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BLOCKCHAIN TECHNOLOGIES AS A DRIVER OF TRANSFORMATION IN THE AGRICULTURAL SECTOR

Purpose. *The main objective of the study is to comprehensively examine the essential characteristics of blockchain technologies and their potential in the agricultural sector, in particular through an analysis and systematising of the prerequisites, areas of practical application and key challenges arising in the process of their implementation.*

Methodology / approach. *To conduct a comprehensive analysis, a combination of general scientific and specialised methods was used, including analysis, synthesis, case studies and bibliometric mapping (VOSviewer). The RStudio software environment was used to process statistical data and create graphs.*

Results. *The study emphasises the urgent need for innovative solutions to enhance transparency, efficiency, and resilience in agricultural operations. Key findings highlight the significant contribution of blockchain technologies to supply chain traceability, financial transactions, crop insurance, and data management. The decentralised nature of the technology ensures transparency and reduces fraud, thereby strengthening consumer trust and promoting sustainable agricultural practices. The analysis of global blockchain applications underscores its transformative impact across various sectors, particularly in agriculture. The study also identifies challenges such as high implementation costs and regulatory uncertainty, emphasising the need for a supportive environment.*

Originality / scientific novelty. *The distinctive feature of this study is the combination of bibliometric analysis of scientific sources with empirical study of real blockchain initiatives, as well as the use of data processing tools in RStudio. This approach allowed us not only to identify key scientific trends but also to outline practical mechanisms for implementing blockchain technologies in the agricultural sector. The novelty lies in the comprehensive consideration of blockchain as a digital innovation capable of systematically responding to the structural challenges of the industry, including supply chain disruptions, limited financial inclusion, and low data transparency.*

Practical value/implications. *The study provides specific recommendations for the practical use of blockchain technologies in agriculture. Based on comparative analysis of 10 countries and Ukrainian case studies (AgriChain, AgroGloryTime, AgroBon), the research highlights mechanisms for improving supply chain traceability, reducing logistics costs, and expanding access to financing through smart contracts. The findings may be applied by agribusiness managers to optimise logistics and quality control, by policymakers to design supportive digitalisation strategies, and by investors to assess innovation potential in the agricultural sector. Implementation of these recommendations will enhance transparency, strengthen resilience under crisis conditions, and create equal opportunities for both small and large agricultural producers.*

Key words: *blockchain technology, agricultural sector, innovation, transformation, logistics, management.*

1. INTRODUCTION

In today's world, innovations are developing rapidly and are being widely adopted across various economic sectors [1]. Technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and blockchain are increasingly integrated into the operations of large holdings and market-leading companies. These technologies primarily aim to automate routine tasks, minimise human error, support data-driven decision-making, and optimise operational costs [2]. For instance, AI is used for trend forecasting, risk management, and enhancing customer service through big data analysis. IoT enables real-time data collection and monitoring, which is particularly vital in logistics, agriculture, and manufacturing. The integration of these technologies provides companies with a competitive advantage, increases productivity, and enhances their adaptability to modern market challenges [3].

Scientists A. Ali and R. Ishaq emphasise the importance of technological innovations in the 21st century, noting that their implementation, when it meets market needs and organisational requirements, boosts operational efficiency, reduces marketing expenses, and increases customer satisfaction [4].

However, the Ukrainian agricultural sector demonstrates insufficient engagement with these technologies, which undermines its global competitiveness. Despite the evident potential of blockchain, AI, and IoT, most agribusinesses either disregard or only partially implement them. In current conditions, neglecting such innovations equates to undermining a business's competitiveness and long-term viability.

Compared to other countries, Ukraine's agricultural sector profoundly experiences modern challenges, including economic instability and the consequences of military conflict. Therefore, it is crucial to implement innovative technologies, particularly blockchain, which can enhance transparency, optimise logistics, secure financial transactions, and foster trust among market participants [5]. The absence of clear and transparent economic mechanisms makes companies vulnerable to systematic errors, misinterpretations, and fraud.

According to J. M. Alston and P. G. Pardey, blockchain can improve transparency and traceability in food supply chains, enhance food safety, and build trust among stakeholders [6]. Nonetheless, technical difficulties, the lack of standards, and regulatory uncertainty remain major barriers requiring further research and resolution.

Considering the above, the main goal of the study is to comprehensively examine the essential characteristics of blockchain technologies and their potential in the agricultural sector, in particular through an analysis and systematising of the prerequisites, areas of practical application and key challenges arising in the process of their implementation. Special attention is given to the opportunities blockchain creates for agribusinesses, including product quality control, logistics automation, crop insurance, and data management improvement – factors essential for enhancing competitiveness in times of crisis. To achieve this goal, the article sets out the following objectives: to present a clear definition of blockchain technology and identify its main areas of application; to provide a structured overview of the key challenges facing the agricultural sector under crisis conditions; and to formulate practical recommendations for the implementation of blockchain-based solutions in agricultural production.

2. LITERATURE REVIEW

To conduct a more in-depth examination of the concept of "blockchain technology" and to determine its position within the modern scientific community, an analysis of the Scopus scientometric database was carried out. The analysis demonstrates a pronounced upward trend in the number of scholarly publications on blockchain technologies over the period from 2014 to 2024. In 2014, only 2 publications were indexed, followed by 7 in 2015, 18 in 2016, 88 in 2017, 300 in 2018, and 538 in 2019. In 2020, there was a significant surge: Scopus indexed 865 publications on this topic. This number continued to grow steadily: 878 publications in 2021, 1,092 in 2022, 1,518 in 2023, and reaching 1,987 in 2024. This consistent increase highlights the growing academic interest in blockchain technologies and confirms their rising significance in driving transformation across various sectors of the economy, particularly in agriculture.

According to Table 1 and Figure 1, leading countries were identified based on citation rates of scholarly publications. The analysis included 95 countries, each with at least five academic works related to "Blockchain Technology" in the selected subject areas – "Business, Management and Accounting" and "Agricultural and Biological Sciences". Ukraine ranked 68th, indicating a moderate level of research activity among Ukrainian scholars in developing and implementing innovative technologies.

Table 1

Leading countries by the number of citations in blockchain technology research

No	Country	Citation	Number of documents
1	The United States	42992	966
2	The United Kingdom	28637	632
3	China	25333	1064
4	India	21025	1351
5	Germany	14421	394
6	Italy	11300	391
7	France	11274	233
8	Australia	10416	312
9	Hong Kong	6342	101
10	Canada	6106	215
...	...	...	...
68	Ukraine	234	49

Source: based on research data by [7].

This result may indicate both the potential for growth and the need to intensify research activities in the field of blockchain technologies, particularly considering their significance for the development of the modern economy in general and the agricultural sector in particular.

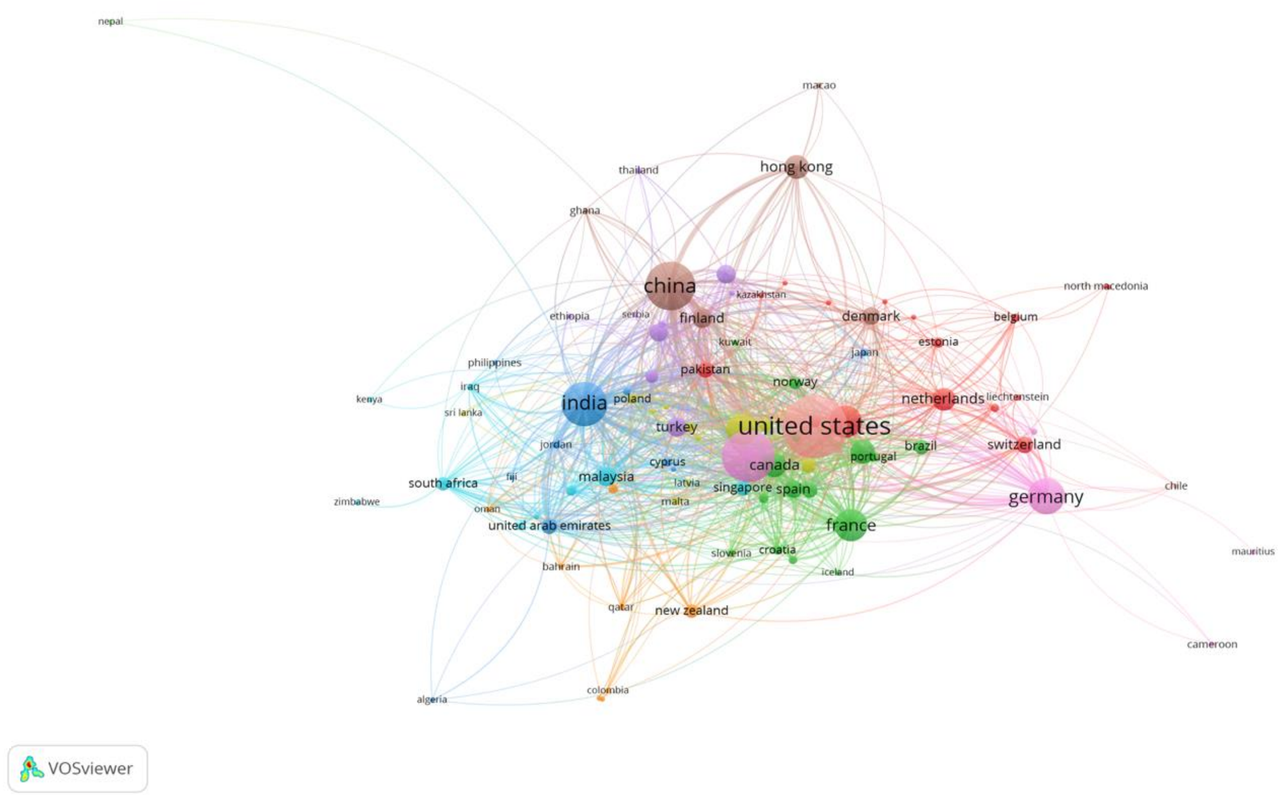

Figure 1. Relationship of countries by citation impact of scientific publications on blockchain technologies

Source: created by the authors using Scopus and VOSviewer [7–8].

