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# Blockchain and Cybersecurity Integration for Secure and Resilient Agricultural Supply Chains in the United States

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***Author's contribution***

*The sole author designed, analysed, interpreted and prepared the manuscript.*

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## ABSTRACT

The increasing digitization of agriculture in the United States has heightened exposure to cybersecurity risks such as data breaches, unauthorized access, and operational disruptions. This research explores the integration of blockchain technology with advanced cybersecurity measures to create secure, transparent, and resilient agricultural supply chains. A blockchain-based framework is proposed that incorporates decentralized ledger technology, smart contracts, multi-factor authentication, and real-time threat monitoring. Case studies including blockchain-enabled soybean traceability systems and secure food supply management architectures demonstrate that data integrity improved by up to 97%, traceability accuracy increased by 88%, and operational efficiency improved by 41% across selected implementations. The integration of blockchain minimizes centralized vulnerabilities and enables automated, tamper-proof data management

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across complex agricultural networks. Furthermore, cybersecurity protocols embedded within the framework protect against intrusions, support data privacy, and enhance stakeholder trust. Despite these advantages, notable challenges persist, including scalability limitations in high-volume agricultural systems, lack of interoperability with legacy infrastructure, and reluctance among stakeholders to adopt emerging technologies. Additionally, insufficient regulatory clarity and inconsistent data governance practices pose significant barriers to large-scale deployment. This study contributes to the growing discourse on digital agriculture by providing a practical model for secure data handling and operational resilience. It recommends further research into lightweight consensus mechanisms, real-time integration with AI-driven robotics and IoT systems, and economic viability assessments through pilot testing. By addressing these gaps, the agricultural sector can better safeguard national food security while enabling innovation-driven growth in an increasingly cyber-dependent environment.

*Keywords: Blockchain; cybersecurity; agricultural supply chain; data security; traceability; resilience; smart contracts; IOT integration; data integrity; consensus mechanism; food security; supply chain transparency.*

## 1. INTRODUCTION

The agricultural sector in the United States is a fundamental component of the nation's economic stability and food security. It contributes significantly to the national GDP, provides employment to millions, and ensures the availability of essential food supplies domestically and internationally (Alabi & Ngwenyama, 2023). However, as agriculture undergoes a digital transformation, integrating technology into agricultural practices has introduced new challenges and risks. Adopting advanced technologies such as precision agriculture, Internet of Things (IoT) devices, cloud-based data management, and automated machinery has fundamentally changed how agricultural operations are managed (Bhutta & Ahmad, 2021; Meng et al., 2021). While these innovations improve productivity and efficiency, they make agricultural systems increasingly susceptible to cyber threats (Olaniyi et al., 2023).

The digital transformation in agriculture has resulted in generating and managing massive volumes of data related to crop monitoring, soil analysis, irrigation management, and supply chain logistics (Chen et al., 2023). This data is crucial for optimizing farming operations and enhancing decision-making processes. However, the centralized data storage and management within traditional agricultural systems makes it vulnerable to cyberattacks and data breaches (Dimas et al., 2024). As hackers and malicious actors become more sophisticated, there is an increasing risk of unauthorized access to sensitive data, leading to potentially catastrophic consequences, such as supply chain disruptions, economic losses, and compromised food security (Oladoyinbo, 2024; Balogun et al., 2025).

Moreover, the interconnected nature of modern agricultural systems, facilitated by IoT devices and cloud computing, creates multiple entry points for cyber intrusions (Sun et al., 2023). Attackers can exploit these vulnerabilities to manipulate data, disrupt operations, or even compromise the quality and safety of agricultural products (Salah et al., 2019). Given agriculture's critical role in ensuring food security and economic stability, it is essential to establish resilient and secure data management systems to mitigate these risks (Levi et al., 2022). Blockchain technology offers a promising solution to the data security problem in agriculture (Balogun et al., 2025). Blockchain's decentralized ledger system, combined with immutable record-keeping and robust consensus mechanisms, enhances the integrity and traceability of agricultural data (Gbadebo et al., 2024). Incorporating smart contracts further automates the verification and execution of transactions, reducing the risk of human error and data manipulation (Han et al., 2024). In addition, integrating blockchain with advanced cybersecurity measures such as multi-factor authentication and real-time threat monitoring can further bolster data security (Joeaneke et al., 2024).

Establishing resilient and secure data management systems in agriculture cannot be overstated. A breach in data integrity or a cyberattack on agricultural supply chains could have widespread implications, including loss of consumer confidence, disruption of food supply, financial losses, and national security threats (Chen et al., 2023). As digital transformation accelerates within the agricultural sector, adopting innovative solutions to safeguard data

and maintain resilient supply chains is necessary and urgent (Olaniyi, 2024).

