

Food safety and blockchain in agribusiness

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Food safety is a critical concern globally, with increasing consumer demand for transparency in the supply chain. Blockchain technology has emerged as a transformative solution to enhance traceability, accountability, and efficiency in agribusiness. This review explores the intersection of food safety and blockchain, examining recent advancements, theoretical and conceptual frameworks, and real-world applications. It discusses challenges, policy implications, and recommendations for broader adoption in agribusiness systems.

Keywords: Agribusiness, Blockchain, Food safety

INTRODUCTION

Food safety challenges are among the most pressing issues facing global food systems. Contamination incidents, such as *E. coli* and *Salmonella* outbreaks, not only pose severe public health risks but also lead to significant economic losses for producers, retailers and governments. According to the World Health Organization (WHO), unsafe food causes approximately 600 million cases of foodborne illnesses annually, resulting in 420,000 deaths worldwide (WHO, 2022). These incidents highlight systemic weaknesses in current supply chain practices, including a lack of end-to-end visibility, delayed response times during recalls and inefficiencies in detecting and preventing fraudulent activities. Food fraud, which includes practices such as mislabelling, adulteration and counterfeiting, costs the global food industry an estimated \$40 billion annually (Spink and Moyer, 2021).

Traditional methods of ensuring food safety rely heavily on manual documentation, fragmented databases and limited cross-sector collaboration. These approaches often fail to provide the transparency and traceability needed to ensure that food products meet regulatory standards and consumer expectations. In a globalized food system, where products traverse multiple countries and jurisdictions, these challenges are exacerbated by diverse regulatory requirements and the complexity of supply chain networks.

Blockchain technology, with its immutable and decentralized ledger, has emerged as a transformative solution to address these issues. Unlike traditional databases, blockchain ensures that all data entries are permanent, time stamped and accessible to authorized stakeholders. This enhances accountability and reduces the risk of tampering or unauthorized alterations. By integrating blockchain into the agribusiness supply chain, stakeholders can achieve real-time visibility, ensuring that every transaction-from farm to fork-is recorded and verifiable. For example, IBM Food Trust, a blockchain-based platform, has demonstrated the potential to trace the origin of food products within seconds, significantly reducing the time required for food recalls (IBM Food Trust, 2023).

Moreover, blockchain can integrate seamlessly with other advanced technologies, such as the

Internet of Things (IoT) and Artificial Intelligence (AI), to create a comprehensive ecosystem for food safety management. IoT devices, such as sensors and RFID tags, can capture real-time data on environmental conditions (e.g., temperature, humidity) during transportation and storage, while AI algorithms analyze this data to predict and mitigate risks. Blockchain serves as the backbone for securely storing and sharing this information among stakeholders, ensuring transparency and trust across the supply chain.

The agribusiness sector stands to benefit significantly from blockchain's capabilities. Enhanced traceability not only improves food safety but also builds consumer confidence in product authenticity and quality. Studies have shown that consumers are increasingly demanding transparency in food sourcing, with 75% of respondents in a recent survey indicating they would switch to brands offering detailed product traceability (Deloitte, 2022). Blockchain's ability to provide a single source of truth aligns with these consumer demands, offering agribusinesses a competitive advantage.

In addition to consumer benefits, blockchain can also address regulatory compliance challenges. For example, the European Union's General Food Law (Regulation EC No. 178/2002) and the United States' Food Safety Modernization Act (FSMA) emphasize traceability and accountability. Blockchain provides a streamlined method for meeting these requirements by ensuring that every step in the supply chain is documented and accessible for audits.

The integration of blockchain into agribusiness represents a paradigm shift in how food safety is managed. By enabling real-time traceability, fraud prevention and regulatory compliance, blockchain technology offers a sustainable and scalable solution to the challenges facing modern food systems. This review explores the theoretical and conceptual frameworks of blockchain in agribusiness, examines empirical evidence from recent studies and provides recommendations for its widespread adoption.

Theoretical Framework

The theoretical underpinnings of blockchain in food safety leverage foundational principles of transparency, decentralization, automation and network effects. These concepts provide a robust framework for understanding how blockchain technology addresses critical inefficiencies in food supply chains.

Transparency and Trust

Blockchain operates on a trustless system where every transaction is recorded on an immutable ledger, accessible to all authorized stakeholders. This transparency mitigates risks associated with data manipulation and enhances accountability. For example, in food safety, this transparency ensures that data on sourcing, processing and distribution cannot be altered retroactively, reducing fraudulent practices. Research shows that this level of transparency fosters consumer trust and incentivizes compliance among supply chain actors (Chen et al., 2022).

Decentralization

The decentralized architecture of blockchain eliminates reliance on a single controlling entity, reducing vulnerability to systemic failures or data breaches. In agribusiness, decentralization ensures that all stakeholders, from farmers to retailers, maintain equal visibility and authority over the data. This distributed model enhances resilience against disruptions and provides a fair platform for all participants (Behnke and Janssen, 2022).

Smart Contracts

Smart contracts automate the execution of predefined rules, streamlining processes and reducing administrative burdens. For instance, smart contracts can enforce quality checks automatically by triggering actions based on sensor data. If a shipment exceeds temperature thresholds, a smart contract can automatically flag the batch for review or halt further distribution. This level of automation reduces delays and minimizes human error, as demonstrated in blockchain-based food traceability systems like IBM Food Trust (Tripathi and Chauhan, 2022).