Figure 2 presents the distribution of the most frequently used keywords in scholarly publications on blockchain technologies. The bibliometric analysis with VOSviewer made it possible to identify several distinct research clusters. The first cluster is centred on “blockchain” and “cryptocurrency”, reflecting the early stage of research (2014–2017), when the technology was mainly studied through the prism of digital currencies and financial transactions. The second cluster, formed around terms such as “supply chain”, “traceability”, and “logistics”, gained prominence after 2017, pointing to the growing attention to blockchain as a tool for ensuring transparency and efficiency in global supply chains, including the agri-food sector. The third cluster, associated with “smart contracts”, “Internet of Things (IoT)”, and “automation”, highlights the convergence of blockchain with other digital technologies and the focus of research on automation, risk management, and data-driven decision-making. The fourth cluster, which includes keywords such as “artificial intelligence”, “sustainability”, and “data management”, has expanded significantly since 2020, signalling the integration of blockchain into cross-sectoral innovation systems and sustainable development practices.

In terms of dynamics, the temporal evolution of keywords demonstrates a gradual transformation of research priorities: from a narrow concentration on financial operations (2014–2016), towards applications in supply chain management and logistics (2017–2019), and most recently (2020–2024) to cross-sectoral integration with IoT, AI, and sustainability frameworks. This shift indicates the broadening of blockchain research horizons and confirms its transition from a financial niche to a systemic driver of transformation across multiple industries, particularly in agriculture.

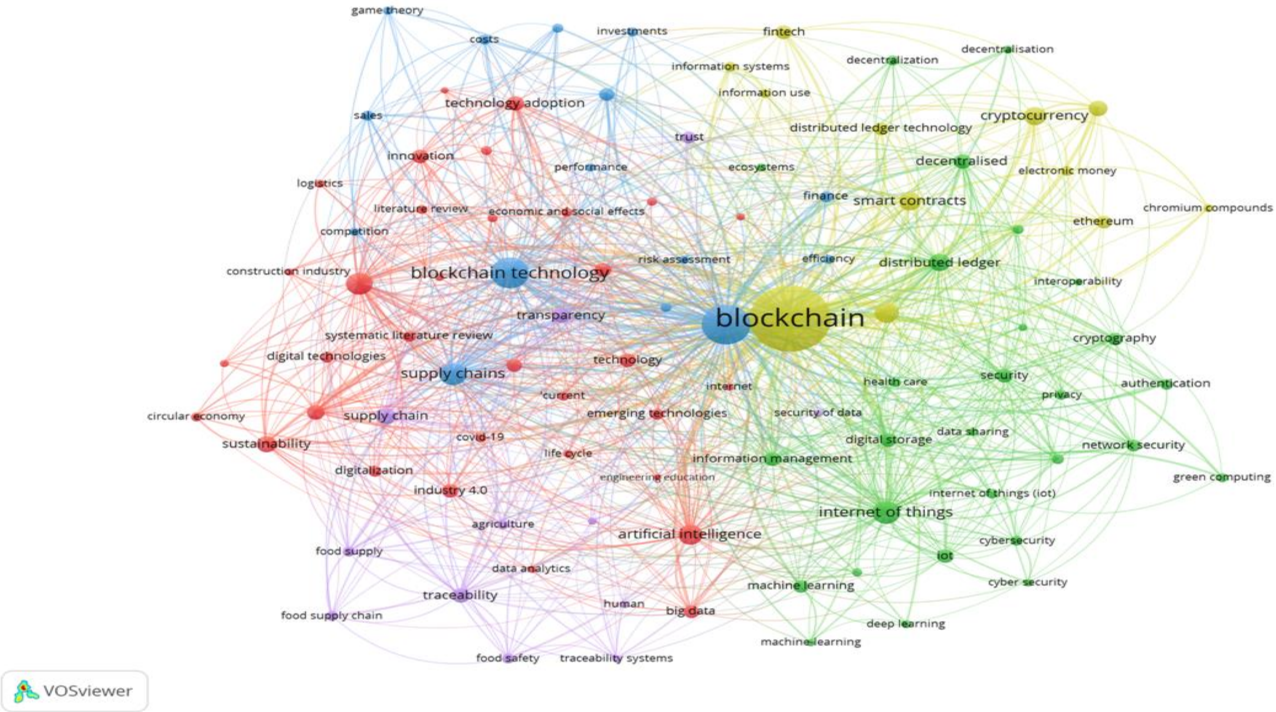

Figure 2. Distribution of the most commonly used keywords in blockchain technology research

Source: created by the authors using Scopus and VOSviewer [7–8].

Table 2 presents data on leading researchers in the field of blockchain technologies who have authored at least ten scientific publications. Among those with the highest numbers of publications and citations, the top contributors are Horst Treiblmaier (Austria) with 40 publications and 2,444 citations, and Joseph Sarkis (United Kingdom) with 26 publications and 4,583 citations. Completing the top three is Tsan-Ming Choi (Hong Kong), who has 21 publications and 3,130 citations.

These findings highlight that the most influential authors represent a diverse range of countries, including Austria, the United Kingdom, China, the United States, and others. Their research contributes to the scientific foundation for the implementation of blockchain technology across various economic sectors, emphasising its cross-sectoral and international character. It is noteworthy that different scholars define blockchain technology from multiple perspectives, reflecting its multidimensional nature and broad potential for transforming modern processes. From a technical perspective, Amazon Web Services and A. Haleem et al. view blockchain as a distributed database mechanism enabling simultaneous recording of transactions across multiple machines [9; 10]. While these definitions clearly capture the decentralised architecture, they often neglect sector-specific applications. From a functional perspective, C. Bhusal characterises blockchain as a transparent system for money exchange that reshapes business operations, while J. Potts emphasises its role in reducing transaction costs and enhancing efficiency in agricultural supply chains [11; 12]. These definitions highlight the practical benefits but tend to focus narrowly on individual sectors, such as finance or logistics. Broader interpretations, such as those of McKinsey & Company and M. Javaid et al., describe blockchain as a secure, shared digital ledger with cross-sectoral potential [13; 14]. Although such views underline versatility, they risk being overly general and lacking operational clarity.

Table 2

Leading authors in the field of blockchain technologies

No	Author	Country	Number of papers	Citation
1	Horst Treiblmaier	Austria	40	2444
2	Joseph Sarkis	The United Kingdom	26	4583
3	Tsan-Ming Choi	Hong Kong	21	3130
4	Chuanheng Sun	China	18	210
5	Abderahman Rejeb	Hungary	16	998
6	Qingyun Zhu	The United States	13	773
7	Na Luo	New Zealand	13	124
8	Anil Kumar	India	13	353
9	Tugrul Daim	The United States	13	583
10	Bin Xing	China	12	88
11	Sandeep Jagtap	Sweden	12	367
12	Abdo Hassoun	France	12	555
13	Nils Urbach	Germany	11	412
14	Khaled Salah	The United Arab Emirates	11	375
15	Mahtab Kouhizadeh	The United States	11	3675
16	Raja Jayaraman	The United States	11	312
17	M. Kabir Hassan	The United States	11	111
18	Sean Stein Smith	The United States	10	129
19	Karim Rejeb	Hungary	10	743
20	Sunil Luthra	India	10	200
21	Angappa Gunasekaran	The United States	10	2985

Source: based on research data by [7–8].

Thus, despite the diversity of interpretations, blockchain can be critically summarised as a decentralised digital ledger that ensures data transparency, immutability, and security, while its functional meaning depends largely on the sector of application. For agriculture, blockchain is most relevant as an infrastructural innovation aimed at improving supply chain traceability, optimising resource management, and enhancing trust among stakeholders.

At the same time, several unresolved issues remain. Existing research often concentrates on technical or financial applications, whereas the agricultural dimension receives limited empirical attention, especially in countries with unstable institutional environments such as Ukraine. Moreover, contradictions persist regarding the scalability, cost-efficiency, and regulatory feasibility of blockchain in agri-food systems. These gaps raise the following research question: how can blockchain technologies be effectively integrated into the agricultural sector to enhance transparency, efficiency, and resilience under crisis conditions? The central hypothesis of this study is that blockchain adoption in agriculture mitigates systemic challenges – including supply chain disruptions, financial exclusion, and low data transparency – thereby strengthening competitiveness and sustainability of the sector.

3. METHODOLOGY

The methodological approach adopted in this study reflects widely accepted practices in exploratory and empirical research and is particularly well suited to assessing the adoption of emerging technologies in dynamic and complex sectors. It ensures academic rigour and reliability while at the same time retaining practical relevance. Figure 3 presents the conceptual framework of the research, illustrating the logical sequence from research drivers and objectives through applied methods to analytical results and conclusions.

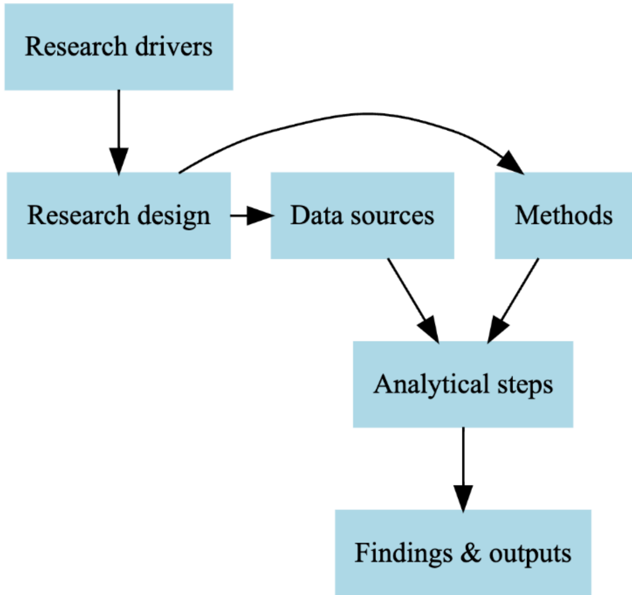

Figure 3. Methodological framework of the study

Source: compiled by the authors using RStudio software.

