey. Key obstacles include insufficient digital literacy among farming communities, financial constraints limiting technology adoption, and the complex task of integrating modern digital solutions with traditional agricultural practices. Addressing these challenges requires a multi-faceted approach incorporating sustained investment in educational programs, infrastructure development, and supportive policy frameworks that promote both innovation and inclusivity.

This comparative analysis underscores the transformative potential of digital agriculture in both contexts. The adoption of technological solutions represents more than a temporary trend; it constitutes a strategic imperative for addressing critical global challenges, including food security and climate change adaptation. As such, policymakers in both countries must prioritize the development and maintenance of robust digital agriculture ecosystems to ensure the long-term sustainability and competitiveness of their agricultural sectors.

Study's added value. This research makes a significant contribution to the existing literature by providing an in-depth comparative analysis of digital agriculture implementation across two distinct economic and agricultural contexts. The study's primary value lies in its comprehensive examination of strengths and weaknesses across multiple dimensions, offering valuable insights for policymakers, agricultural stakeholders, and researchers in both countries and beyond.

Research limitations Several important limitations must be acknowledged in this study. First, the dynamic nature of technological advancement means that specific findings may become outdated relatively quickly. Second, while the study provides valuable macro-level insights, it may not fully capture the nuanced challenges faced by individual farmers at the micro level. Third, variations in data availability and consistency between the two countries may affect the comprehensiveness of certain comparative analyses.

Future research directions Future research should prioritize:

– Detailed quantitative assessment of the economic impact of digital agriculture implementation in both countries;
– Comprehensive case studies examining successful digital transformation initiatives at the farm level;
– Systematic analysis of policy effectiveness in promoting and supporting digital agriculture adoption;
– In-depth investigation of social and cultural factors influencing technology acceptance in rural communities;
– Longitudinal studies assessing the sustainability of digital agricultural practices across different regional contexts.

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