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BARRIERS AND DRIVERS OF DIGITAL TRANSFORMATION IN AGRICULTURAL ENTERPRISES: INTERNATIONAL EXPERIENCE AND LESSONS FOR UKRAINE

The article examines the relevance of digital transformation in agriculture under conditions of structural heterogeneity, institutional asymmetry, market volatility, and crisis-related disruptions, with a particular focus on Ukraine as a transitional and war-affected economy. Digitalisation is conceptualised not merely as a technological modernisation process, but as a systemic transformation that reshapes production models, governance mechanisms, and value-chain coordination within agri-food systems. In this context, digital technologies function as instruments of productivity growth, environmental sustainability, traceability compliance, and long-term sectoral resilience.

The purpose of the study is to identify, compare, and systematise the key drivers and barriers influencing the adoption of digital technologies in agricultural enterprises across diverse international contexts, and to formulate analytically grounded and policy-relevant lessons for Ukraine. The research is based on comparative qualitative analysis of peer-reviewed international literature, thematic synthesis of technological, economic, organisational, and institutional determinants, and contextual assessment of global digitalisation models adapted to Ukrainian infrastructural, regulatory, and crisis-related realities.

The findings demonstrate that barriers to digital transformation operate as an interconnected systemic configuration in which constraints in infrastructure, finance, governance, and human capital reinforce one another, thereby limiting the effectiveness of isolated or sector-specific interventions. The study also identifies distinct digitalisation trajectories in developed, emerging, and innovation-driven agricultural systems, revealing differences in policy coordination, innovation ecosystems, and market incentives.

A novel concept of resilience-driven digitalisation is proposed to explain technology adoption under extreme uncertainty, where digital tools are implemented not primarily for efficiency gains but to ensure operational continuity, remote management, risk monitoring, and adaptive decision-making in crisis environments.

Keywords: digital transformation; agricultural enterprises; adoption drivers; systemic barriers; resilience-driven digitalisation; crisis-affected agricultural systems; digital governance; innovation ecosystems.

Problem Statement. The digital transformation of the agricultural sector has become a critical driver of productivity growth, sustainability, and competitiveness across global agri-food systems. Rapid advances in Internet-of-Things (IoT) devices, smart machinery, cloud-based decision-support tools, satellite monitoring, and artificial intelligence are reshaping production models and enabling data-driven management practices. For agriculture, digitalisation is not merely an element of technological modernisation but a strategic necessity for long-term resilience.

However, the pace and depth of digital adoption differ substantially across countries. While technologically advanced economies demonstrate rapid integration of digital tools, many developing or transitional agricultural systems continue to face financial, infrastructural, institutional, and organisational constraints. For Ukraine, these disparities are further amplified by wartime disruptions, damaged infrastructure, logistics instability, and the need to align with European sustainability and traceability standards. Under these conditions, identifying and systematising the barriers and drivers of digital transformation becomes essential for designing effective policies and supporting strategic decision-making in the agricultural sector.

Literature Review. International research demonstrates a wide spectrum of factors influencing digital transformation in agriculture. Studies from developing regions, such as India, Kenya, and Brazil, highlight infrastructure deficiencies, high technology costs, limited technical support, and low digital literacy as primary constraints to the adoption of IoT- and data-driven solutions. For example, the 2023 analysis of IoT adoption barriers in India shows that connectivity gaps, lack of standardisation, and the high cost of sensors significantly limit technological diffusion. Kenyan research similarly emphasises financial accessibility and skill shortages as decisive barriers to climate-smart technologies.

In contrast, literature from the EU and Canada identifies different patterns. There, adoption is shaped not only by economic and technological considerations but also by institutional frameworks, policy incentives, sustainability requirements, and the availability of innovation ecosystems. The JRC report on digital agriculture in the EU emphasises environmental policy, regulatory drivers, and structured support mechanisms as major determinants of digital transition. Canadian studies (e.g., Lassoued et al.) point to the importance of agri-tech clusters, research networks, public-private partnerships, and sophisticated R&D infrastructures.

Although existing research provides substantial insights into individual barriers and drivers, it remains fragmented across regions and rarely integrates multiple country experiences into a coherent analytical framework. This gap substantiates the need for a comparative synthesis that examines how technological, economic, organisational, and institutional factors interact across different agricultural contexts and what lessons can be drawn for Ukraine.