The research is based on a comprehensive methodological approach that combines bibliometric, comparative, and case-study analyses, supported by secondary data and the authors' own observations. This integrative design makes it possible to examine blockchain technologies as a driver of transformation in the agricultural sector in a systematic and multidimensional way, while also taking into account both global trends and the specific Ukrainian context.

The bibliometric analysis was conducted using the Scopus scientometric database, which provides one of the most complete sources of peer-reviewed publications. The search query was based on the phrase "Blockchain Technology", chosen deliberately broadly to capture the overall dynamics of scientific research, identify key thematic clusters, and trace the interdisciplinary application of blockchain. The dataset was processed with the VOSviewer software (version 1.6.20), which enabled the visualisation of research activity, the detection of prominent clusters of keywords, and the identification of leading authors, institutions, and thematic shifts over time. At the same time, given the sectoral focus of this study, a more detailed review of publications related specifically to agriculture is presented separately in section 4.4. Such a combination made it possible, on the one hand, to preserve the integrity of the bibliometric overview and, on the other, to highlight the agricultural dimension that is central to the research.

The empirical component of the study was designed to assess the readiness of agriculture for blockchain adoption in an international comparative context. Ten countries were selected for analysis, namely Canada, Denmark, France, Germany, Hungary, Italy, the Netherlands, Poland, Spain, and Ukraine. This choice was motivated by several factors: first, the countries represent diverse models of agricultural development and different levels of digital maturity, thus providing a contrasting basis for analysis; second, comparable statistical data are available for these cases; and third, the inclusion of Ukraine makes it possible to align national dynamics with the experience of the EU and North American countries. The analysis focused on three indicators: the share of enterprises using information and communication technologies (ICT); agricultural R&D expenditure as a percentage of agricultural GDP; and the extent of traceability systems in agriculture. The specific set of countries differs slightly across figures due to variations in data availability, which reflects the limitations of official statistics and the need to adapt the sample to the analytical task.

In order to ensure the robustness of findings, several research methods were applied in an interrelated manner. Analysis and synthesis were used to conceptualise the subject area, identify key challenges, and integrate theoretical foundations with practical observations. The abstract-logical method supported the generalisation of information, and the formulation of conclusions based on the observed patterns of blockchain implementation. Bibliometric methods provided insights into the development of academic interest in blockchain and its interdisciplinary applications, while comparative methods allowed the evaluation of geographical distribution, research intensity, and digital readiness across the selected countries. In addition, case-study analysis was used to examine Ukrainian blockchain-based initiatives in the agricultural sector, enabling the connection of conceptual results with real-world practice. To improve communicative value, visualisation techniques were actively applied: tables, graphs, and diagrams were generated using RStudio to ensure clarity, transparency, and reproducibility of results.

4. RESULTS

4.1. Blockchain technologies: main characteristics, advantages, disadvantages and principles of work. Blockchain technologies began to be actively used in 2009, with their initial application limited exclusively to the management of cryptocurrencies such as Bitcoin [15]. However, over time, these technologies have found applications in other domains due to their unique characteristics, including decentralisation, transparency, immutability of records, and enhanced security.

For the purposes of this study, blockchain is defined as a decentralised digital ledger technology that enables secure, transparent, and immutable recording of agricultural operations – from input supply and production to logistics, sales, and consumer access. This definition emphasises blockchain's role not only as a general digital innovation but specifically as a tool for strengthening efficiency, resilience, and trust in agri-food systems. Accordingly, blockchain can be defined as a complex technology that integrates transparency, security, and decentralisation, serving as a foundation for innovation across multiple sectors of the economy.

It is important to note that blockchain technologies represent an innovative method of information storage in the form of a digital ledger used for recording transactions, agreements, or contracts. According to Figure 4, an analysis of blockchain implementation from a technical perspective indicates that one of the key advantages of this technology lies in decentralised data storage, as the ledger is not located in a single physical location but is distributed across hundreds or even thousands of computers in various countries [16]. Thus, blockchain operates through a virtual platform accessible only via the Internet.

Blockchain is a multifunctional and multilevel information technology designed for accounting for various assets

Blockchain 1.0 is currency (cryptocurrency used in various money-related applications: transfer systems and digital payments)

Blockchain 2.0 is contracts (entire classes of economic, market, and financial applications working with various financial instruments: stocks, bonds, smart assets, and smart contracts)

Blockchain 3.0 is applications that extend beyond monetary calculations, finance, and markets (areas of public administration, healthcare, education, culture, etc.)

Figure 4. Typology of blockchain technologies

Source: created by the authors based on research data by [16].

To fully comprehend the potential of blockchain technologies, it is essential to consider both their key advantages and limitations. Figure 5 presents a structured overview of the main aspects that determine the practical value and challenges associated with the use of blockchain across various domains.

Advantages and disadvantages of blockchain technologies

Advantages:
1. Improved accuracy by eliminating the human factor in verification.
2. Reduce costs by eliminating third-party verification.
3. Decentralisation complicates falsification.
4. Transactions are secure, private, and efficient.
5. Transparent technology.
6. Provides a banking alternative and way to protect personal information for citizens of countries with unstable or underdeveloped governments

Disadvantages:
1. Significant technological costs.
2. Low number of transactions per second.
3. History of use in illegal activities (darknet).
4. Regulation varies by jurisdiction and remains uncertain.
5. Data storage limitations

Figure 5. Advantages and disadvantages of blockchain technologies

Source: created by the authors based on research data by [17].

Considering the outlined strengths and weaknesses, it can be concluded that the effectiveness of blockchain technologies largely depends on the context of their application. The successful integration of this technology requires careful consideration of sector-specific characteristics, as well as a thorough assessment of potential risks and costs.

The next important step in exploring blockchain technology is understanding the principles of its operation. Figure 6 illustrates a simplified diagram of how blockchain works, illustrating data transfer in a decentralised network. Each block in this schematic contains a set of transactions encrypted using cryptographic methods and is linked to the previous block via a hash.

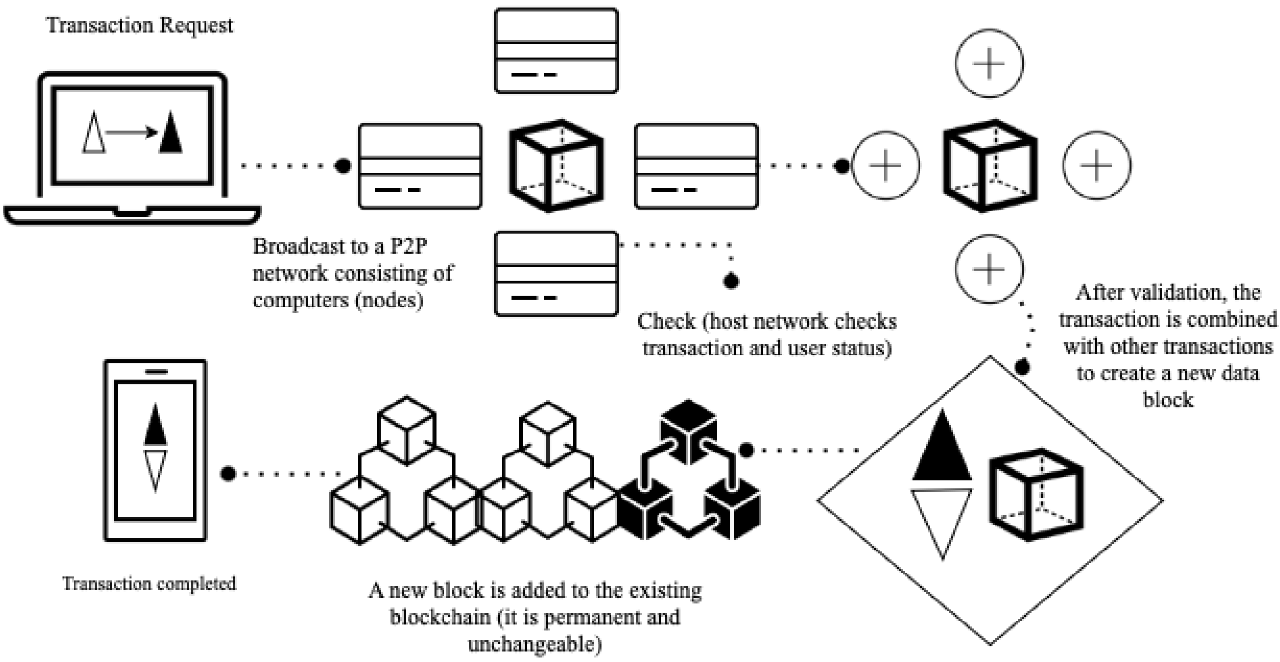

Figure 6. Visualisation of the work of blockchain technology

Source: created by the authors based on [18].

This structure ensures data immutability and transaction transparency, while also preventing unauthorised interference. One of the key elements of this system is the consensus mechanism, which ensures that all network participants agree on the records in the chain. This is achieved through specific algorithms, such as Proof-of-Work or Proof-of-Stake, depending on the blockchain implementation [19].

Accordingly, the visualisation of the model provides insight into how the individual elements of the system interact to ensure security and decentralisation, making blockchain a unique technology for application across various sectors.

4.2. The main directions of implementation of blockchain technologies. In today’s world, blockchain technologies are rapidly gaining popularity due to their ability to provide security, transparency, and efficiency across various sectors. As illustrated in Figure 7, blockchain has become critically important in areas such as finance, logistics, real estate, healthcare, and agriculture.

In the financial sector, blockchain not only accelerates transactions but also minimises risks associated with fraud. In logistics, it enhances transparency and traceability within supply chains – an essential factor for global markets. Real estate benefits from the automation of purchase and sale processes and the assurance of the authenticity of property ownership records. In healthcare, blockchain contributes to the protection of patients' data and the optimisation of access to electronic medical records. As for agricultural production, this sector gains significant advantages from blockchain through the ability to track product origin, manage supply chains, and ensure compliance with quality standards. This leads to reduced losses, increased consumer trust, and more efficient resource utilisation.

