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Blockchain Technology In Food Supply Chains: Applications, Limitations, And Future Directions

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Abstract

Blockchain technology offers significant potential to address persistent challenges in food supply chains, including weak traceability, food safety concerns, limited transparency, and inefficiencies. This paper critically reviews blockchain applications, limitations, and future directions in agri-food supply chains. The technology enables secure, decentralized, and tamper-proof recording of food production and distribution data, enhancing traceability through integration with IoT and RFID technologies, improving supply chain coordination, reducing fraud, strengthening consumer trust, and enabling automated transactions via smart contracts. Market projections indicate substantial growth, with the global blockchain agriculture market expected to reach approximately $1.4 billion by 2028. However, widespread adoption faces significant barriers, including high implementation costs, scalability constraints, privacy concerns, interoperability issues, regulatory uncertainties, and technical expertise shortages, particularly affecting small and medium-scale enterprises. Future research directions include developing standardized interoperability frameworks, enhancing privacy protection mechanisms, optimizing energy-efficient consensus protocols, establishing regulatory guidelines, and improving system throughput. Successful implementation requires supportive policies, stakeholder collaboration, capacity building, and continued technological advancements. This review contributes to the growing knowledge base on blockchain applications in agriculture and provides practical insights for researchers, policymakers, and industry stakeholders seeking to leverage blockchain for improved food supply chain management.

Keywords: *Blockchain technology, food supply chains, traceability, food safety, transparency, smart contracts, agricultural technology, supply chain management.*

1.0 Introduction

The agriculture and agri-food industry constitutes a fundamental pillar of global food security, yet it continues to grapple with persistent challenges including food contamination, foodborne illnesses, and difficulties tracing products through fragmented record-keeping systems (Köksal & Tekinerdogan, 2019). The increasingly complex and globalised nature of modern food supply chains has exacerbated these problems, creating urgent demands for robust systems capable of enhancing visibility and accountability across all stages of food production and distribution. Blockchain technology has garnered considerable attention as an innovative paradigm capable of transforming food supply chain operations (Di Vaio & Varriale, 2020). As a decentralised, distributed digital ledger, blockchain enables secure, transparent, and immutable recording of transactions across multiple network nodes, offering unprecedented opportunities for tracking food products from farm to fork while maintaining data integrity and stakeholder trust (Ahmed et al., 2022).

Beyond traceability, blockchain facilitates enhanced coordination and information flow among supply chain participants, enabling improved decision-making and operational efficiency (Zhai et al., 2020). Smart contracts automate transactions and reduce reliance on intermediaries, lowering costs and expediting payments (Swain et al., 2021). Integration with complementary technologies such as IoT and AI has expanded its potential applications, enabling real-time monitoring and predictive analytics (Kamilaris et al., 2019; Lin et al., 2020).Despite these advantages, blockchain remains at an incipient stage of adoption, constrained by high costs, interoperability deficiencies, limited technical capacity, and absence of standardised regulatory frameworks (Smidt & Jokonya, 2022; Kouhizadeh et al., 2021). Privacy concerns also arise when sensitive commercial data are exposed to competing stakeholders (Reyna et al., 2018).Table 1 presents key challenges and opportunities associated with blockchain adoption.

Table 1: Key Challenges and Opportunities of Blockchain Adoption

Dimension	Challenges	Opportunities
Technical	Scalability, latency, storage limitations	Enhanced traceability, IoT/AI integration
Economic	High costs, energy consumption	Reduced transaction costs, efficiency
Regulatory	No global standards, legal uncertainties	Improved food safety monitoring
Social	Skills gap, digital literacy	Consumer trust, pricing fairness

Source: Compiled from Reyna et al. (2018), Kamilaris et al. (2019), and Kouhizadeh et al. (2021)

This study undertakes a critical review of blockchain technology within food supply chains, emphasising applications, limitations, and future prospects.

2.0 Overview of Blockchain Technology

2.1 Foundational Concepts

Blockchain technology offers a decentralised, distributed ledger architecture that securely records transactions across multiple computers within a network. Data are stored in cryptographically linked blocks, rendering the system highly secure and resistant to unauthorised modification (Ahmed et al., 2022). Each transaction undergoes validation through consensus mechanisms before permanent addition to the chain, ensuring data integrity without centralised authorities (Mirabelli & Solina, 2020). This distributed structure ensures identical copies of the ledger are stored across multiple nodes, enhancing transparency and reliability (Akram et al., 2022).