Unresolved Aspects Of The Problem. Despite substantial progress in the study of digital transformation in agriculture, several important knowledge gaps remain. First, most existing studies examine barriers and drivers within individual countries or narrow regional contexts, which limits the possibility of forming a holistic and comparative understanding of digitalisation processes across different types of agricultural systems. Research focusing on developing economies emphasises infrastructural and financial limitations, while literature from the EU and North America highlights institutional complexity, sustainability-driven incentives, and advanced innovation ecosystems. However, few studies integrate these perspectives into a unified analytical framework that captures both structural similarities and contextual differences.

Second, the interaction between technological, economic, organisational, and institutional factors often remains insufficiently explored. Existing research tends to analyse these components separately, resulting in a fragmented understanding of how they jointly determine farmers' decision-making and the overall digital readiness of agricultural enterprises.

Third, there is a notable lack of studies addressing digital transformation in transitional and crisis-affected agricultural systems. Ukraine represents a unique case where digitalisation is influenced not only by economic and technological factors but also by wartime disruptions, infrastructure damage, logistical uncertainty, human-capital losses, and the accelerated need for regulatory alignment with the European Union. Current international literature offers no integrated framework that would accommodate such conditions or provide evidence-based guidance relevant to post-war reconstruction and sectoral resilience.

These gaps highlight the need for a comprehensive comparative assessment of digital transformation drivers and barriers across diverse international contexts, followed by a synthesis of practical lessons that can inform Ukraine's agricultural development strategy.

Purpose of the article. The purpose of this article is to systematically identify, compare, and synthesise the key drivers and barriers of digital transformation in the agricultural sector based on international evidence, and to formulate policy-relevant lessons for Ukraine, considering its infrastructural challenges, wartime disruptions, and strategic alignment with European digital and sustainability standards.

Methodology. This study is based on a systematic qualitative analysis of peer-reviewed literature from both developed and developing agricultural economies. The methodology includes: comparative analysis; thematic synthesis: grouping barriers and contextual analysis: aligning international evidence with conditions specific to Ukraine; analytical structuring.

Results. Cross-country evidence demonstrates that digital transformation in agriculture evolves under widely different structural conditions. In technologically advanced regions such as the EU and Canada, digitalisation is supported by developed broadband infrastructure, innovation ecosystems, and targeted policy frameworks. Conversely, in emerging economies like India, Kenya, and Brazil, adoption remains constrained by infrastructural gaps, financial limitations, and fragmented extension services. These contrasts highlight the need for a comparative understanding of digitalisation processes and justify the synthesis of common barrier categories demonstrated in this study.

Technological Barriers. Across the reviewed literature, technological constraints consistently appear as a foundational barrier to agricultural digitalisation, yet they manifest differently depending on the structure and maturity of each agricultural system. In regions with extensive and heterogeneous agricultural landscapes, such as parts of Latin America, digital tools often face operational challenges linked to irregular connectivity, difficult terrain, and climatic stressors that reduce equipment durability. By contrast, in fast-growing agricultural economies in South Asia, the core issue lies not in terrain but in the uneven development of rural digital infrastructure and the absence of interoperable platforms capable of linking sensors, machinery, and analytics into a coherent system. Even in areas with relatively advanced digital ecosystems, such as the European Union, technological barriers persist in the form of incompatibility among devices, cybersecurity vulnerabilities, and fragmentation across digital service providers. These diverse examples highlight that technological barriers are not uniform but context-dependent, reflecting the interaction between local environmental conditions and wider infrastructural deficits [0, 2, 3].

Economic Barriers. Economic constraints represent one of the most persistent inhibitors of digital transformation. While the specific drivers of financial risk vary by region, the underlying mechanism

remains similar: when the perceived economic return is uncertain, investment capacity diminishes. In many emerging agricultural systems, high upfront costs for digital equipment and limited access to affordable credit create a structural disadvantage for smaller farms. Meanwhile, in middle-income countries with dual agricultural structures, digitalisation tends to cluster among larger, export-oriented producers able to amortise technology over extensive land areas. Conversely, in highly regulated agricultural economies, the financial burden may arise not from lack of credit but from the rising cost of compliance with environmental and traceability requirements, which often necessitate the adoption of digital tools. These patterns underscore that economic barriers are shaped by market structure, regulatory environment, and scale of production rather than by technology availability alone [0, 4].