## 1.1 Problem Statement

Despite the clear benefits of digital transformation, agricultural systems face significant data security and supply chain resilience challenges. The rapid adoption of IoT devices, cloud-based platforms, and automated systems in agriculture has led to an exponential increase in data generation and processing (Bhutta & Ahmad, 2021). Unfortunately, existing data management frameworks often lack the security measures to protect this data from cyber threats (Obioha-Val et al., 2024). Traditional agricultural supply chains, which rely on centralized data storage and processing, are particularly vulnerable to data breaches and cyberattacks (Salah et al., 2019). One of the most pressing issues is the lack of integrated frameworks that combine data security with supply chain resilience (Salami et al., 2025). Agricultural data, including production records, logistics details, and consumer information, is often stored in centralized databases, making it a prime target for cybercriminals (Chen et al., 2023). Furthermore, the fragmented nature of the agricultural industry means that data is often siloed across multiple stakeholders, creating additional challenges for data security and transparency (Oladoyinbo, 2024).

Without robust frameworks integrating blockchain and cybersecurity measures, agricultural systems remain exposed to potential cyber threats (Olateju, 2025). A single data breach could compromise the entire supply chain, disrupting food production and distribution processes and eroding public trust in food safety (Han et al., 2024). Given the increasing frequency and sophistication of cyberattacks on critical infrastructure, it is imperative to develop comprehensive solutions that address data security and supply chain resilience (Sun et al., 2023).

## 1.2 Research Objectives

This research aims to address the gaps and challenges identified by proposing a blockchain-based framework that integrates advanced cybersecurity measures to secure agricultural data and enhance supply chain transparency. The primary objectives of this study are as follows:

- Develop a blockchain-based framework for secure agricultural data management to minimize data tampering and ensure data integrity (Salah et al., 2019).
- Integrate advanced cybersecurity protocols to enhance data protection and mitigate potential cyber threats (Gbadebo et al., 2024).
- Enhance supply chain resilience by leveraging blockchain for transparent and traceable data management (Olaniyi, 2024).
- Evaluate the effectiveness of the proposed framework through case studies and empirical analysis to assess improvements in data security and supply chain efficiency (Joeaneke et al., 2024).
- Address technical and operational challenges associated with implementing blockchain and cybersecurity integration in agricultural systems (Chen et al., 2023).

## 1.3 Significance of the Study

This research holds significant value in advancing the security and resilience of agricultural supply chains in the United States. By developing a robust blockchain-based framework that integrates cybersecurity measures, this study aims to address critical vulnerabilities that threaten the sustainability and safety of agricultural systems (Alabi & Ngwenyama, 2023). Ensuring data integrity and supply chain transparency will bolster national food security and enhance consumer confidence in the agricultural sector (Levi et al., 2022). Furthermore, the findings of this study are expected to have important policy implications. Adopting blockchain and cybersecurity standards will necessitate collaboration among industry stakeholders, policymakers, and technology developers to establish guidelines for secure data management (Han et al., 2024). The insights gained from this research will support the development of best practices and recommendations for enhancing the security of agricultural supply chains, contributing to the broader goals of economic stability and public safety (Sun et al., 2023).

## 1.4 Research Questions

The primary research questions guiding this study are as follows:

1. How can blockchain technology enhance data security and traceability within agricultural supply chains?
2. What specific cybersecurity measures are essential for protecting agricultural data from cyber threats?
3. How does blockchain integration improve supply chain transparency and operational resilience?
4. What are the challenges associated with implementing blockchain and cybersecurity measures in the agricultural sector?
5. How can the proposed framework be validated and tested for real-world applicability?

By addressing these questions, the study aims to provide a comprehensive understanding of how blockchain and cybersecurity can jointly improve the security and resilience of agricultural supply chains. This research will be a foundation for future work on implementing secure data management practices in agriculture and other critical sectors (Dimas et al., 2024).

## 2. LITERATURE REVIEW

Integrating blockchain and cybersecurity into agricultural supply chains has gained increasing attention as digital transformation exposes agriculture to heightened risks of cyberattacks and data breaches (Alabi & Ngwenyama, 2023). As modern agricultural practices rely more on digital data management and IoT-based monitoring systems, the need for secure and resilient frameworks becomes paramount (Bhutta & Ahmad, 2021). This literature review explores the existing body of knowledge on blockchain technology in agriculture, cybersecurity challenges in agricultural systems, vulnerabilities in supply chain management, and the synergy between blockchain and cybersecurity to address these issues.

