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Review Article

Blockchain Technology in Agriculture: Enhancing Transparency and Traceability in Food Systems

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ABSTRACT

Blockchain technology has emerged as a transformative digital infrastructure for addressing critical challenges in agricultural food supply chains, including lack of transparency, food fraud, and inefficient traceability systems. This review paper critically examines the current applications of blockchain technology in agriculture, with particular emphasis on its role in strengthening supply chain transparency, enhancing farm-to-fork traceability, and ensuring food safety. The study synthesizes existing literature on blockchain-enabled solutions such as distributed ledger traceability platforms, smart contracts for automated compliance and payments, and integration with Internet of Things (IoT) devices and Artificial Intelligence (AI) for real-time monitoring. Key case studies, including Walmart's IBM Food Trust initiative, demonstrate the practical viability of blockchain in reducing food recall times from days to seconds. Despite its considerable promise, widespread blockchain adoption in agriculture remains constrained by high implementation costs, scalability limitations, regulatory ambiguities, and the digital divide among smallholder farmers. This review identifies major opportunities and future research directions to advance blockchain deployment in building more transparent, resilient, and sustainable agricultural food systems.

Keywords: *Blockchain Technology; Food Supply Chain; Agricultural Traceability; Smart Contracts; Food Safety.*

INTRODUCTION

The global agricultural food supply chain is an extraordinarily complex network encompassing farmers, processors, distributors, retailers, and consumers, operating across multiple geographies and regulatory jurisdictions. Traditional supply chain management systems have long suffered from fragmented information flows, lack of real-time data sharing, and opacity that breeds food fraud, safety hazards, and consumer distrust (Kamilaris et al., 2019).

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According to the World Health Organization, approximately 600 million people worldwide fall ill annually due to contaminated food, underscoring the critical need for robust traceability mechanisms. In developing economies, post-harvest losses can reach up to 40% of total produce due to inadequate logistics and monitoring infrastructure (Kshetri, 2021). Blockchain technology, originally conceived as the backbone of cryptocurrency systems, has rapidly evolved into a versatile digital infrastructure with applications far beyond finance. At its core, blockchain is a decentralized, distributed ledger technology that records transactions across multiple nodes in a tamper-proof and chronologically ordered chain of cryptographic blocks (Tian, 2017). Each transaction, once validated through a consensus mechanism, becomes immutable and transparent to all authorized participants. This fundamental architecture makes blockchain particularly suited for agricultural supply chains, where multiple stakeholders require trusted, verifiable, and real-time information sharing.

The global blockchain in agriculture and food supply chain market has witnessed remarkable growth, projected to expand at a compound annual growth rate (CAGR) of approximately 36% from 2025 to 2035 (Future Market Insights, 2025). This growth is driven by increasing consumer demand for food provenance information, stringent regulatory frameworks such as the European Union's General Food Law and the United States Food Safety Modernization Act (FSMA), and the convergence of blockchain with complementary technologies including the Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing (Tripathi & Chauhan, 2022). This review paper aims to comprehensively examine the current state of blockchain applications in agriculture, evaluate key benefits and challenges, and identify future directions for research and implementation.

2. Blockchain Technology: Fundamentals and Architecture

Blockchain technology operates as a peer-to-peer distributed ledger system in which data is stored in sequential blocks, each linked to the previous block through cryptographic hash functions. The architecture can be categorized into three primary types: public blockchains, which offer complete transparency but face scalability constraints; private blockchains, which restrict access to authorized participants for faster processing; and consortium blockchains, which combine collaborative governance among multiple organizations (Wenhua et al., 2023). In agricultural applications, consortium blockchains such as Hyperledger Fabric have gained prominence due to their balance of transparency, performance, and data privacy.