Organisational Barriers. Digital transformation also depends on the organisational capacity of enterprises to integrate new technologies into their operational routines. In systems dominated by smallholder or family-run farms, limited digital literacy and risk aversion frequently restrict the uptake of complex technologies. In contrast, agricultural enterprises that operate within cooperative structures or innovation networks tend to demonstrate higher readiness, as shared learning processes and collective experimentation reduce perceived risk and accelerate competence building. In technologically progressive regions, organisational barriers often stem not from lack of skills but from misalignment between traditional workflows and data-driven decision-making systems. This mismatch results in partial integration, where digital tools exist alongside legacy practices without fully transforming operational processes. Such cases illustrate that organisational barriers are not only a reflection of human capital deficiencies but also a function of workflow rigidity, trust in technology, and the broader socio-cultural environment in which farms operate [0, 5].

Institutional Barriers. The institutional environment strongly shapes the conditions under which digital transformation can occur. In countries with decentralised governance structures, policy fragmentation leads to regional disparities in access to digital infrastructure and public support programmes. Meanwhile, in rapidly digitalising economies with strong central coordination, institutional challenges often stem from limited local implementation capacity and insufficient extension systems capable of transferring knowledge to farmers. Even in highly integrated policy environments such as the EU, institutional barriers persist due to the complexity of aligning digital regulations with sustainability frameworks and the administrative burden placed on smaller producers. Across contexts, uncertainties around data ownership, cybersecurity, and digital compliance represent emerging institutional barriers that affect both producers and technology developers. These cross-country observations indicate that institutional challenges are multifaceted, reflecting governance capacity, regulatory design, and coordination effectiveness [3, 6].

To systematise the identified constraints and to provide a structured analytical overview, the main categories of barriers, their key manifestations, and their practical implications for agricultural enterprises are summarised in Table 1.

Table 1

Barriers to Digital Transformation in Agricultural Enterprises

Group of Barriers	Key Manifestations	Impact on Agricultural Enterprises
Technological	Insufficient rural broadband and digital infrastructure. Lack of interoperability between digital platforms, sensors, and machinery. High cybersecurity risks. Limited compatibility between digital tools and legacy farm systems.	Incomplete integration of digital solutions into production processes. Increased operational risks due to system failures or cyber threats. Reduced efficiency of precision farming technologies. Dependence on external technical support and service providers.
Economic	High upfront investment costs for digital equipment and software. Uncertain return on investment (ROI). Financial risks associated with small-scale production structures.	Delayed or partial adoption of digital technologies. Concentration of digitalisation among large agribusinesses. Increased inequality between technologically advanced and lagging farms.
Organisational	Low digital literacy among farm managers and workers. Resistance to change and risk-averse decision-making culture. Weak integration of digital tools into existing workflows. Lack of internal digital transformation strategies.	Underutilisation of installed digital systems. Inefficient data-driven decision-making. Slow organisational learning and innovation diffusion. Reduced adaptability under crisis conditions.
Institutional	Policy fragmentation and inconsistent regulatory frameworks. Unclear data ownership and governance rules. Administrative burden related to digital compliance and reporting. Insufficient public support programs.	Increased regulatory uncertainty and compliance costs. Limited trust in digital data exchange systems. Regional disparities in access to digital infrastructure.

Source: Compiled by the author

As shown in Table 1, technological, economic, organisational, and institutional barriers are closely interconnected. These categories do not operate independently; rather, they form an interconnected system where weaknesses in one domain amplify vulnerabilities in others. For example, insufficient public coordination can increase financial risk for producers, which in turn limits organisational investment in training and reduces the effectiveness of digital tools. Equally, technological shortcomings such as poor interoperability force institutions to regulate evolving technologies prematurely, creating further administrative uncertainty. Recognising these systemic interdependencies is essential for designing policy solutions capable of addressing root causes rather than symptoms.

International Drivers of Digitalisation. Despite widespread barriers, global cases reveal several drivers facilitating digital transformation. In Canada and the EU, advanced agricultural R&D, public-private partnerships, and strong agri-tech markets support rapid technological adoption. In Brazil, economic incentives arise from the need to manage vast agricultural territories more efficiently, motivating large farms to adopt remote sensing and precision farming systems. In India, the affordability and mass availability of mobile technologies create low-level entry points for digitisation, especially for advisory services and weather-based farming decisions. In Kenya, cooperative structures and community-based learning networks serve as organisational drivers of technology diffusion [0, 2, 7, 12].