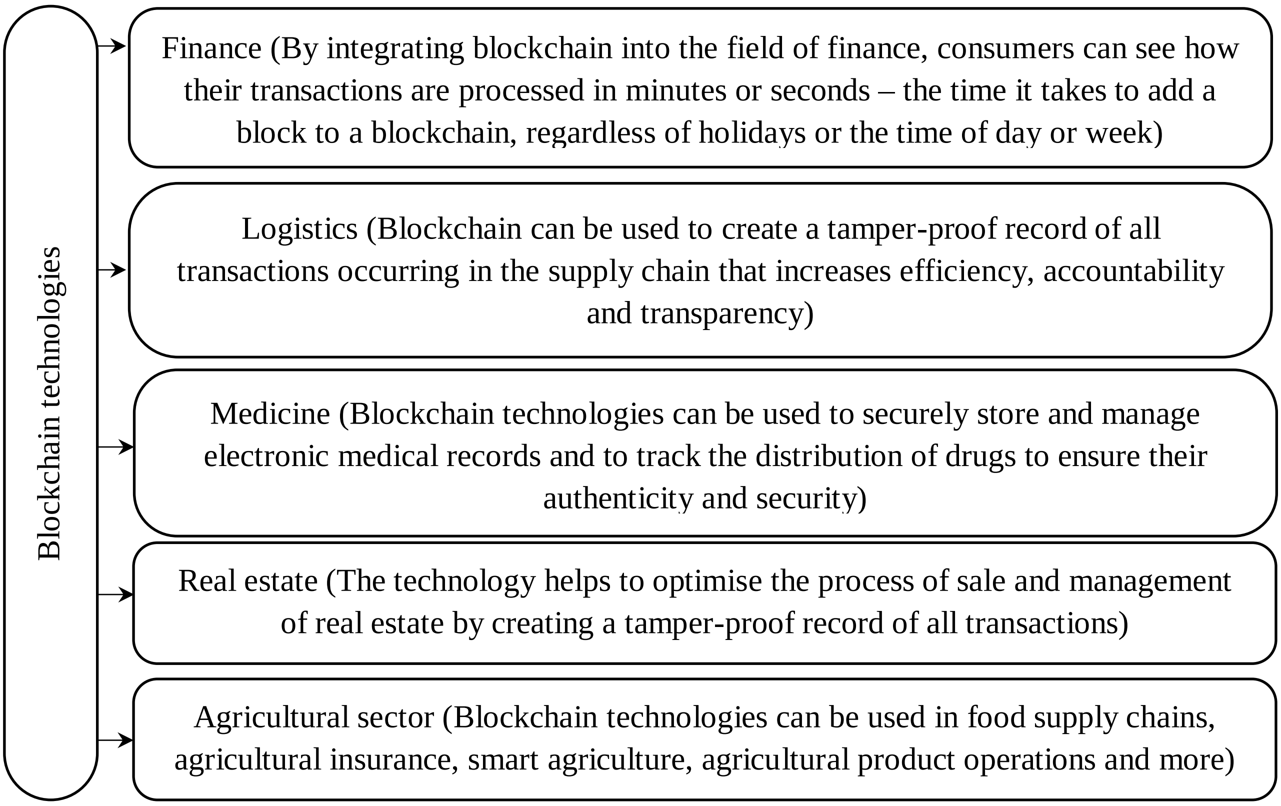

Figure 7. Areas of implementation of blockchain technologies

Source: created by the authors based on research data by [17; 20; 21].

Today, blockchain is more than just a technology – it is a foundation for building new economic models and governance systems. The continued development of blockchain, particularly its integration with fields such as artificial intelligence, will enable even more transformative changes in business operations, service delivery, and data interaction. This confirms that blockchain is not merely a technology of the future, but a present-day reality that is shaping new standards in the global economy. According to leading market analysts, Figure 8 shows the structure of blockchain technology implementation in various sectors of the economy.

The financial sector leads with a 44% share of integration, underscoring the critical role of blockchain in ensuring transparency and security in financial transactions. The public sector accounts for 10%, reflecting the gradual adoption of the technology in government administration. In the insurance industry, blockchain technologies are used in 7% of cases, contributing to automation and improved service efficiency. The food sector represents 6%, indicating a growing interest in enhancing supply chain transparency. The remaining 33% is attributed to other industries, highlighting the substantial potential for further blockchain development across diverse areas of the economy.

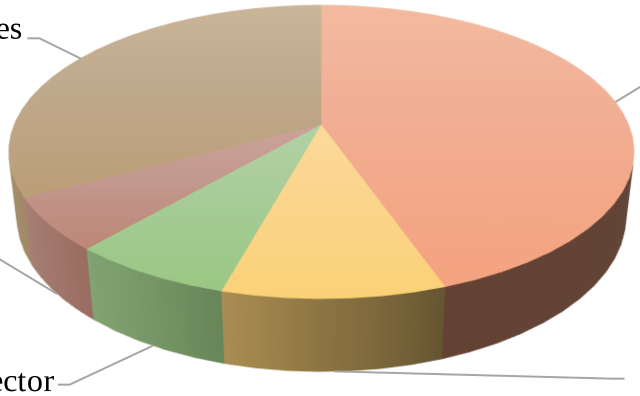

Figure 8. Structure of implementation of blockchain technologies in various sectors of the economy in the world, %

Source: based on research data by [22].

Thus, blockchain technologies not only transform traditional approaches to data management but also open new horizons for innovation in key economic sectors. Their implementation enables the resolution of complex challenges previously faced by enterprises, further confirming the relevance and long-term potential of this technology. In addition to the global trends described above, the Ukrainian agricultural sector is also witnessing the emergence of blockchain-based solutions. Several domestic companies and startups have already introduced digital platforms aimed at enhancing supply chain transparency, improving logistics efficiency, and attracting investment. Table 3 provides an overview of key Ukrainian initiatives that demonstrate the practical implementation of blockchain technologies in agriculture.

Table 3

Examples of Ukrainian companies implementing blockchain in the agricultural sector

Company	Description
AgriChain (Astarta-Kyiv)	Develops digital solutions for agribusiness management: land bank, production, crop monitoring, logistics, and warehouse management. Partners with Planet Labs, One Soil, and Sentinel Hub
AgroGloryTime	Implements blockchain to increase transparency and reduce costs in agribusiness. Introduced AGTI tokenisation and ensures secure data storage and access
AgroBon	Innovative digital project integrating blockchain technologies in Ukraine's agrisector, aimed at attracting European investments
Sandbox for AI and Blockchain Startups	Supports startups in AI and blockchain, including solutions for the agrisector; provides access to prototypes and consulting for innovation development

Source: based on research data by [23–26].

The examples presented in Table 3 confirm that Ukrainian agribusiness, despite operating under conditions of uncertainty and crisis, is gradually integrating blockchain solutions into its operations. These initiatives not only improve transparency and efficiency but also highlight the potential for Ukraine to align with global innovation trends in the agricultural sector.

4.3. Agricultural sector: modern challenges and potential of blockchain technologies. Currently, the agricultural sector is undergoing a complex transformational period driven by a combination of internal and external challenges. Modern agriculture faces multifaceted problems that require immediate strategic response. Key among these are resource constraints (progressive depletion of natural resources, degradation of agricultural land quality, critical shortages of water resources, and the continuous rise in production costs); climate change (intensifying adverse effects of climate transformation, increased frequency of extreme weather events, soil erosion, and declining natural fertility); socio-economic determinants (disruptions in supply chain stability, significant shortages of skilled labour, and urbanisation processes negatively impacting rural areas); institutional challenges (inefficient management of energy resources, low levels of innovation, and a widening gap between public expectations and the actual condition of the agricultural sector); and other contributing factors [27]. Research conducted by leading experts, including [28], confirms the systemic nature of these issues and highlights the need for a comprehensive, integrated approach to their resolution (Table 4).

Successfully overcoming these challenges requires the implementation of innovative technologies, diversification of production, development of human capital, and the formation of adaptive agricultural policies. It is worth noting that alongside these challenges, new opportunities for innovative solutions are emerging, particularly through the implementation of blockchain technologies.

Blockchain, as a decentralised technology, has the potential to address some critical issues, such as enhancing the transparency of supply chains, reducing administrative and operational costs, and increasing the level of trust among stakeholders in the agricultural market. A significant portion of both domestic and international research is devoted to the challenges of the agricultural sector, with a particular emphasis on the importance of implementing innovative technologies. In their studies, scholars analyse the necessity of modernising and adapting agricultural enterprises to new conditions, as well as improving their competitiveness through the integration of advanced technologies into production processes.

Modern challenges of the agricultural sector are multidimensional and closely linked to global food security, enterprise competitiveness, and labour market dynamics. Ensuring food security in developing countries requires not only sustainable production, but also the integration of new technologies and improved management practices. As noted in several studies, agriculture plays a decisive role in stabilising food supply, which makes its modernisation a strategic priority [29]. In this context, the competitiveness of agricultural enterprises becomes a key determinant, as businesses are forced to adapt to globalisation and economic instability through innovative management approaches and technological renewal [30]. Another critical aspect is the shortage of qualified labour, which was exacerbated during the COVID-19 pandemic. Researchers point out that automation, diversification of labour sources, and the adoption of digital solutions can mitigate the risks of workforce deficits and ensure greater resilience of agri-food systems [31].