The key technical features relevant to agricultural traceability include decentralization, which eliminates reliance on a single authority and minimizes data tampering risk; immutability, ensuring that recorded data cannot be altered without network-wide consensus; transparency, enabling all authorized stakeholders to access the same verified information in real time; and smart contracts, which are self-executing protocols that automatically trigger predetermined actions such as payments, alerts, or compliance verifications when specified conditions are fulfilled (Thakur & Naan, 2026). Figure 1 illustrates the conceptual framework of a blockchain-based agricultural food supply chain system.

3. Applications of Blockchain in Agricultural Food Systems

3.1 Supply Chain Traceability and Transparency

The most prominent application of blockchain in agriculture is enabling end-to-end traceability of food products from farm to consumer. By recording every transaction and event—including planting, harvesting, processing, packaging, and distribution—on an immutable ledger, blockchain creates a comprehensive and verifiable audit trail (Tian, 2017).

This traceability is particularly valuable for high-risk and high-value commodities including fresh produce, meat, dairy, and organic products. The TRACE-RICE pilot project in Portugal successfully demonstrated blockchain-enabled traceability for Mediterranean rice production, utilizing ArcGIS-based field data recording linked to blockchain-verified QR codes on consumer packaging (TRACE-RICE, 2025).

3.2 Smart Contracts for Automated Transactions

Smart contracts represent one of the most transformative applications of blockchain in agricultural commerce. These self-executing digital agreements automatically enforce contractual terms without requiring intermediaries. In agricultural contexts, smart contracts can automate payment release upon confirmed delivery, trigger quality compliance actions based on sensor data, and enforce certification requirements at each supply chain node (Tripathi & Chauhan, 2022). For instance, platforms like GrainChain have deployed smart contracts to connect farmers directly with buyers, automating payments upon product delivery and significantly reducing disputes and delays, particularly benefiting smallholder farmers in Latin America. Figure 2 illustrates the smart contract workflow in agricultural transactions.

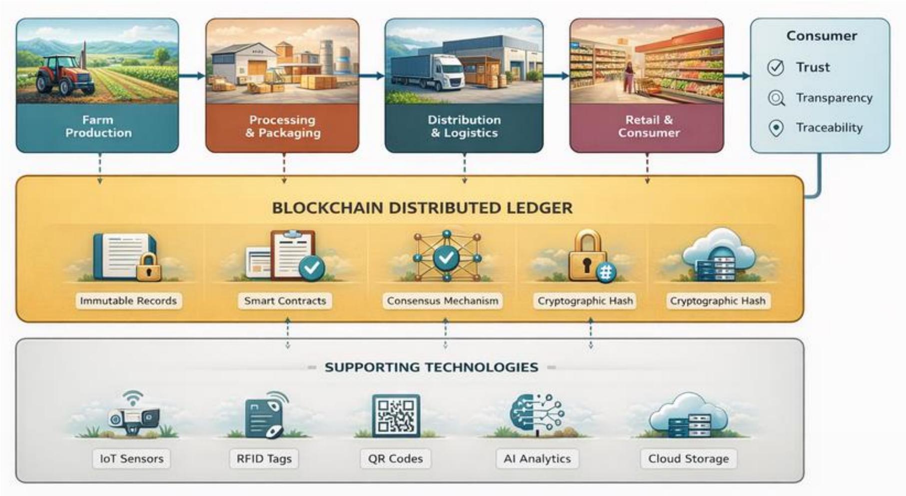

Figure 1: Blockchain-Based Agricultural Food Supply Chain Framework Showing Distributed Ledger Integration Across Supply Chain Stages with Supporting Technologies