Resilience-Driven Digitalisation. A central innovation of this article is the introduction of the concept of resilience-driven digitalisation, a driver of technology adoption that emerges uniquely in crisis-affected agricultural systems. Unlike traditional digitalisation drivers – efficiency, productivity, sustainability, or market competitiveness – resilience-driven adoption is motivated by the need to maintain operational continuity under extreme uncertainty. This driver does not appear in the international literature examined here, as none of the reviewed studies focus on contexts characterised by widespread infrastructural destruction, severe logistical disruptions, or war-related risks.

Resilience-driven digitalisation describes a process in which farmers and agricultural enterprises adopt digital tools not primarily to increase yields or reduce costs, but to ensure basic functionality, safety, and remote operability. In Ukraine's wartime context, access to fields may be limited by security threats, transportation may be disrupted due to damaged infrastructure, and traditional monitoring methods may be unsafe or impossible. Under such conditions, remote sensing, satellite imaging, unmanned aerial vehicles, and automated machinery become essential. Similarly, distributed data systems and cloud platforms provide redundancy in case of physical damage to local infrastructure. Digital tools thus support not only economic objectives but also survival-oriented needs such as hazard detection, landmine monitoring, logistics planning, and crop-status evaluation without physical presence.

Moreover, resilience-driven digitalisation intersects with institutional and organisational dimensions in unique ways. At the institutional level, it requires the rapid development of emergency data governance frameworks, cybersecurity protocols, and decentralised information systems capable of operating during infrastructure outages. At the organisational level, it fosters new types of competencies related to remote operations, digital risk assessment, and crisis-informed decision-making. These capabilities, although developed under wartime conditions, may remain strategically valuable in the reconstruction phase, enabling Ukrainian agriculture to become more adaptive, automated, and risk-aware than many peacetime systems.

By identifying resilience-driven digitalisation as a novel driver, this article expands the conceptual vocabulary available for analysing technology adoption in crisis settings. This has broader implications for countries facing climate shocks, disasters, or political instability, where resilience, not efficiency, may become the primary rationale for digital innovation. The recognition of this driver provides a foundation for future research on crisis-oriented digitalisation pathways and establishes Ukraine as a pioneering case in the global digital transformation discourse.

A comparative synthesis of international cases shows that agricultural digitalisation evolves through diverse structural configurations shaped by the interaction of markets, institutions, innovation systems, and resource conditions. Although countries differ in emphasis and policy orientation, the underlying patterns confirm that effective digital transformation requires coherence between technological capabilities, organisational readiness, and supportive governance frameworks. These insights form the basis for deriving lessons for Ukraine.

First, the interdependence of barriers across technological, economic, organisational, and institutional categories indicates that digital transformation requires a systemic, multi-level approach, rather than isolated interventions. Lessons from the EU suggest that harmonised data standards and sustainability-oriented policies accelerate digital adoption, but only when coordinated with financial incentives and extension services. Therefore, Ukraine must adopt not only infrastructure-first strategies but also establish a coherent digital governance framework that aligns domestic regulations with EU requirements.

Second, the Canadian and North American experience demonstrates the value of innovation ecosystems, including agri-tech clusters, university-industry partnerships, and markets that encourage rapid technological experimentation. Ukraine can build similar ecosystems by establishing digital agriculture hubs, demonstration farms, and joint research programmes with technology companies. These ecosystems would be essential during both wartime and reconstruction phases to transfer knowledge, test technologies, and provide accessible training.

Third, insights from India and China demonstrate the effectiveness of state-led mass-scaling mechanisms, which provide equal access to technologies in rural regions and help overcome market failures. For Ukraine, implementing national-level digital extension services, subsidised adoption programs, and public investment in rural broadband could significantly reduce regional inequalities in digital access.

Fourth, the Israeli model of deep-tech innovation highlights opportunities for niche technological specialisation, particularly in water management, resource-efficient irrigation, and remote sensing. Given Ukraine's climate risks, water variability, and the need for low-touch farming solutions in high-risk areas, adopting elements of this model could offer both economic and security-related benefits.