Table 4

Modern challenges in the agricultural sector

No	Challenges	Description
1	Climate change	Climate change is characterised by long-term global temperature and weather condition shifts caused by global warming. Consequences include extreme weather events, reduced agricultural yields, and increased environmental risks, with agriculture and land use accounting for 23% of greenhouse gas emissions. Addressing climate change-related challenges requires immediate comprehensive international actions to minimise ecological and socio-economic risks
2	Soil erosion	Soil erosion is a natural process of land resource destruction by water or wind, which negatively impacts agricultural production. Currently, only 12% of global lands are used for agriculture, and research shows a high rate of land degradation. Erosion consequences include reduced productivity, crop yields, irrigation efficiency, and land suitability for agricultural use
3	Land limitations	Not every soil is suitable for growing all agricultural crops due to specific requirements, including structure, texture, fertility, water availability, and agro-meteorological conditions. These factors limit land suitability for agriculture, with both natural characteristics and farmers' land use practices influencing soil quality and condition
4	Urbanisation and migration	Urbanisation triggers significant population migration to cities due to better educational and professional opportunities, with serious implications for agriculture. Urban area expansion leads to arable land loss, agricultural area reduction, and creates challenges including workforce shortages and food production decline
5	Management and related issues	Agriculture is a complex multi-stage activity encompassing various operational processes: land and water resource management, plant nutrition, pest and disease control, crop processing and storage. Successful agricultural management requires specific skills, experience, and timely response to challenges at each production cycle stage. Industry efficiency directly depends on the qualification and professionalism of human resources
6	Investment	Agricultural investments are minimal and limited, especially in developing countries. A prevalent myth suggests these investments are unprofitable due to dependence on uncontrollable factors like weather conditions. The dominance of small and marginal farmers restricts their ability to invest in complex technologies, further complicating industry development
7	Adoption of new technologies	Farmers in developing countries are predominantly poor with small land holdings, which limits their access to modern technologies. They are compelled to rely on subsidies and discounts from companies to acquire technological equipment. Even when new technologies are implemented, significant obstacles emerge training costs, lack of skilled labour, technical maintenance and repair challenges, and shortages of mechanics and safety specialists

Source: based on research data by [27; 28; 32–35].

Taken together, these findings confirm that the systemic problems of agriculture – food security, competitiveness, and labour shortages – require a complex response.

A common conclusion is the urgent need for innovation and technological modernisation, where blockchain, alongside other digital tools, can act as a transformative solution for increasing transparency, efficiency, and trust in the agricultural sector.

The study [11] highlights that agriculture is one of the sectors where blockchain technology can bring about a real breakthrough by addressing systemic issues such as product fraud, traceability, price manipulation, and lack of consumer trust. At the same time, the author underlines that blockchain adoption in agriculture is still at an early stage and constrained by factors including high implementation costs, privacy concerns, scalability, and security. Despite these challenges, the technology holds significant potential to transform agricultural systems and ensure greater transparency and trust across the industry. This conclusion aligns with the broader body of research, which consistently highlights the necessity of adopting innovative digital solutions – particularly blockchain – to increase resilience and competitiveness in agriculture.

4.4. Implementation of blockchain technologies in the agricultural sector: key aspects and prospects. In the contemporary agricultural sector, data protection has become increasingly significant due to the digitalisation of business processes and the adoption of innovative technologies. As previously noted, one of the promising directions involves the use of blockchain technologies, which ensure transparency, reliability, and security in data processing. Figure 9 presents a diagram illustrating the mechanism for applying blockchain to ensure data protection and detect violations within agricultural enterprises.

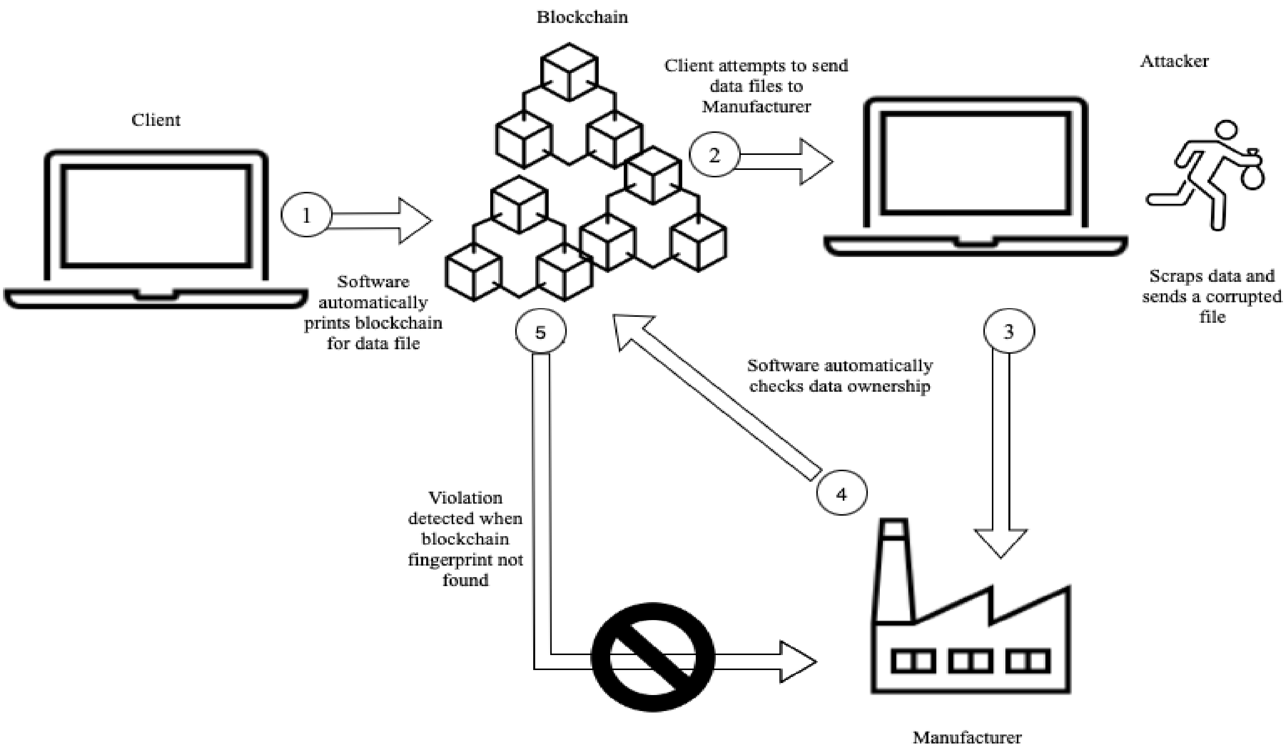

Figure 9. Using blockchain to ensure data protection and identify violations in agricultural enterprises

Source: created by the authors based on [36].

As shown in Figure 9, the fundamental principle of blockchain technology lies in the automatic tracking of changes and the verification of data through a distributed network. The client transmits data to the producer, while the blockchain ensures verification of data ownership rights and detects potential violations. If unauthorised modifications are identified, the system blocks access and notifies network participants. The use of this technology in the agricultural sector helps minimise the risk of data loss or theft, increases trust among partners, and supports more efficient business process management.

Figure 10 presents the key types of blockchain technologies that are already being actively used or have the potential for implementation in the agricultural sector. These technologies provide control over supply chains, financing, and insurance, as well as contribute to the effective management of agricultural data. Each of these directions not only enables optimisation of internal processes within agricultural enterprises but also enhances transparency and trust among all participants in the supply chain.

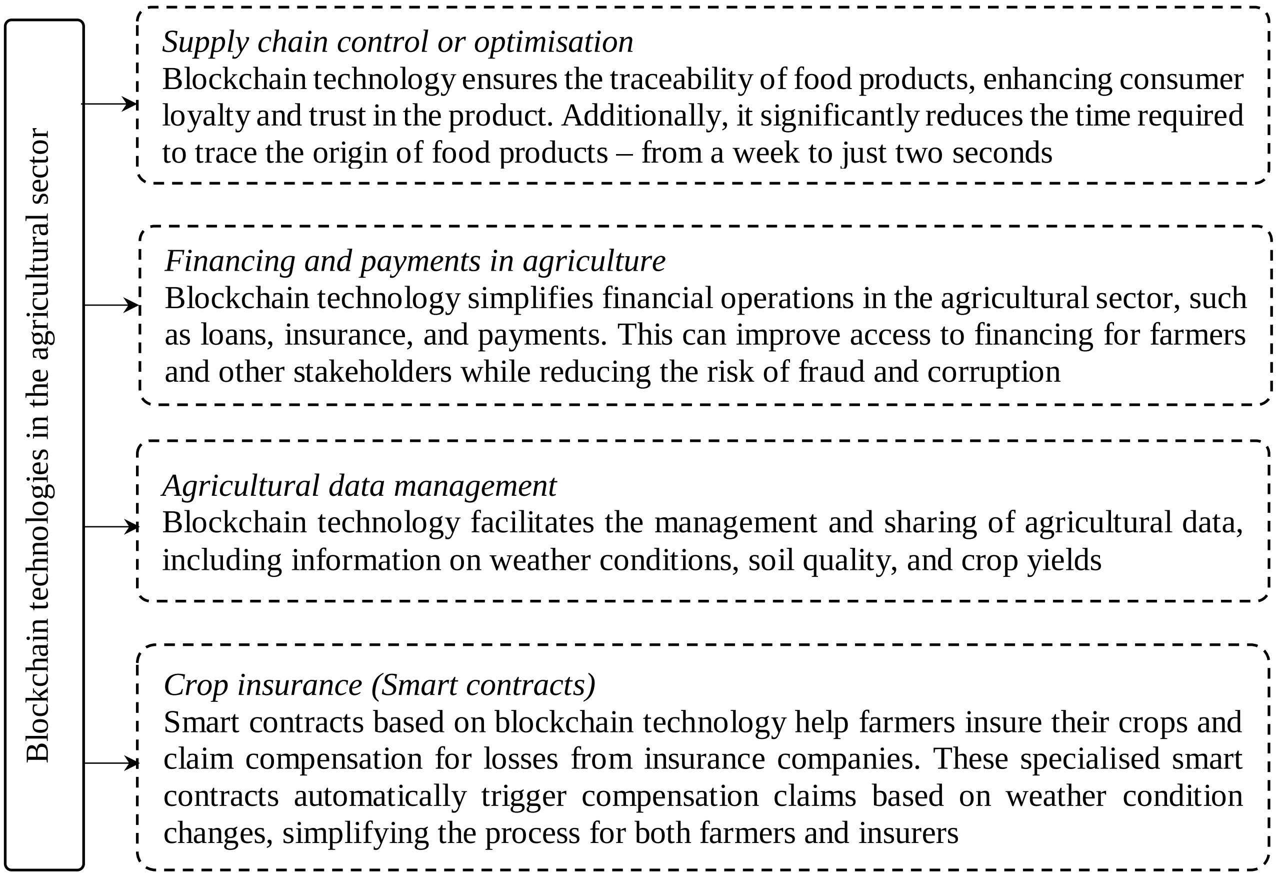

Figure 10. Types of blockchain technologies in the agricultural sector

Source: created by the authors based on research data by [33].