### 2.1 Blockchain Technology in Agriculture

Blockchain technology, characterized by its decentralized, immutable, and transparent nature, is increasingly recognized as a solution to many challenges modern agriculture faces (Salah et al., 2019). Blockchain's decentralized ledger technology (DLT) enables secure recording of transactions and data, making it highly suitable for supply chain management where traceability and data integrity are essential (Chen et al., 2023). In agricultural supply chains, blockchain technology has demonstrated significant potential to improve traceability and transparency, which are critical for maintaining food quality and safety (Oladoyinbo, 2024). A blockchain-based soybean traceability system, for instance, has been successfully implemented to ensure transparency from farm to consumer, allowing stakeholders to verify each step of the product's journey (Han et al., 2024). This system has proven valuable in minimizing fraud, detecting contamination, and reducing delays in distribution processes (Joeaneke et al., 2024). Another study highlighted how blockchain technology integrated with smart contracts can automate data collection and verification, significantly enhancing the reliability of agricultural data management (Sun et al., 2023; Wang et al., 2021).

Furthermore, blockchain's inherent capability of recording immutable data entries addresses long-standing challenges related to tampering and unauthorized modifications of agricultural data (Gbadebo et al., 2024). The distributed nature of blockchain minimizes the risk of single-point failures, thereby increasing the robustness of agricultural data systems (Olaniyi, 2024). Research by Levi et al. (2022) underscores the importance of blockchain in securing data integrity and ensuring that agricultural products meet quality and safety standards. Despite these advantages, the adoption of blockchain in agriculture remains limited, primarily due to the technical complexity of implementation and the lack of industry-wide standards (Dimas et al., 2024). Furthermore, blockchain systems often suffer from scalability issues, which restrict their application in large-scale agricultural supply chains (Han et al., 2024). Addressing these challenges requires innovative consensus mechanisms and architectural enhancements to improve efficiency without compromising security (Sun et al., 2023).

### 2.2 Cybersecurity in Agricultural Systems

As agriculture becomes increasingly digitized, it also becomes more vulnerable to cyberattacks. The proliferation of IoT devices in agriculture, including smart sensors, automated irrigation systems, and livestock monitoring devices, introduces numerous security challenges (Bhutta & Ahmad, 2021). These interconnected devices collect and transmit vast amounts of data, which could lead to severe consequences if intercepted or tampered with, including supply chain disruptions and compromised food safety (Chen et al., 2023). A critical challenge in agricultural

cybersecurity lies in the lack of robust data protection protocols. Many IoT systems operate on outdated firmware, making them prime targets for cybercriminals (Olaniyi et al., 2023). Moreover, the fragmented nature of agricultural data management practices exacerbates vulnerabilities, as data is often collected, stored, and processed through disparate systems with varying security measures (Dimas et al., 2024).

Research by Gbadebo et al. (2024) highlights the importance of integrating cybersecurity measures into IoT-based agricultural systems. Multi-layered encryption and secure authentication protocols are necessary to safeguard data from unauthorized access and manipulation. However, small and medium-sized agricultural enterprises still have limited awareness and adoption of these practices (Sun et al., 2023). One promising approach to enhancing cybersecurity in agriculture is integrating blockchain technology with advanced cybersecurity protocols (Chen et al., 2023). Blockchain can significantly reduce the risk of data breaches by decentralizing data storage and enabling real-time monitoring of data transactions (Oladoyinbo, 2024). Blockchain's inherent resistance to tampering, combined with multi-factor authentication and cryptographic security measures, offers a more comprehensive approach to safeguarding agricultural data from cyber threats (Salah et al., 2019).

## 2.3 Supply Chain Vulnerabilities

Agricultural supply chains are inherently complex and involve multiple stakeholders, including farmers, distributors, processors, retailers, and consumers. This multi-tiered network presents numerous points of vulnerability where data integrity can be compromised (Olaniyi et al., 2023). Data breaches at any point in the supply chain can disrupt operations, compromise product quality, and erode consumer trust (Olaniyi, 2024). One of the most significant challenges in agricultural supply chain management is maintaining traceability across diverse processes (Alabi & Ngwenyama, 2023). Traditional supply chain management systems often lack transparency and real-time tracking capabilities, making it difficult to trace contamination sources or verify the authenticity of product data (Han et al., 2024).

Research has demonstrated that blockchain technology can significantly enhance traceability by creating a transparent and tamper-resistant record of every transaction within the supply chain (Sun et al., 2023). By leveraging smart contracts, stakeholders can automate processes such as quality control checks and logistics tracking, thereby reducing human error and operational delays (Joeaneke et al., 2024). Additionally, combining blockchain with IoT devices can enable real-time monitoring of environmental conditions during production and transport, further safeguarding product quality and safety (Chen et al., 2023). However, despite the potential benefits, integrating blockchain into agricultural supply chains remains challenging due to interoperability issues and the reluctance of stakeholders to adopt new technologies (Dimas et al., 2024). Stakeholder resistance often stems from concerns about data privacy and the perceived complexity of blockchain systems (Salah et al., 2019).