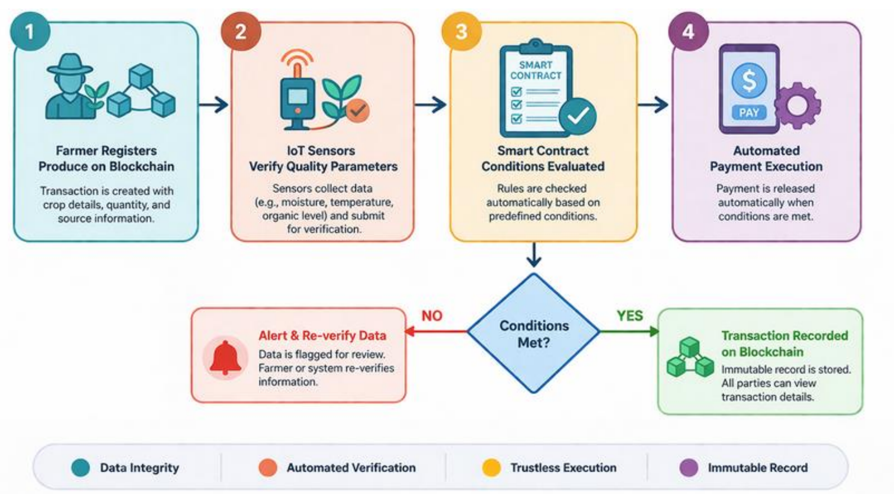

Figure 2: Smart Contract Workflow in Agricultural Transactions Depicting Automated Verification, Conditional Evaluation, and Immutable Recording of Transactions

3.3 Food Safety and Rapid Recall Systems

Perhaps the most compelling real-world demonstration of blockchain's value in agriculture is Walmart's partnership with IBM to develop the IBM Food Trust platform, built on Hyperledger Fabric. In a landmark pilot project, Walmart traced the provenance of mangoes sold in its U.S. stores, reducing the time required to identify the source farm from nearly seven days to just 2.2 seconds (Yiannas, 2018). This dramatic improvement has profound implications for food safety, as rapid traceability enables precise identification of contaminated batches, allowing targeted recalls within hours rather than days, thereby minimizing public health risks and economic losses. Walmart now traces over 25 products from five different suppliers and has mandated that all suppliers of fresh leafy greens participate in the blockchain traceability network (Linux Foundation, 2023).

3.4 Integration with IoT and AI Technologies

The convergence of blockchain with IoT and AI technologies has created powerful synergies for precision agriculture and smart farming. IoT sensors deployed across farms, transportation vehicles, and storage facilities capture real-time environmental data—including temperature, humidity, soil moisture, and GPS location—which is then recorded on the blockchain to ensure tamper-proof data integrity (Torky & Hassanein, 2020). AI algorithms analyze this data to generate predictive insights for crop health management, pest detection, and supply chain optimization. Platforms like Farmonaut combine satellite imagery, AI advisory tools, and blockchain-based verification to deliver comprehensive farm-to-consumer traceability solutions (Vancelian, 2025). The four-layer architecture comprising device nodes, fog nodes, cloud servers, and end users has been proposed as an efficient framework for blockchain-IoT integration in smart farming environments (Jothikumar et al., 2021).

3.5 Certification Verification and Fraud Prevention

Blockchain technology offers a robust solution for verifying agricultural certifications, including organic, fair-trade, and carbon-neutral labels. Traditional paper-based certification systems are vulnerable to fraud and counterfeiting, undermining consumer trust and market integrity. By recording certification data on an immutable distributed ledger, blockchain enables consumers and regulatory authorities to independently verify product claims through QR codes linked to blockchain-verified records (Thakur & Naan, 2026). This digital verification mechanism has been shown to significantly reduce certification fraud while simplifying audit processes and supporting ethical sourcing practices across global agricultural supply chains.

4. Market Growth and Industry Adoption

The blockchain in agriculture and food supply chain market has experienced substantial growth, driven by increasing demand for transparent and trustworthy food systems. According to Future Market Insights (2025), the global market is projected to grow at a CAGR of 36.0% from 2025 to 2035, with food supply chain control contributing approximately 21.6% of market revenue. Major industry players including Walmart, Nestlé, Unilever, Kroger, Tyson Foods, and Carrefour have adopted blockchain-based traceability platforms. Government-backed initiatives, particularly in the European Union and Asia-Pacific regions, have further accelerated adoption through regulatory mandates and consortium-based pilot projects. Figure 3 presents the projected market growth trajectory.