Thus, blockchain technologies hold significant potential for transforming the agricultural sector. First, blockchain helps reduce risks related to human harm by ensuring the quality and safety of agricultural products. Through data transparency and the ability to trace supply chains, blockchain prevents fraud and counterfeiting – an especially critical issue for organic agriculture. Consumers can verify the origin of products and trace their journey "from farm to table". Second, decentralised ledgers simplify transactional processes and create equal opportunities for small-scale farmers and agricultural producers, thereby increasing their competitiveness in the market. Finally, the implementation of blockchain technologies enhances the efficiency and productivity of agriculture, supports decision-making, and fosters the development of research initiatives. This makes blockchain a vital tool for building resilient agricultural systems.

As noted by A. Adewusi, "...blockchain technology has become a powerful tool for enhancing transparency and traceability in agriculture, offering significant benefits across supply chains" [37]. Indeed, the use of blockchain enables farmers, producers, and consumers to access accurate information regarding product origin, production conditions, and quality attributes. Due to the decentralised nature of blockchain technology, all data are stored in an immutable format, making any falsification virtually impossible. Moreover, blockchain strengthens trust among all participants in the agricultural supply chain. Producers can verify the quality of their products, while consumers are empowered to make informed purchasing decisions. This approach is particularly important in the context of the growing demand for organic and environmentally friendly food products, where transparency is a key factor.

The technology also opens new opportunities for creating sustainable and efficient management systems in agriculture, ultimately contributing to food security and the sustainable development of the agricultural sector. Table 5 provides an overview of key blockchain startups operating in the agricultural sector as of 2021.

Table 5

Examples of blockchain startups in agriculture in the world

Blockchain startups	Characteristics
1	2
AgriLedger	It is aimed at improving the efficiency of the agricultural sector, allowing farmers to plan and harvest more efficiently, access markets, and confirm their identity and income to financial institutions. As a result, it provides transparency and trust throughout the supply chain, allowing you to track each unit of production from seed to consumer
TE-FOOD	It allows companies to differentiate their products from competitors, increase operational efficiency, directly interact with consumers, position premium products, meet the requirements of import legislation, and automate and reduce the number of product recalls
AgriDigital	Uses blockchain technology to provide real-time payments for physical grain deliveries
AgriChain	A software solution that transmits information between participants in the agricultural supply chain. It combines mobile software for farmers and logistics providers with a web-based business administration application to provide end-to-end visibility of the supply chain. It automates the delivery process and collects data at each point in the supply chain, which is marked by time and updated in real time for all parties. agricultural supply chain
Ambrosus	Focuses on tracking and traceability of supply chains in agriculture and food processing. It uses smart contracts and sensors to track the movement of agricultural products, providing transparency and accountability throughout the supply chain

Continuation of Table 5

1	2
Etherisc	A decentralised insurance platform that aims to make insurance fair and affordable. They develop a protocol that enables the collective creation of insurance products. Their goal is to make insurance cheaper, faster and easier by harnessing the power of blockchain technology
Dozrila	Creates a transparent digital food supply chain that uses quality food data to map the food path and provides the food blockchain (providing customers with personalised real-time analytics via a mobile app or PC and using the blockchain ledger to ensure ongoing access to data). The platform enables food supply chain partners to offer quality food and ensure transparency by tracking the path of food from seed to sale, ensuring that consumer needs are met

Source: based on research data by [36; 39; 11].

An analysis of the data presented in Table 5 demonstrates that blockchain startups in the agricultural sector play a crucial role in addressing key challenges. As emphasised in the study [38], the modern agricultural industry faces numerous difficulties, including economic instability, climate change, and disruptions in supply chains. The authors highlight the significant potential of blockchain technologies to enhance transparency, efficiency, and resilience within the sector. The practical recommendations proposed by the researchers include implementing decentralised platforms for supply chain traceability, automating financial transactions, and establishing trust among all market participants. It is worth noting that blockchain technology enables the automation of processes, thereby minimising human involvement and reducing the risk of errors. This contributes to improved resource management and enhances the adaptability of the sector to global challenges. Thus, the adoption of blockchain technologies is not only a promising direction for the development of the agricultural sector but also a necessary condition for its sustainable operation in the context of contemporary crises.

4.5. Comparative data analysis of blockchain adoption readiness in agriculture. To study in-depth the processes of implementing blockchain technologies in the agricultural sector, a comparative analysis was carried out based on three key indicators: the level of development of information and communication technologies, the amount of research funding, and the availability of product traceability systems. The United States of America, several European Union countries, and Ukraine were chosen for the analysis as representative examples of different degrees of digital transformation of agriculture.

It should be emphasised that the introduction of blockchain technologies in the field of agricultural production is impossible without an adequate level of development of the information and communication infrastructure. This is primarily since blockchain technology operates exclusively in a digital environment, where all participants in the agri-food chain – producers, processors, logistics operators, and regulators can create, synchronise and store data in real time.

In this context, the availability of a stable Internet connection, especially in rural areas, is a critical condition for the effective functioning of such technologies. These are the areas where the bulk of agricultural production is concentrated, but they often have lower digital coverage than urbanised areas. The high level of network access allows agricultural producers to use blockchain tools: connect to digital traceability platforms, apply smart contracts, integrate data from IoT devices, exchange information through cloud services, etc.

Therefore, the level of development of digital infrastructure, including ICT penetration in rural areas, can be seen as an indicator of a country's readiness to implement blockchain technologies in agriculture. In this regard, the study analysed the relevant quantitative indicators for the period 2019–2024 on the example of Canada, selected EU countries and Ukraine (Figure 11). Figure 11 presents an analysis of related industries (transport, trade, etc.) that form a significant part of the agri-food chain. These data allow us to indirectly assess the level of digitalisation required for the integration of blockchain solutions into agriculture.

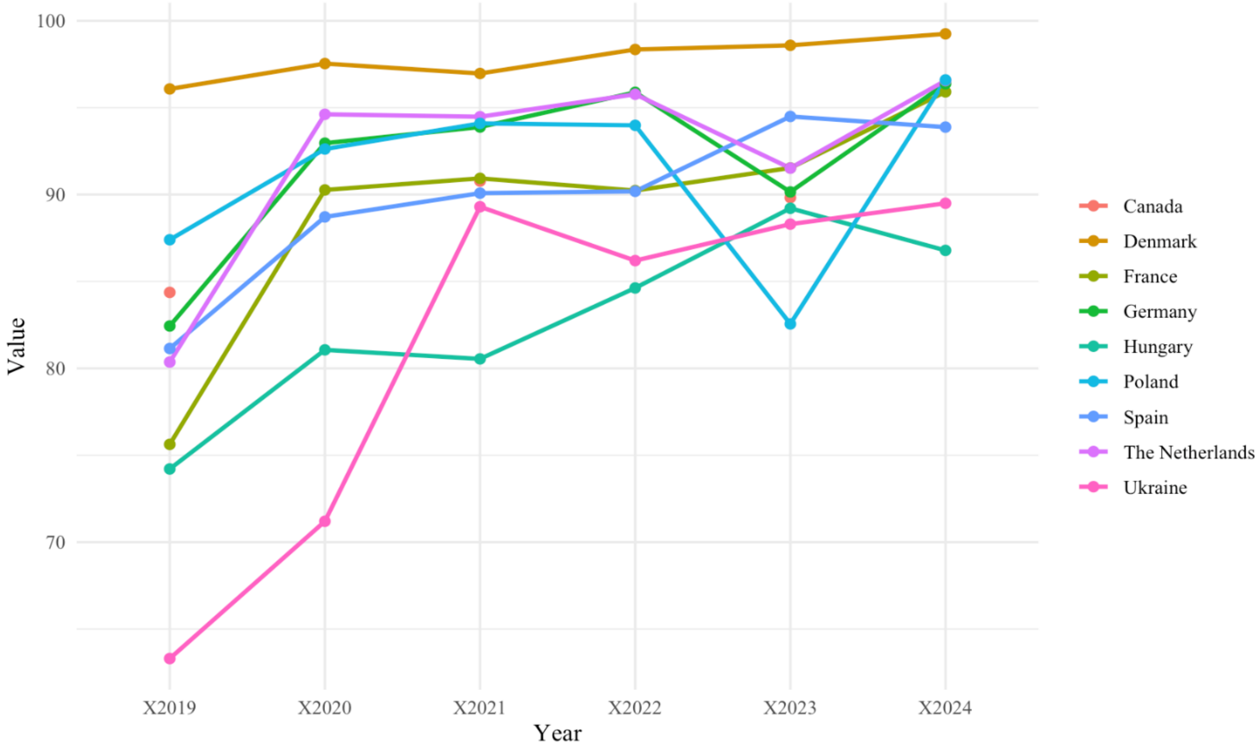

Figure 11. Share of enterprises using ICT, 2019–2024, %

Source: compiled by the authors on the basis of statistical data using RStudio software [40; 41].