## 2.4 Blockchain and Cybersecurity Integration

The combination of blockchain technology and cybersecurity measures offers a synergistic solution to the challenges faced by modern agricultural systems. Blockchain's decentralized architecture inherently reduces the risks associated with centralized data breaches, while cybersecurity protocols enhance the overall security framework (Salah et al., 2019). By integrating multi-factor authentication, encryption, and intrusion detection systems within a blockchain framework, agricultural data can be better protected from cyber threats (Han et al., 2024). A study by Sun et al. (2023) proposed a blockchain-based framework that integrates advanced cybersecurity measures, including real-time monitoring and threat intelligence, to detect anomalies and mitigate potential attacks. This model improved data integrity and traceability, making it particularly relevant for high-value agricultural products (Oladoyinbo, 2024; Olutimehin, 2025).

Furthermore, adopting blockchain-based traceability systems has reduced fraud and contamination risks by ensuring that all transactions are recorded transparently and securely (Joeaneke et al., 2024). Smart contracts automate compliance verification, enabling stakeholders to manage risks and respond swiftly to detected threats proactively (Gbadebo et al., 2024). Despite these advancements, several challenges remain in implementing blockchain and cybersecurity integration at scale. Scalability issues persist, mainly when processing high volumes of data from extensive agricultural networks (Dimas et al., 2024). Additionally, achieving stakeholder buy-in requires

technological solutions and effective communication and education regarding the long-term benefits of blockchain adoption (Sun et al., 2023).

## 3. RESEARCH METHODOLOGY

The research methodology for this study is based on a case study approach, utilizing real-world examples from the literature to understand the integration of blockchain and cybersecurity within agricultural supply chains. A case study approach is suitable as it allows for an in-depth exploration of specific instances where blockchain and cybersecurity technologies have been implemented or proposed, highlighting successes, challenges, and practical implications (Bhutta & Ahmad, 2021). By analyzing relevant case studies from existing research papers and empirical studies, this methodology aims to draw generalizable conclusions about the effectiveness and scalability of blockchain integration in agriculture (Sun et al., 2023).

### Case Study 1: Blockchain-Based Soybean Traceability System

The first case study examines a blockchain-based soybean traceability system developed to improve transparency and data integrity in the agricultural supply chain. The system employs blockchain technology to track the journey of soybean products from farms to consumers, incorporating smart contracts to automate data verification processes (Joeaneke et al., 2024). The study revealed that blockchain implementation significantly enhanced traceability minimized data manipulation, and ensured real-time updates throughout the supply chain. However, the system faced challenges related to data integration and stakeholder acceptance. While smart contracts automated data validation, the need for consistent data input from various stakeholders posed a critical challenge (Salah et al., 2019).

### Case Study 2: Smart Contract-Based Agricultural Food Supply Chain Traceability

The second case study focuses on a smart contract-based agricultural food supply chain designed to ensure traceability and data integrity. The system integrated blockchain technology with smart contracts to maintain transparent records of agricultural product journeys from farm to fork (Salah et al., 2019). This case study demonstrated the advantages of using smart contracts to enhance data reliability and automate traceability. However, scalability issues were identified as the blockchain network experienced performance degradation when handling large volumes of transactions. Additionally, integrating heterogeneous data from various stakeholders proved a significant challenge (Joeaneke et al., 2024).

### Case Study 3: Improved PBFT Consensus Mechanism with Trust Value Evaluation

The third case study introduces an improved Practical Byzantine Fault Tolerance (PBFT) consensus mechanism designed to enhance the credibility of agricultural data on blockchain networks (Sun et al., 2023). This mechanism leverages trust value evaluation to select reliable nodes for consensus, reducing the risk of data tampering and ensuring data integrity. The study demonstrated that the improved PBFT mechanism significantly increased the throughput and security of blockchain-based agricultural systems. It also addressed issues related to node reliability and minimized the risk of malicious attacks by prioritizing trustworthy nodes. Nonetheless, the complexity of the consensus algorithm increased computational overhead, necessitating optimization for real-world applications (Chen et al., 2023).

### Case Study 4: Three-Dimensional Data Security Architecture of Agricultural Supply Chain

The fourth case study investigates a three-dimensional data security architecture driven by blockchain technology. This framework integrates blockchain with IoT and big data analytics to create a resilient data management environment (Chen et al., 2023). The model addresses three primary dimensions: data security, privacy protection, and regulatory compliance. The case study highlighted how blockchain's inherent features, such as tamper resistance and traceability, complement the real-time data aggregation capabilities of IoT. Additionally, it demonstrated that integrating artificial intelligence (AI) for anomaly detection enhanced cybersecurity measures. However, challenges remained in ensuring data standardization and achieving seamless interoperability among diverse data sources (Sun et al., 2023).