Finally, the concept of resilience-driven digitalisation suggests that Ukraine must design a digital transformation strategy that accounts explicitly for crisis conditions. This includes investment in satellite monitoring, autonomous agricultural machinery, risk-prediction AI systems, and decentralised cloud databases. These technologies enable continuity of production even when normal field operations are disrupted. Such a strategy would strengthen both wartime survival and post-war competitiveness, positioning Ukraine as a global leader in adaptive, crisis-informed digital agriculture.

Together, these lessons form a comprehensive roadmap for Ukraine's digital transformation, one that integrates global best practices with unique domestic needs and incorporates both efficiency- and resilience-oriented priorities.

Conclusions. The study demonstrates that digital transformation in agriculture is influenced by a combination of technological, economic, organisational, and institutional factors whose interactions determine the pace and depth of adoption. Cross-country evidence confirms that digitalisation does not evolve uniformly but reflects differences in sectoral structures, policy

environments, innovation capacities, and resource availability. This article synthesises these diverse findings into an integrated understanding of how barriers and drivers interact across agricultural systems, offering a holistic perspective that is often missing from country-specific studies.

A further contribution of the study is the identification of resilience-driven digitalisation – a unique driver emerging in crisis-affected agricultural systems, particularly relevant for Ukraine. Unlike traditional motivations such as efficiency or sustainability, this driver reflects the need for operational continuity under conditions of disruption, insecurity, and infrastructural risk. Recognising this factor expands the conceptual understanding of digitalisation processes and highlights Ukraine's potential to become a leader in crisis-adaptive agricultural innovation.

Future research directions. Future research should further investigate cross-country patterns of agricultural digitalisation to determine how structural, institutional, and technological conditions shape adoption trajectories. Comparative empirical studies in transitional and post-crisis economies would be particularly valuable for validating the systemic interaction of barriers identified in this article. Further work is also needed to conceptualise and operationalise resilience-driven digitalisation, including developing indicators, examining its long-term effects on productivity and labour allocation, and comparing it with resilience-oriented innovation in other crisis contexts.

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БАР'ЄРИ ТА ДРАЙВЕРИ ЦИФРОВОЇ ТРАНСФОРМАЦІЇ АГРАРНИХ ПІДПРИЄМСТВ: МІЖНАРОДНИЙ ДОСВІД ТА УРОКИ ДЛЯ УКРАЇНИ

У статті досліджується цифрова трансформація аграрного сектору в умовах структурної неоднорідності, економічної нестабільності та кризових викликів, з особливою увагою до України. Цифровізація розглядається як комплексний процес модернізації виробничих систем, управлінських підходів і механізмів координації в агропродовольчих ланцюгах. У сучасних умовах вона виступає важливим чинником підвищення продуктивності, конкурентоспроможності, прозорості та довгострокової стійкості аграрних підприємств.

Метою статті є виявлення, систематизація та порівняння ключових драйверів і бар'єрів упровадження цифрових технологій в аграрних підприємствах на основі міжнародного досвіду, а також формування практичних рекомендацій для України з урахуванням її інституційних, інфраструктурних та кризових умов.

Методологічну основу дослідження становлять порівняльний якісний аналіз наукових джерел, тематичний синтез технологічних, економічних, організаційних та

інституційних чинників, а також контекстуальна адаптація міжнародних моделей цифровізації до українського середовища.

У результаті встановлено, що бар'єри цифрової трансформації мають системний характер і формують взаємопов'язану структуру обмежень, у межах якої інфраструктурні проблеми, фінансові ризики, інституційна фрагментація та недостатній рівень цифрових компетенцій посилюють один одного. Це знижує ефективність ізольованих заходів підтримки та потребує комплексного підходу до цифрової політики. У статті також виокремлено різні моделі цифрового розвитку аграрного сектору в розвинених і перехідних економіках. Обґрунтовано концепцію цифровізації, зумовленої резильєнтністю, яка пояснює впровадження технологій в умовах високої невизначеності з метою забезпечення безперервності виробництва, дистанційного моніторингу та мінімізації ризиків. Практична цінність роботи полягає у формуванні аналітичної рамки та рекомендацій для розробки системної та адаптивної стратегії цифрової трансформації аграрного сектору України.

Ключові слова: *цифрова трансформація аграрного сектору; аграрні підприємства; драйвери впровадження технологій; системні бар'єри; цифровізація, зумовлена резильєнтністю; інституційні чинники; цифрове врядування*