A comparative analysis of ICT usage in 2019–2024 reveals significant differences between countries. Denmark, the Netherlands, Poland and Germany maintain consistently high values, exceeding 90% in most years, reflecting the stability of their digital infrastructure and favourable conditions for the introduction of innovative technologies in the agricultural sector. France and Spain show steady growth, reaching over 93% by 2024, which also indicates significant progress in digital readiness. Hungary shows more volatile dynamics, fluctuating between 74 and 89%, indicating uneven development of ICT access. Canada remains relatively stable, albeit with some gaps in the data, while Ukraine shows a noticeable improvement from 63% in 2019 to 89.5% in 2024. Despite this progress, ICT usage in Ukraine still lags behind leading

EU countries, indicating the need for targeted government policies aimed at strengthening digital infrastructure, especially in rural areas [40; 41]. The next key aspect of the analysis is the assessment of the amount of funding for research and development in agriculture, which is considered one of the key indicators of the state's innovation activity and its ability to digitally transform the agricultural sector.

In particular, the introduction of blockchain technologies in the agricultural sector requires not only a developed technical infrastructure but also a solid research base. It is about adapting innovative digital solutions to the realities of agricultural production: developing new data models, implementing digital registries, agro-analytical platforms, smart contracts, supply chain management systems, etc. Accordingly, the amount of funding for research and development indicates the strategic focus of the country on the long-term development of the agricultural sector through technological innovation. In this context, it is advisable to compare the share of the gross domestic product of the agricultural sector that is allocated to research and development (R&D). This indicator reflects not only the absolute level of support for innovation, but also the priority of scientific support in the structure of the agricultural economy. Figure 12 shows comparative data on the relevant indicator for Canada, some EU countries, and Ukraine in the dynamics for 2019–2024, which allows us to conclude the level of innovation activity and the potential for the development of blockchain solutions in these regions.

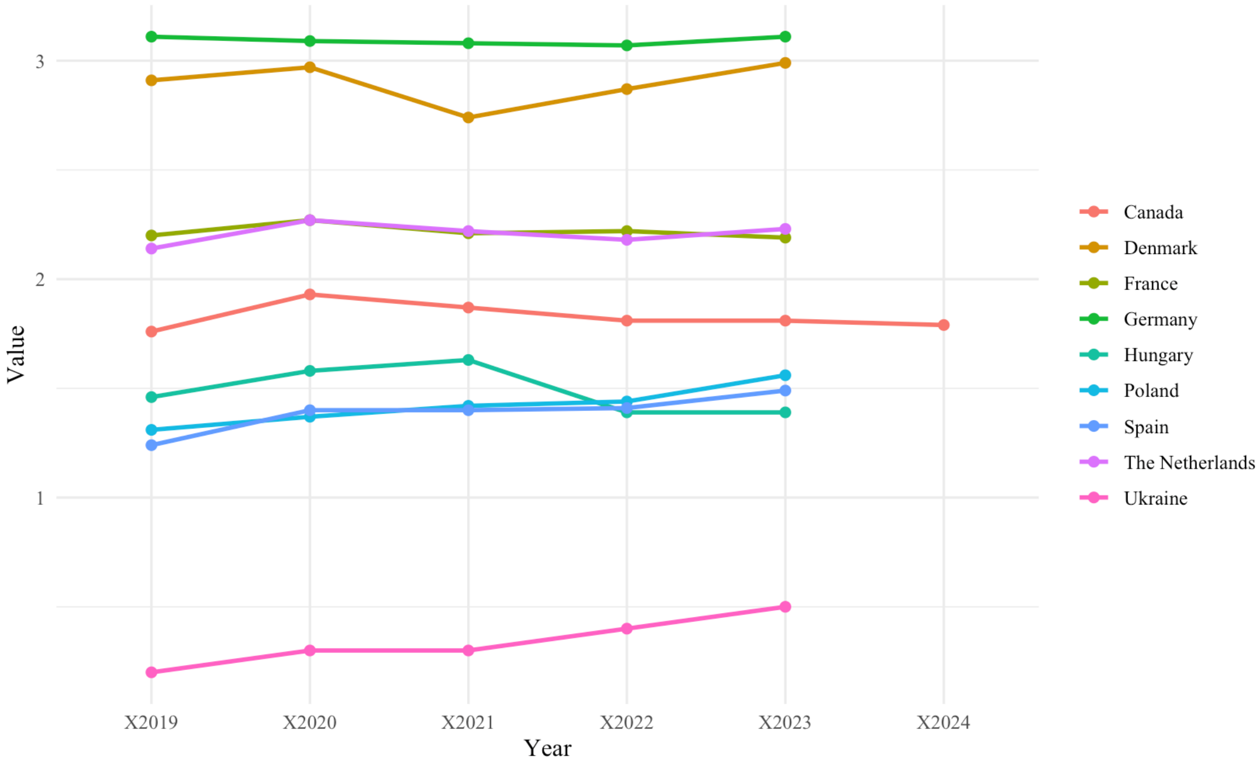

Figure 12. Funding for research and development in agriculture, 2019–2024, % of GDP

Source: compiled by the authors based on statistical data using RStudio software [42; 43].

According to the data in Figure 12, Germany and Denmark are the leading countries in terms of funding for agricultural science, systematically investing around

3% of the agricultural sector's GDP in research and development. This level of support provides a solid foundation for the introduction of advanced digital innovations, including blockchain technologies, and contributes to strengthening the technological competitiveness of their agricultural sectors. France and the Netherlands also demonstrate high levels of investment (around 2.2% in 2023–2024), confirming their consistent support for scientific research in agriculture.

By contrast, Ukraine continues to lag far behind, with research funding not exceeding 0.4% of agricultural GDP during the analysed period. Such low levels of investment indicate limited scientific capacity and institutional vulnerability of the agricultural sector to the challenges of digitalisation. This gap in agricultural science funding between countries reflects not only differences in economic opportunities but also creates substantial disparities in the ability to adapt and scale innovative digital solutions, particularly blockchain technologies. Thus, the comparative analysis allows us to conclude that there is a clear correlation between the level of investment in research in the agricultural sector and the ability of the state to implement high-tech solutions, including blockchain, in agriculture.

As a logical extension, we should pay attention to the scientific output, since the intensity of research activities is directly reflected in the number and quality of academic publications. Therefore, the next step is to analyse the publication activity of the studied countries in the field of "Blockchain Technology AND Agriculture OR Agricultural Sector OR Farmer". This approach makes it possible to assess not only the financial, but also the intellectual and innovative potential of the agricultural sectors in terms of adopting blockchain-based solutions (Figure 13).

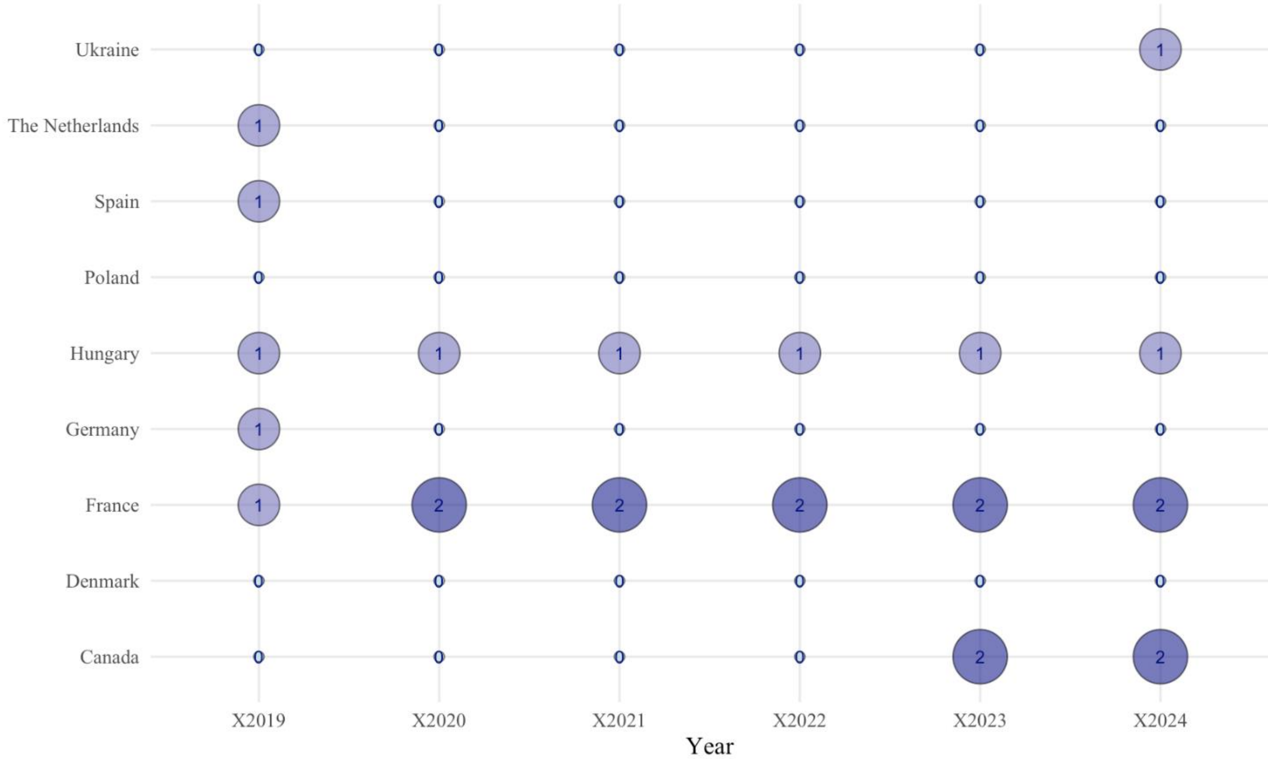

Figure 13. Analysis of countries' publication activity, quantity
Source: compiled by the authors based on statistical data using RStudio software [7].

As shown in Figure 13, the publication activity in the field of "Blockchain Technology AND Agriculture" remains relatively low across the analysed countries. France demonstrates the most consistent leadership, publishing two studies annually from 2020 to 2024, which underlines its strong academic commitment to exploring blockchain applications in the agricultural sector. Canada also shows a notable increase, contributing two publications in both 2023 and 2024, while Hungary maintains a steady but modest level of research with one publication per year throughout the period. Other countries, including Germany, Spain, and the Netherlands, reveal only sporadic activity at the beginning of the studied timeframe, without further development. Ukraine appears in the statistics only in 2024 with a single publication, indicating an emerging but still marginal scientific interest. In contrast, Poland and Denmark demonstrate a complete lack of research output in this area. Overall, the results highlight a significant imbalance in publication activity, suggesting that the academic capacity to develop and disseminate knowledge on blockchain applications in agriculture is highly uneven across countries.