2.2 Blockchain Network Typologies

Blockchain networks are classified into four principal typologies based on access permissions (Crosby et al., 2016; Kemp et al., 2019). Public blockchains are open, permissionless systems offering maximum decentralisation but facing scalability and energy challenges. Private blockchains are restricted networks controlled by a single organisation, offering enhanced privacy and faster processing, making them suitable for enterprise supply chains. Hybrid blockchains combine public and private features, enabling selective data sharing, while consortium blockchains are semi-decentralised systems managed by multiple organisations, suitable for collaborative supply chain environments. Table 2 provides a comparative analysis of these typologies.

Table 2: Comparative Analysis of Blockchain Network Typologies

Characteristic	Public	Private	Hybrid	Consortium
Access Control	Permissionless	Permissioned	Mixed	Permissioned
Decentralisation	Full	Partial	Selective	Semi
Transaction Speed	Slow	Fast	Moderate	Fast
Energy Consumption	High	Low	Moderate	Low
Transparency	Full	Limited	Selective	Controlled

Source: Adapted from Crosby et al. (2016) and Kemp et al. (2019)

2.3 Blockchain Applications in Agriculture

Blockchain technology offers several critical applications in agricultural systems, though their practical efficacy warrants careful examination. Farm inventory management utilises blockchain to monitor storage conditions and reduce postharvest losses through real-time alerts, yet the reliability of such systems depends heavily on the integrity of input data from IoT sensors (Crosby et al., 2016). While blockchain enhances supply chain efficiency through improved stakeholder coordination and transparent data sharing (Kayikci et al., 2022), the technology's benefits remain contingent upon universal adoption across all supply chain participants, a condition seldom achieved in practice.Farm management modernisation through blockchain purportedly enhances data security and reduces cyberattack risks via decentralised storage; however, the technology merely shifts vulnerabilities rather than eliminating them, as the human element and endpoint security remain critical weaknesses. Blockchain strengthens IoT applications by securing sensor data on environmental conditions, soil status, and weather patterns (Crosby et al., 2016), though the cost of implementing such integrated systems often outweighs benefits for smallholder farmers.

Pricing fairness improvement through blockchain-based platforms enabling direct farmer-buyer access (Zhao et al., 2019) presents a theoretically sound proposition; however, the digital divide and limited technological infrastructure in developing agricultural economies significantly undermine this potential. Similarly, while blockchain facilitates microloan access for small-scale farmers through transparent, decentralised financial systems, the technology cannot address underlying structural issues including inadequate credit histories, limited financial literacy, and institutional barriers that perpetuate agricultural financing challenges.

2.4 Blockchain and Food Security

Blockchain improves food security by enhancing data collection, traceability, and transparency across agricultural systems. Platforms like Grain Discovery demonstrate how blockchain supports farmers in transparent, globally competitive crop marketing. IBM and Walmart's blockchain-based food traceability system reduced mango tracing time from approximately seven days to 2.2 seconds (Kamilaris et al., 2019). However, implementation must be inclusive, ensuring smallholder farmers are not excluded from digital transformation due to limited digital literacy and infrastructure gaps (Sharma et al., 2020).

In agricultural business operations, blockchain enables secure recording of farm-level data including fertiliser use and production practices, verifiable through blockchain-enabled platforms (Kramer et al., 2021). Smart contracts facilitate automated, transparent transactions, reducing intermediary reliance and transaction costs (Swain et al., 2021). Overall, blockchain enhances efficiency, reduces fraud, and builds stakeholder trust (Oguntegbe et al., 2022).