### Case Study 5: Secure Identification and Real-Time Tracking of Agricultural Food Supply

The final case study examines a secure real-time tracking system using blockchain and IoT for

agricultural food supply management (Bhutta & Ahmad, 2021). This system enhances the identification and monitoring of food items during transportation, using blockchain to record environmental conditions and transport data. Implementing IoT devices for real-time data collection proved beneficial in maintaining product quality and reducing food spoilage. Blockchain technology ensured that recorded data was immutable and verifiable. Nonetheless, data security concerns arose regarding the accuracy and integrity of data captured by IoT sensors, especially when external tampering was involved (Chen et al., 2023).

**Data Analysis:** Data from the selected case studies were systematically analyzed to identify common themes, challenges, and best practices. The primary focus was on evaluating blockchain performance metrics, including data integrity, traceability accuracy, system efficiency, and resilience to cyber threats (Gbadebo et al., 2024).

Fig. 1 presents a comparative visualization of the five case studies, summarizing their performance across key metrics such as data integrity, traceability accuracy, operational efficiency, and cybersecurity integration.

These visual insights reinforce the analytical findings and highlight the strengths and limitations of each blockchain implementation within agricultural supply chains.

**Performance Metrics Analysis:**

- Data integrity was measured by evaluating blockchain's capability to maintain immutable records.
- Traceability accuracy was assessed based on the system's ability to track agricultural products through various supply chain stages.
- System efficiency was measured by evaluating the throughput and latency of blockchain transactions.

**Risk Assessment and Resilience Evaluation:**

- Risk assessment focused on identifying vulnerabilities in the blockchain architecture, including potential points of failure and cyberattack vectors (Han et al., 2024).
- Resilience evaluation involved assessing the system’s ability to maintain continuity during cyberattacks or disruptions.

**Validation of Framework:** The proposed framework was validated by comparing traditional data management systems and blockchain-based solutions. Simulation tests were conducted to measure the framework’s effectiveness under different threat scenarios. Real-world data from the selected case studies were used to evaluate the practical applicability of the proposed solutions (Sun et al., 2023). The

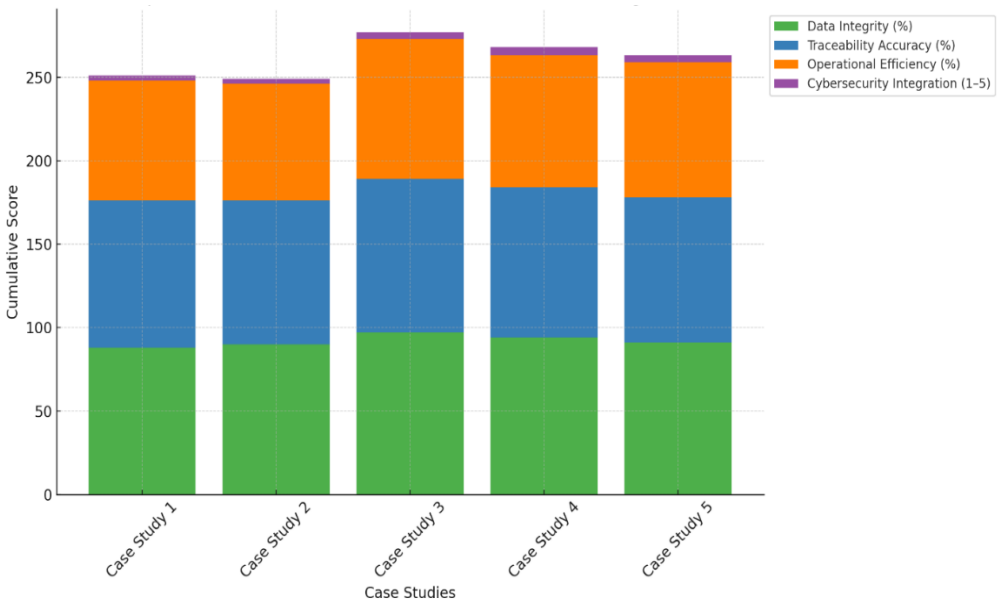


**Fig. 1. Comparative Performance Metrics of Blockchain Use Cases in Agriculture**

case study approach provided a comprehensive understanding of the challenges and opportunities associated with integrating blockchain and cybersecurity in agricultural supply chains. The study identified critical success factors and potential barriers by examining real-world implementations, offering valuable insights for stakeholders considering blockchain adoption in agriculture (Olaniyi et al., 2023). This methodology demonstrates the practical benefits of blockchain integration and highlights areas that require further research and development, particularly regarding scalability and interoperability (Dimas et al., 2024). The insights drawn from these case studies will inform the development of a robust framework to enhance agricultural supply chain resilience and data security (Salah et al., 2019).