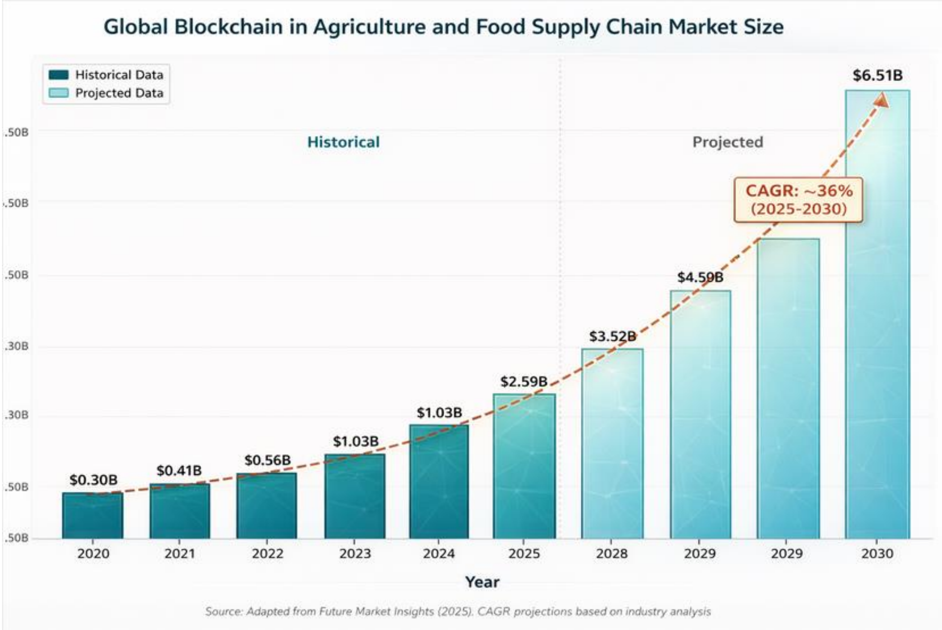

Figure 3: Global Blockchain in Agriculture and Food Supply Chain Market Size (2020–2030) with Projected CAGR of Approximately 36%

5. Key Benefits and Impact Assessment

The adoption of blockchain technology in agriculture delivers multifaceted benefits across the entire value chain. Enhanced traceability and transparency provide immutable, auditable records that improve accountability and strengthen consumer trust. Food safety is significantly improved through rapid, targeted recall capabilities that reduce response times from weeks to seconds. Smart contract automation streamlines payment processing, reduces administrative friction, and eliminates disputes between trading partners. Furthermore, blockchain empowers smallholder farmers by providing transparent market access, fair trade opportunities, and reliable digital identities, enabling them to command premium prices for verified products (Kshetri, 2021). Regulatory compliance is facilitated through blockchain's capacity to generate tamper-proof audit trails that meet international food safety standards including HACCP, EU General Food Law, and FSMA requirements. Figure 4 summarizes the key benefits across the agricultural value chain.