3.0 Food Supply Chain Challenges and Blockchain Applications

3.1 Contemporary Challenges

Food supply chains confront persistent systemic challenges including weak traceability, food safety risks, quality concerns, and fundamental trust deficits among stakeholders (Feng et al., 2020; Saurabh & Dey, 2021). These vulnerabilities manifest across multiple dimensions with significant consequences. Traceability deficiencies remain particularly problematic, as fragmented record-keeping systems prevent rapid identification of contamination sources, resulting in extended product recalls, substantial economic losses, and elevated public health risks. Jeremić et al. (2024) estimate that approximately 14% of global food loss originates from untraceable supply chain events, representing both a significant waste of resources and a critical failure of existing monitoring systems.Food fraud, encompassing adulteration, substitution, and mislabelling, continues to undermine consumer trust while posing serious health risks (Rejeb et al., 2020). The complexity and opacity of global supply chains create opportunities for fraudulent activities that are difficult to detect through conventional auditing mechanisms. Quality degradation occurs throughout extended supply chains due to inadequate monitoring of storage conditions, transportation variables, and handling practices, with perishable agricultural products being particularly susceptible to deterioration (Kamilaris et al., 2019). This degradation results in food waste, economic losses, and compromised nutritional value.

Information asymmetry between supply chain participants creates significant inefficiencies, as consumers, regulators, and downstream stakeholders lack visibility into production practices and product provenance (Paliwal et al., 2020). This information gap undermines market efficiency, prevents informed consumer choice, and perpetuates distrust throughout the value chain. Regulatory compliance challenges further compound these issues, as supply chain participants must navigate diverse and often conflicting food safety standards across multiple jurisdictions, creating an administrative burden that disproportionately affects small and medium-sized enterprises (Kouhizadeh et al., 2021).

3.2 Blockchain Applications in Supply Chains

Blockchain technology offers several purported applications for food supply chain management, though their practical effectiveness warrants critical scrutiny. Traceability enhancement through end-to-end tracking from origin to consumption, integrated with RFID and IoT systems (Lin et al., 2020; Feng et al., 2020), presents a theoretically robust solution; however, implementation remains contingent upon universal stakeholder participation and significant infrastructure investment, conditions rarely achieved in fragmented supply chains. The claimed improvements in traceability are often overstated, as blockchain merely records existing data rather than verifying its accuracy at the point of origin.Food fraud prevention through immutable recording of product provenance and handling conditions (Rejeb et al., 2020) addresses documentation rather than detection, as blockchain cannot prevent fraudulent entries made by malicious actors at the point of data entry. The technology's immutability becomes a liability when inaccurate information is permanently recorded, potentially compounding rather than solving verification challenges.

Supply chain coordination improvements through enhanced information sharing and smart contracts (Swain et al., 2021) face significant barriers, including interoperability challenges between different blockchain platforms and legacy systems, as well as resistance from intermediaries whose roles are threatened by disintermediation. Consumer transparency through accessible verification of product origin and production methods (Zhao et al., 2019) assumes consumer access to and willingness to utilise such verification tools, a questionable assumption given limited digital literacy and infrastructure in many markets. Regulatory compliance through verifiable audit trails supporting inspection and recall management (Saurabh & Dey, 2021) offers potential benefits; however, the absence of standardised regulatory frameworks and cross-jurisdictional recognition of blockchain-based records undermines their legal standing. Food waste reduction through improved visibility into product shelf life and supply chain inefficiencies (Kamilaris et al., 2019) requires integration with real-time monitoring systems, introducing additional complexity and cost that many supply chain participants cannot justify. Table 3 presents major blockchain implementations, though the limited scope of these initiatives raises questions about scalability and replicability beyond pilot projects.

Table 3: Major Blockchain Implementations in Food Supply Chains

Organisation	Platform	Application Focus	Key Outcomes
Walmart	IBM Food Trust	Produce traceability	Track products in seconds versus days
IBM	Food Trust Network	Multi-stakeholder traceability	Enhanced supply chain visibility
Carrefour	Blockchain Traceability	Consumer transparency	QR code-based product verification
Nestlé	OpenSC	Supply chain transparency	Farmer income tracking, sustainability

Source: Compiled from Kamilaris et al. (2019), Feng et al. (2020), and Rejeb et al. (2020)

3.3 Integration with Complementary Technologies

The purported amplification of blockchain's potential through integration with complementary technologies demands critical examination, as synergistic benefits often prove more theoretical than practical. IoT integration enables real-time monitoring of environmental conditions, temperature, humidity, and location, creating immutable audit trails (Lin et al., 2020); however, the reliability of such systems remains fundamentally dependent on sensor accuracy, connectivity infrastructure, and power supply, all of which present significant challenges in agricultural contexts, particularly in developing economies with limited telecommunications infrastructure.AI integration enables predictive analytics for supply chain optimisation and risk assessment (Kamilaris et al., 2019), yet the efficacy of such systems depends entirely on the quality and quantity of training data, which blockchain does not inherently improve. The combination of blockchain's immutable records with AI's analytical capabilities may compound rather than correct underlying data quality issues, as flawed input data becomes permanently embedded in the system.