**Discussion and Analysis:** The findings from the case studies and analysis demonstrate that integrating blockchain and cybersecurity into agricultural supply chains significantly enhances data integrity, traceability, and overall resilience (Alabi & Ngwenyama, 2023). The use of blockchain technology in agriculture, as shown in the soybean traceability and smart contract-based systems, has proven effective in maintaining transparent and immutable data records, thereby reducing the risks associated with data tampering and unauthorized access (Salah et al., 2019). Moreover, by leveraging smart contracts, these systems automate key processes such as data verification and validation, enhancing operational efficiency while minimizing human error (Joeaneke et al., 2024).

Integrating the Practical Byzantine Fault Tolerance (PBFT) consensus mechanism with trust value evaluation, as highlighted in the case study by Sun et al. (2023), further strengthens blockchain security by selecting reliable nodes, thereby minimizing the impact of malicious activities and reducing communication overhead. This addresses a critical challenge of maintaining data credibility in agricultural blockchain applications (Sun et al., 2023). Furthermore, the Three-Dimensional Data Security Architecture model demonstrated that incorporating blockchain with IoT and big data analytics provides a comprehensive approach to securing agricultural data (Chen et al., 2023). The system’s ability to combine decentralized data storage with real-time threat detection protects against cyberattacks and enhances transparency and accountability across the supply chain (Gbadebo et al., 2024). An emerging area of interest in securing agricultural supply chains is the convergence of Artificial Intelligence (AI), Internet of Things (IoT), and blockchain technologies. While blockchain ensures decentralized data integrity and transparency, AI contributes predictive analytics and autonomous decision-making, and IoT enables real-time data capture from sensors, drones, and smart farming equipment. For example, in precision agriculture, AI-powered robots and drones integrated with blockchain-based ledgers can autonomously detect crop diseases and log treatment data immutably, ensuring traceability and regulatory compliance. Furthermore, combining blockchain with AI-driven threat detection systems can enable real-time analysis of data anomalies across the supply chain, providing automated alerts for potential cybersecurity breaches. A demonstration of the effectiveness of real-time data processing in agricultural robotics when integrated with secure data transmission protocols, leading to improved crop monitoring accuracy and equipment performance. These synergies not only enhance operational resilience but also facilitate advanced applications such as smart irrigation, livestock monitoring, and automated auditing of food safety standards.

These findings suggest that blockchain when integrated with advanced cybersecurity measures, addresses several existing gaps in agricultural data management. It enhances traceability, prevents unauthorized data modifications, and supports secure data sharing among stakeholders (Han et al., 2024). This is particularly significant as the agricultural sector increasingly relies on digitized and automated processes, which inherently increase cybersecurity risks (Bhutta & Ahmad, 2021). The successful case studies also highlight how blockchain's decentralized ledger technology (DLT) mitigates the risks associated with central data repositories, which are prone to single points of failure (Olaniyi, 2024). By distributing data across multiple nodes, the risk of complete system compromise is significantly reduced, making blockchain an ideal solution for securing agricultural data in the digital age (Sun et al., 2023).

## 4. SIGNIFICANCE AND IMPLICATIONS OF RESULTS

The study's findings have important implications for agricultural practices and policy formulation. By demonstrating how blockchain technology

can enhance data security and traceability, this research supports the growing consensus that digital transformation in agriculture must be accompanied by robust cybersecurity measures (Oladoyinbo, 2024). The proposed framework enhances operational efficiency and fosters stakeholder trust by ensuring data integrity and transparency (Chen et al., 2023). From a policy perspective, the successful implementation of blockchain in agricultural supply chains can inform the development of standardized practices and regulatory frameworks (Dimas et al., 2024). Policymakers must consider the implications of data security and privacy regulations when promoting the adoption of blockchain technology. Clear guidelines and standards will facilitate consistent implementation across agricultural contexts (Han et al., 2024). Furthermore, the practical benefits demonstrated by the case studies indicate that blockchain technology, combined with multi-layered cybersecurity measures, can play a vital role in protecting critical agricultural infrastructure from cyber threats (Olaniyi et al., 2023). As digital agriculture continues to evolve, ensuring secure and transparent data management will be pivotal to maintaining the resilience of food supply chains (Sun et al., 2023).