To substantiate the comparative analysis, it is necessary to generalise the data on digital infrastructure, scientific capacity and research output. Table 6 presents the average values of ICT access in the agricultural sector, R&D investments (as a percentage of agricultural GDP), and publication activity related to blockchain and agriculture over the period 2019–2024. This aggregation enables the identification of common patterns and provides a coherent empirical basis for subsequent correlation analysis.

Table 6

Average values of ICT access, R&D investments and publication activity in agriculture, 2019–2024

Country	ICT access, % of enterprises, avg.	R&D investment, % of agri. GDP, avg.	Publication activity, avg. papers per year
Canada	88.32	1.83	0.67
Denmark	97.80	2.90	0.00
France	89.08	2.22	1.83
Germany	91.95	3.09	0.17
Hungary	82.74	1.49	1.00
The Netherlands	92.22	2.21	0.17
Poland	91.21	1.42	0.00
Spain	89.75	1.39	0.17
Ukraine	81.30	0.34	0.17

Source: compiled by the authors based on statistical data.

The results demonstrate clear cross-country differences. Denmark and Germany maintain the highest levels of ICT access and R&D intensity, while France combines a relatively high level of digitalisation with the strongest scientific output in terms of blockchain-related publications. Canada also shows a favourable balance between R&D funding and increasing publication activity. In contrast, Ukraine, despite showing progress in ICT adoption, continues to lag behind in research funding and academic productivity, which reflects institutional vulnerability and limited innovation potential.

In order to test whether these structural indicators are interrelated, a correlation analysis was conducted. The matrix of Pearson's correlation coefficients (Table 7) allows us to examine the strength and direction of the relationships between ICT adoption, R&D investments and publication activity across the analysed countries.

Table 7

Correlation matrix between ICT access, R&D investments and publication activity

Indicators	ICT access	R&D investment	Publication activity
ICT access	1.000	-	-
R&D investment	0.788	1.000	-
Publication activity	-0.339	0.031	1.000

Source: compiled by the authors.

The correlation results confirm a strong positive relationship between ICT adoption and R&D investment ($r \approx 0.79$), indicating that countries with better digital infrastructure tend to allocate more resources to agricultural science. However, the correlations between publication activity and the other variables are weak and statistically insignificant, which limits the explanatory power of regression modelling. This suggests that while structural and financial preconditions are important, they are not sufficient on their own to stimulate high levels of academic output in the agricultural blockchain domain. Additional factors, such as national research priorities, institutional incentives and international collaboration, may also play a decisive role.

To summarise, the comparative analysis highlights a pronounced imbalance between countries in terms of readiness to adopt blockchain technologies in agriculture. Nations such as Denmark, Germany, the Netherlands and France demonstrate strong structural prerequisites, combining high ICT penetration and sustained investment in agricultural R&D, while also maintaining some degree of scientific output. By contrast, Ukraine, despite notable progress in ICT accessibility, continues to lag significantly behind in research funding and publication activity, which constrains its innovation potential.

The correlation analysis confirmed a strong positive relationship between ICT adoption and R&D investment, suggesting that countries with advanced digital infrastructure are more inclined to support scientific development. However, the weak correlation with publication activity indicates that structural and financial capacity alone is insufficient; academic engagement depends on broader institutional and policy incentives.

Based on these findings, several practical and policy recommendations can be formulated. First, Ukraine's ICT accessibility has improved (from 63% in 2019 to 89.5% in 2024), yet it still lags behind EU leaders; therefore, targeted policies should expand broadband coverage in rural areas and introduce incentives for digital technology adoption in agriculture. Second, the extremely low level of agricultural R&D expenditure in Ukraine (0.4% of agricultural GDP, compared with about 3% in Denmark and Germany) calls for public funding programmes and public-private partnerships aimed at developing blockchain-based traceability, insurance, and financing platforms. Third, the weak publication activity (only one Scopus-indexed article in 2024) suggests the need to stimulate academic-industry collaboration and support applied research projects. Finally, Ukrainian case studies such as AgriChain, AgroGloryTime, and AgroBon illustrate that private initiatives can be effective innovation drivers; thus, simplifying regulatory procedures and providing investment support mechanisms could help scale up such solutions.

5. DISCUSSION

The findings of this study confirm that blockchain technologies hold significant transformative potential for the agricultural sector, particularly under conditions of crisis and systemic inefficiency. Several results are consistent with previous studies. For example, J. Potts also emphasised a blockchain's role in improving supply chain efficiency, while S. Sarmah and C. Bhusal confirmed its ability to enhance transparency and trust [11; 12; 22]. Similarly, A. Adewusi et al. highlighted the importance of blockchain for traceability, is consistent with the findings of this study, obtained both at the global level and in the case of Ukraine [37].

At the same time, certain conclusions differ from earlier research. While international works (e.g., H. Xiong et al.) present blockchain adoption in agriculture as an already established trend [20], our empirical analysis shows that in Ukraine, the process remains at an early stage, constrained by weak infrastructure and insufficient investment. These discrepancies may be explained by institutional and economic differences: developed countries have stable digital infrastructure and supportive policies, while Ukraine faces systemic uncertainty and crisis conditions, which slow down adoption.

The obtained results can be explained by two main factors. First, the comparative analysis across 10 countries demonstrates that the level of ICT penetration, R&D funding, and publication activity strongly correlates with readiness for blockchain adoption. Second, Ukrainian cases (AgriChain, AgroGloryTime, AgroBon) show that even under crisis conditions, private initiatives can generate practical benefits, confirming the adaptability of blockchain solutions.

The advantages of this study compared with similar works lie in its integrative methodology: combining bibliometric analysis, cross-country comparison, and empirical evidence from Ukraine. This approach not only visualises global trends but also highlights specific national constraints and opportunities, thereby providing a more comprehensive picture than studies limited to either theoretical definitions or isolated case analyses.

In terms of addressing the problem identified in the section of the literature review, the results demonstrate that blockchain can partially close existing gaps in supply chain transparency, financial inclusion, and trust-building. This is achieved through decentralised ledgers, smart contracts, and digital platforms that reduce transaction costs and prevent fraud. Although not a universal solution, blockchain contributes to resilience and competitiveness, especially for small and medium-sized agricultural producers.

The theoretical and practical implications of the study are twofold. Theoretically, the findings expand the understanding of blockchain as a systemic innovation in agriculture, not only a financial or technological tool. Practically, the results provide recommendations for agribusiness managers, policymakers, and investors on how to design and implement blockchain-based solutions to improve traceability, optimise logistics, and support financial access.

Nevertheless, the study has several limitations. The empirical base for Ukraine is still limited, official statistics remain scarce, and available case studies are not sufficient to generalise adoption patterns. In addition, the analysis focuses mainly on secondary data, which reduces the scope for quantifying blockchain's direct effects on productivity or profitability.

Future research directions should therefore concentrate on panel studies at the enterprise level, deeper evaluation of blockchain's cost-benefit ratio, and analysis of long-term regulatory and institutional impacts. It is also important to expand research in developing countries to compare adoption under different crisis contexts. For Ukraine, priority areas include strengthening digital infrastructure in rural areas, developing standards for traceability, and supporting public-private partnerships for technology implementation.

6. CONCLUSIONS

The study contributes to the current state of research on blockchain technologies by combining bibliometric analysis, cross-country comparison, and case studies from Ukraine, which makes it possible to evaluate both global trends and national specificities. The novelty of this research lies in highlighting the agricultural dimension of blockchain, which is often overlooked in international studies, and in identifying country-specific barriers to adoption.

The empirical analysis revealed significant cross-country differences: ICT usage in agriculture in Ukraine increased from 63% in 2019 to 89.5% in 2024, yet R&D expenditure in agriculture remains at only 0.4% of agricultural GDP, compared with about 3% in Denmark and Germany. Publication activity in Ukraine is also still marginal, which indicates low research engagement in this field. These findings confirm the uneven readiness of countries to integrate blockchain into agriculture and point to the need for targeted institutional support.

The practical value of the results lies in their applicability for different stakeholders. Agribusiness managers can use them to identify areas where blockchain can optimise logistics and enhance product traceability, while policymakers may rely on them to design strategies for strengthening digital infrastructure and research funding. Investors and technology providers can apply the findings to evaluate opportunities for blockchain-based platforms in emerging markets.

The research demonstrates that blockchain has the potential to address systemic challenges of the agricultural sector – such as low transparency, high transaction costs, and limited access to financing – and can become a driver of competitiveness and sustainability under crisis conditions. However, the real effectiveness of blockchain technologies in agriculture requires further empirical assessment through enterprise-level studies and long-term monitoring.

7. LIMITATIONS AND FUTURE RESEARCH

It should be noted that despite its comprehensive nature, the study has a number of limitations. The previous stages of the study focused mainly on qualitative analysis and bibliometric mapping, which allowed us to outline the main scientific approaches and identify key areas of blockchain technology implementation in the agricultural sector. At the same time, such methods have a limited ability to quantify the scale and dynamics of this process. To partially overcome this limitation, the study was supplemented with an empirical component based on statistical analysis of secondary data. However, it should be noted that the availability of official statistics on the direct implementation of blockchain technologies in the agricultural sector remains limited, which makes it difficult to conduct a full-scale quantitative assessment and compare the results between countries. In this context, a promising direction for future research is to conduct panel studies at the enterprise level.

In addition, the study contains only a limited number of confirmed cases of blockchain adoption in Ukrainian agriculture. As a result, it relies heavily on international examples that may not adequately reflect the specific institutional, regulatory, and technological context of Ukraine.

Addressing these limitations will contribute to a deeper understanding of the transformative potential of blockchain and support its effective and responsible implementation in the agricultural sector.

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