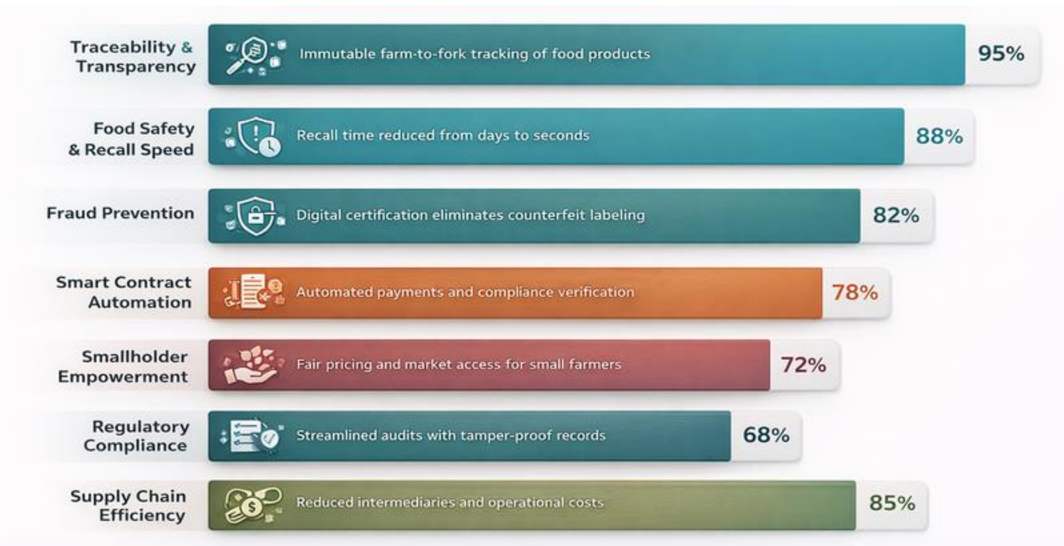

Figure 4: Key Benefits of Blockchain Technology Across the Agricultural Value Chain Based on Synthesis of Reviewed Literature

6. Challenges and Limitations

Despite its transformative potential, blockchain adoption in agriculture faces several significant barriers. High implementation costs, including substantial investment in hardware, software, and technical expertise, remain prohibitive for small and medium-sized agricultural enterprises, particularly in developing countries (Nagariya et al., 2022). Scalability limitations pose technical challenges, as blockchain networks can struggle to process the massive volumes of data generated across complex agricultural supply chains, leading to latency and throughput constraints (Kamilaris et al., 2019).

Regulatory ambiguity represents another major obstacle, as many jurisdictions lack clear legal frameworks governing smart contracts and blockchain-based data management, creating uncertainty for stakeholders (Frizzo-Barker et al., 2020). The digital divide in rural areas, characterized by limited internet connectivity, low digital literacy among farmers, and inadequate technological infrastructure, exacerbates existing inequalities and restricts equitable access to blockchain benefits. Data accuracy concerns also persist, as blockchain's immutability means that erroneous data entries cannot be easily corrected once recorded. Additionally, energy-intensive consensus mechanisms, particularly Proof of Work protocols, raise environmental sustainability concerns that contradict agriculture's sustainability objectives (Saberi et al., 2020). Addressing these challenges requires coordinated efforts among policymakers, technology developers, financial institutions, and agricultural stakeholders.

CONCLUSION

Blockchain technology represents a paradigm shift in agricultural supply chain management, offering unprecedented capabilities for enhancing transparency, traceability, and trust across food systems. This review has demonstrated that blockchain-enabled solutions—including distributed ledger traceability platforms, smart contracts, IoT-integrated monitoring, and digital certification verification—hold significant potential to address the persistent challenges of food fraud, safety hazards, and supply chain inefficiency. Real-world implementations such as Walmart's IBM Food Trust initiative, the TRACE-RICE pilot project, and platforms like GrainChain and Farmonaut provide compelling evidence of blockchain's practical viability in agricultural contexts.

However, the path to widespread adoption remains fraught with challenges, including high implementation costs, scalability constraints, regulatory uncertainties, and the critical need to bridge the digital divide affecting smallholder farmers globally. Future research should focus on developing cost-effective and scalable blockchain architectures tailored to diverse agricultural contexts, establishing comprehensive regulatory frameworks, creating user-friendly interfaces for technologically underserved farming communities, and exploring advanced integration with AI-driven analytics for predictive decision support. As blockchain technology matures with lower costs and greater accessibility, supported by policy incentives and collaborative stakeholder engagement, it is positioned to become a foundational infrastructure for building more transparent, resilient, and sustainable global food systems.

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Author Contributions:
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