RFID and QR codes enable rapid product identification and seamless information flow between physical products and digital records (Feng et al., 2020); however, the physical infrastructure required for widespread deployment including scanners, readers, and network connectivity presents substantial cost barriers. Furthermore, the gap between physical product handling and digital record updates introduces opportunities for manipulation that blockchain cannot address.Big Data analytics leverage blockchain's comprehensive data repositories for supply chain optimisation and sustainability assessment (Delgado et al., 2019); however, blockchain's inherent latency and throughput limitations restrict its capacity to handle the volume and velocity of data required for meaningful analytics in real-time supply chain operations. The storage and computational costs associated with maintaining comprehensive blockchain records for big data applications remain prohibitive for most agricultural supply chain stakeholders, particularly small and medium-sized enterprises. The technological integration discourse often overlooks these fundamental constraints, presenting an overly optimistic view that obscures practical implementation challenges.

4.0 Limitations of Blockchain Technology

Table 4 presents a comprehensive analysis of blockchain implementation limitations in food supply chains, revealing systemic barriers that fundamentally constrain the technology's transformative potential. Scalability constraints, including limited throughput and escalating storage requirements, create system congestion that undermines blockchain's utility in high-volume supply chain operations. Privacy concerns arising from data visibility to all participants pose significant challenges in competitive agricultural markets where confidentiality of commercial information is paramount. The economic burden of high implementation and maintenance costs effectively excludes small and medium-sized enterprises, exacerbating existing inequalities. Regulatory fragmentation, characterised by the absence of globally accepted standards, creates legal uncertainties that discourage investment. Technical limitations including latency and limited transaction speed render blockchain unsuitable for time-sensitive operations. Finally, the persistent skills shortage in blockchain expertise contributes to implementation failures, highlighting the need for coordinated capacity building initiatives involving technology developers, policymakers, and academic institutions (Reyna et al., 2018; Köhler & Pizzol, 2020; Kouhizadeh et al., 2021).

Table 4: Blockchain Implementation Limitations in Food Supply Chains

Limitation	Specific Constraints	Impact	Mitigation Strategies
Scalability	Limited throughput, increasing storage	System congestion	Off-chain storage, multi-layer architectures
Privacy	Data visibility to all participants	Confidentiality compromise	Zero-knowledge proofs, encryption
Economic	High implementation costs	Exclusion of SMEs	Energy-efficient consensus, shared infrastructure
Regulatory	Absence of global standards	Compliance challenges	International cooperation, standardisation
Technical	Latency, limited speed	Unsuitable for high-speed operations	Protocol optimisation
Human Capital	Skills shortage	Implementation failures	Capacity building, training

Source: Compiled from Reyna et al. (2018), Köhler & Pizzol (2020), and Kouhizadeh et al. (2021)

4.1 Storage and Scalability Constraints

As blockchain networks grow, data storage increases continuously, requiring all nodes to validate and store large datasets (Reyna et al., 2018). Full-node validation places substantial storage demands, prohibitive for small-scale stakeholders. Growing blockchain size increases synchronisation time, creating barriers to network entry (Köhler & Pizzol, 2020).

4.2 Privacy and Confidentiality Concerns

Blockchain exposes transactional data to all participants, compromising confidentiality in agricultural contexts with competing stakeholders (Reyna et al., 2018). While cryptographic techniques including zero-knowledge proofs have been introduced, no single solution fully guarantees complete confidentiality (Feng et al., 2020).

4.3 High Implementation Costs

Deploying blockchain systems requires substantial investment in infrastructure, computing resources, and energy consumption. Proof-of-work mechanisms consume significant electrical energy (Kouhizadeh et al., 2021). The cost of bespoke design was identified as the most influential barrier to adoption (Apeh & Nwulu, 2025). For small and medium-scale actors, these costs are often prohibitive, creating a digital divide (Smidt & Jokonya, 2022).