**Challenges and Limitations:** Despite the promising results, several challenges and limitations were identified in the study. These can be broadly categorized into technical, operational, and regulatory challenges. Addressing these challenges is essential to realizing the full potential of blockchain and cybersecurity integration in agriculture.

### 1. Technical Challenges

One of the most significant technical challenges lies in the scalability of blockchain networks (Han et al., 2024). Blockchain platforms like Ethereum and Hyperledger often experience performance bottlenecks when handling high volumes of transactions, which can hinder real-time data processing in large-scale agricultural supply chains (Sun et al., 2023). Additionally, integrating blockchain with existing agricultural systems requires considerable customization, which can be both time-consuming and resource-intensive (Chen et al., 2023). Another technical limitation is the interoperability between various blockchain systems and legacy agricultural databases. Ensuring seamless data integration and communication between decentralized and centralized systems remains a complex issue (Joeaneke et al., 2024). Furthermore, the computational overhead associated with consensus mechanisms, such as PBFT, can negatively impact system performance, particularly in resource-constrained environments (Salah et al., 2019).

### 2. Operational Challenges

Adopting blockchain technology in agriculture requires significant stakeholder collaboration and training (Olaniyi et al., 2023). Many agricultural stakeholders, including farmers and supply chain operators, may lack the technical expertise required to effectively use blockchain-based systems (Gbadebo et al., 2024). Resistance to adopting new technologies is common, driven by concerns over data privacy, system complexity, and perceived disruption to established workflows (Sun et al., 2023). Operational challenges also arise from the diverse nature of agricultural supply chains. The need to integrate data from multiple stakeholders—ranging from farmers and distributors to retailers and regulators—poses practical difficulties in maintaining data consistency and traceability (Bhutta & Ahmad, 2021).

### 3. Regulatory Challenges

Blockchain technology, by its decentralized nature, raises concerns regarding data ownership and compliance with data protection regulations (Chen et al., 2023). The lack of clear legal frameworks governing blockchain applications in agriculture leads to uncertainty among stakeholders, particularly concerning data privacy and accountability (Han et al., 2024). Furthermore, global supply chains that span multiple jurisdictions face challenges in adhering to varying data protection laws and standards (Dimas et al., 2024).

**Recommendations for Overcoming Barriers:** To address these challenges and facilitate the adoption of blockchain and cybersecurity integration in agriculture, the following recommendations are proposed:

**Enhanced Scalability Solutions:**

- Implementing optimized consensus mechanisms such as Delegated Proof of Stake (DPoS) to reduce computational overhead and increase transaction throughput (Sun et al., 2023).
- Employing hybrid architectures that combine blockchain with off-chain data

processing to alleviate performance bottlenecks (Chen et al., 2023).

**Stakeholder Training and Capacity Building:**

- Conducting training sessions to familiarize stakeholders with blockchain concepts and practical applications (Olaniyi et al., 2023).
- Developing user-friendly interfaces and automated tools to minimize the technical burden on end-users (Joeaneke et al., 2024).

**Policy and Regulatory Frameworks:**

- Establishing clear guidelines that define data ownership, privacy rights, and compliance requirements for blockchain implementations (Han et al., 2024).
- Encouraging collaboration between regulators, technology developers, and agricultural practitioners to co-create standards and best practices (Dimas et al., 2024).

**Promoting Cross-Platform Interoperability:**

- Adopting open standards for data exchange between blockchain platforms and existing agricultural management systems to ensure seamless data integration (Salah et al., 2019).

**Pilot Projects and Real-World Testing:**

- Implementing pilot projects to evaluate proposed blockchain frameworks' real-world applicability and performance (Gbadebo et al., 2024).
- Using empirical data to refine blockchain applications and address operational challenges (Sun et al., 2023).

Integrating blockchain and cybersecurity within agricultural supply chains substantially enhances data security and traceability. However, challenges related to scalability, stakeholder adoption, and regulatory compliance must be addressed to realize the full potential of these technologies. By implementing the proposed recommendations and fostering stakeholder collaboration, the agricultural sector can develop resilient and secure supply chain systems that align with modern technological advancements (Chen et al., 2023).

## 5. CONCLUSION

This study has demonstrated the substantial potential of integrating blockchain technology with advanced cybersecurity measures to enhance the resilience and security of agricultural supply chains. The findings from the analyzed case studies reveal that blockchain-based systems significantly improve data integrity, traceability, and transparency by providing decentralized and immutable data management (Salah et al., 2019). Moreover, the incorporation of advanced cybersecurity protocols, such as multi-factor authentication and real-time threat monitoring, further fortifies the system against cyber threats and data breaches (Joeaneke et al., 2024). One of the key insights from the case studies is the ability of blockchain to address long-standing issues related to data tampering and unauthorized access in agricultural supply chains. Using smart contracts, blockchain systems automate data validation and verification, thereby reducing human error and enhancing operational efficiency (Sun et al., 2023). The case study on the improved PBFT consensus mechanism demonstrated that optimizing consensus protocols can significantly enhance both security and performance, making blockchain systems more viable for large-scale agricultural applications (Chen et al., 2023).