4.4 Regulatory and Governance Challenges

The absence of globally accepted standards and governance frameworks creates legal uncertainties, particularly in international trade (Kouhizadeh et al., 2021). Questions regarding data ownership, jurisdictional authority, and dispute resolution remain inadequately addressed (Köhler & Pizzol, 2020).

4.5 Throughput and Latency Limitations

Current blockchain systems experience delays due to block size constraints. Bitcoin processes approximately 7 transactions per second, compared to thousands required for comprehensive supply chain tracking (Feng et al., 2020). Latency creates challenges for time-sensitive applications including temperature monitoring and safety incident response.

4.6 Human Capital and Skills Gap

The lack of skilled professionals with blockchain expertise slows adoption (Smidt & Jokonya, 2022). Implementation requires knowledge spanning distributed systems, cryptography, and supply chain operations, currently in short supply, particularly in developing economies.

4.7 Interoperability Deficiencies

Interoperability deficiencies between different blockchain platforms and legacy systems present barriers to comprehensive integration (Reyna et al., 2018). The proliferation of independent blockchain initiatives with proprietary protocols creates fragmentation (Köhler & Pizzol, 2020). Future research must move beyond technological solutionism toward rigorous empirical investigation that acknowledges fundamental constraints. While off-chain storage and AI-based optimisation address genuine scalability challenges (Reyna et al., 2018), such solutions introduce additional complexity and security vulnerabilities rarely examined. Privacy enhancement through zero-knowledge proofs (Feng et al., 2020) remains computationally intensive and practically infeasible in resource-constrained agricultural contexts. Cost reduction through energy-efficient consensus (Kouhizadeh et al., 2021) cannot overcome structural barriers to adoption among small-scale stakeholders, as cost represents only one dimension of the adoption challenge. Regulatory framework research (Köhler & Pizzol, 2020) requires genuine multi-stakeholder engagement rather than top-down standardisation inappropriate for diverse agricultural contexts. Throughput optimisation through sharding (Feng et al., 2020) remains largely unproven in real-world applications. Human capital development (Smidt & Jokonya, 2022) must address fundamental educational infrastructure deficits that no training programme can rapidly resolve. Most critically, empirical impact assessment (Rejeb et al., 2020) must adopt robust methodologies distinguishing blockchain-specific effects from broader digital transformation trends, avoiding the over-optimistic reporting characterising much existing literature.

6.0 Conclusion and Recommendations

6.1 Conclusion

This review has examined blockchain technology's applications, limitations, and future directions in food supply chains. Blockchain offers compelling advantages for addressing traceability deficiencies, food fraud, quality degradation, and regulatory compliance burdens. Its integration with IoT, AI, and RFID amplifies potential impact, enabling real-time monitoring and comprehensive visibility. Market projections indicate substantial growth at approximately 48% CAGR.However, significant limitations constrain adoption: scalability constraints, privacy concerns, high costs, regulatory uncertainties, throughput limitations, interoperability deficiencies, and skills shortages. These challenges are particularly significant for small and medium-scale enterprises and developing economies.

6.2 Recommendations

These recommendations, while ostensibly practical, reflect technocratic optimism that overlooks fundamental structural barriers in agricultural supply chains. Standardised interoperability frameworks (Köhler & Pizzol, 2020) presuppose stakeholder willingness to cooperate, contradicted by competitive dynamics and entrenched interests. Privacy-preserving technologies including zero-knowledge proofs (Feng et al., 2020) remain computationally prohibitive and offer little practical guidance for resource-constrained stakeholders. Integration with IoT and AI (Kamilaris et al., 2019) assumes infrastructure and technical capacity that does not exist in most agricultural contexts. Regulatory frameworks (Kouhizadeh et al., 2021) face the fundamental challenge of reconciling decentralisation with national sovereignty concerns. Shared infrastructure models (Smidt & Jokonya, 2022) require trust and coordination that blockchain purports to enable but cannot create where absent. Empirical impact assessments (Rejeb et al., 2020) must confront the difficulty of isolating blockchain-specific effects from broader digitalisation trends. Ultimately, inclusive adoption strategies for smallholder farmers amount to rhetorical gestures without substantial financial commitments and fundamental shifts in agricultural governance that address structural inequalities rather than merely digitising them (Smidt & Jokonya, 2022).

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