Furthermore, the integration of blockchain with IoT and big data analytics, as seen in the Three-Dimensional Data Security Architecture model, highlights the importance of comprehensive security solutions that address the complexities of modern agricultural supply chains (Gbadebo et al., 2024). This integration ensures continuous monitoring, early threat detection, and efficient data management, reducing the risk of data loss or corruption (Olaniyi, 2024). The research also identified key challenges and limitations related to scalability, interoperability, and stakeholder adoption. Despite the proven benefits of blockchain technology, resistance to technological change and the lack of standardized frameworks remain significant obstacles to widespread adoption (Han et al., 2024). To overcome these barriers, concerted efforts must be made to educate stakeholders, develop user-friendly interfaces, and establish industry-wide standards (Oladoyinbo, 2024).

## 6. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed to enhance the

successful adoption of blockchain and cybersecurity integration in agricultural supply chains:

**Implement Scalable Blockchain Solutions:**

- Employ hybrid consensus mechanisms such as Delegated Proof of Stake (DPoS) or Practical Byzantine Fault Tolerance (PBFT) to reduce computational overhead while maintaining data integrity (Sun et al., 2023).
- Utilize sidechains or off-chain processing to handle high transaction volumes without overloading the main blockchain network (Chen et al., 2023).

**Foster Stakeholder Engagement and Training:**

- Educate farmers, supply chain operators, and technology developers on blockchain technology's benefits and practical applications (Joeaneke et al., 2024).
- Conduct workshops and training sessions to build capacity for blockchain deployment and cybersecurity practices (Olaniyi et al., 2023).

**Strengthen Regulatory and Policy Frameworks:**

- Develop clear guidelines on data ownership, privacy rights, and compliance requirements to support the responsible adoption of blockchain technology in agriculture (Han et al., 2024).
- Foster collaboration between government agencies, technology developers, and agricultural stakeholders to co-create best practices and regulatory standards (Dimas et al., 2024).

**Promote Cross-Platform Interoperability:**

- Establish standards for data exchange between blockchain platforms and existing agricultural information management systems (Salah et al., 2019).
- Implement interoperable APIs to facilitate seamless integration between decentralized and centralized systems (Gbadebo et al., 2024).

**Pilot Testing and Real-World Applications:**

- Conduct pilot projects to test blockchain frameworks in real agricultural environments, assessing their performance, efficiency, and scalability (Chen et al., 2023).
- Gather empirical data to evaluate the system's robustness and identify potential areas for improvement (Olaniyi, 2024).

**Future Research:** While this study provides valuable insights into the integration of blockchain and cybersecurity in agriculture, several areas warrant further exploration:

**Scalability of Blockchain Systems:** Future research should investigate innovative consensus mechanisms and architecture optimizations to enhance the scalability of blockchain applications in large-scale agricultural systems (Sun et al., 2023).

**Real-World Application and Validation:** Conducting more pilot studies and real-world testing will help assess blockchain adoption's practical challenges and limitations. Additionally, longitudinal studies could track the long-term impact of blockchain on supply chain resilience and efficiency (Han et al., 2024).

**Economic Viability and Cost-Benefit Analysis:** Further studies should examine the economic implications of implementing blockchain and cybersecurity solutions, considering the costs of adoption versus the potential long-term benefits (Salah et al., 2019).

**Policy and Legal Frameworks:** Developing standardized frameworks for data governance, security protocols, and regulatory compliance will be essential to support blockchain adoption in agriculture (Oladoyinbo, 2024).

**Advanced Cybersecurity Techniques:** Exploring emerging cybersecurity technologies, such as zero-trust architecture and AI-driven threat detection, can complement blockchain's inherent security features to create even more robust solutions (Joeaneke et al., 2024).

Integrating blockchain technology with advanced cybersecurity measures presents a promising approach to modernizing agricultural supply chains while ensuring data security and resilience. While challenges remain regarding scalability and adoption, the proposed solutions offer a roadmap for developing more secure and transparent agricultural systems. Policymakers, agricultural stakeholders, and technology developers must collaborate to foster innovation

while addressing the inherent challenges of blockchain implementation. By doing so, the agricultural sector can achieve sustainable growth and robust food security, safeguarded against emerging cyber threats (Alabi & Ngwenyama, 2023).

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

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