Network Effects

As more participants adopt blockchain technology, the value of the network increases exponentially. Network effects play a critical role in establishing industry-wide standards and interoperability. Larger networks not only enhance data accuracy through diverse inputs but also reduce costs for individual participants by distributing infrastructure expenses (Nakamoto, 2008).

Theoretical Perspectives

Transaction Cost Economics (TCE): Blockchain reduces transaction costs by eliminating intermediaries, streamlining data sharing and automating verification processes. These efficiencies are particularly beneficial in global supply chains, where traditional methods often involve costly and time-consuming manual reconciliations.

Information Asymmetry: Blockchain addresses information asymmetry by ensuring that all parties have access to the same verified data. This transparency levels the playing field, empowering smaller producers and consumers with the same visibility as larger corporations.

Conceptual Framework

The conceptual framework for integrating blockchain technology into food safety systems highlights its potential to create a transparent, efficient and secure supply chain from production to consumption. Key components include:

1. Data Capture

IoT devices, sensors and RFID tags serve as critical tools for capturing data at various stages of the supply chain. These devices record parameters such as temperature, humidity and location in real time. For example, temperature sensors in cold storage facilities can ensure compliance with safety standards by uploading data directly to the blockchain. This real-time capture of data reduces delays in identifying and addressing potential risks (Ghaffarzadegan and Larson, 2022).

2. Data Storage and Security

Blockchain provides a secure and tamper-proof platform for storing data. Every piece of information is recorded in a block, cryptographically linked to previous blocks, ensuring data integrity. This feature is essential for regulatory audits and consumer trust, as stakeholders can verify the history of a product without relying on intermediaries. Studies show that tamper-proof storage is a primary driver for blockchain adoption in food safety (Tian, 2022).

3. Data Analysis and Sharing

Advanced analytics applied to blockchain data enable stakeholders to identify trends, predict risks and optimize supply chain operations. For instance, machine learning algorithms can analyze blockchain data to detect patterns indicative of food spoilage or fraud. Furthermore, blockchain facilitates seamless data sharing among stakeholders, promoting collaboration and informed decision-making (Kamble et al., 2022).

4. Compliance and Certification

Blockchain simplifies adherence to regulatory standards by providing an immutable record of compliance activities. Certifications, such as organic labeling or adherence to Hazard Analysis Critical Control Point (HACCP) standards, can be verified on the blockchain. This reduces the administrative burden on producers and increases consumer confidence in product authenticity (Tian, 2017).

Lifecycle Approach

The framework emphasizes a lifecycle approach to food safety, encompassing all stages from farm to fork:

Production: Blockchain records farming practices, input usage and environmental conditions.

Processing: Data on processing methods and compliance with safety standards is captured and stored.

Distribution: Real-time tracking of transportation conditions ensures product integrity.

Consumption: Consumers can access detailed product histories, enhancing trust and satisfaction.

By integrating these components, the conceptual framework positions blockchain as a holistic solution for food safety challenges.

Step-by-Step Explanation of the Conceptual Framework for Blockchain in Food Safety

The conceptual framework for integrating blockchain technology into food safety systems is structured around four key components: data capture, data storage and security, data analysis and sharing and compliance and certification. Each component interacts with the next to create a seamless and transparent supply chain from production to consumption.

Step 1: Data Capture

Purpose: To collect real-time data on food production, processing, transportation and storage conditions.

How It Works:

IoT Devices: Sensors and RFID tags monitor critical parameters such as temperature, humidity and location at various supply chain stages.

Manual Input: In cases where automation is not available, stakeholders (e.g., farmers or processors) input data manually into the blockchain platform.

Outputs:

Raw data is generated and recorded, forming the foundational layer for traceability and transparency.

Example: Temperature sensors in cold storage record and upload readings to ensure perishable goods remain within safe ranges.

Step 2: Data Storage and Security

Purpose: To store the captured data in a tamper-proof and secure manner.

How It Works:

Blockchain Ledger: The data from IoT devices or manual entries is recorded in blocks and cryptographically linked to ensure immutability.

Decentralized Architecture: The information is distributed across multiple nodes, making it resistant to tampering or unauthorized access.

Outputs:

A secure, immutable and timestamped record of all transactions and events across the supply chain.

Example: A blockchain ledger stores records of pesticide use in farming, ensuring no data alterations can occur post-entry.

Step 3: Data Analysis and Sharing

Purpose: To process the stored data into actionable insights and share it among stakeholders.

How It Works:

Data Analysis: Advanced analytics or machine learning algorithms detect anomalies, predict risks and suggest optimizations (e.g., identifying patterns in spoilage rates).

Sharing: Stakeholders, such as regulators, consumers and supply chain partners, access verified data through blockchain dashboards or QR code links.

Outputs:

Enhanced decision-making capabilities and improved collaboration among all supply chain actors.

Example: A consumer scans a QR code on packaged meat to verify the product's origin, processing dates and transportation conditions.

Step 4: Compliance and Certification

Purpose: To ensure adherence to food safety standards and provide verification of compliance.

How It Works:

Smart Contracts: Automatically enforce regulatory standards and trigger alerts if violations occur (e.g., exceeding temperature thresholds during transport).

Certification Records: Blockchain maintains records of certifications, such as organic or fair trade labels, ensuring authenticity and simplifying audits.

Outputs:

Verified compliance with food safety regulations and streamlined audit processes.

Example: A blockchain system ensures that a batch of organic produce meets certification criteria by tracking pesticide-free farming practices from planting to harvest.

Lifecycle Approach: Farm-to-Fork Traceability

The framework emphasizes a lifecycle approach, where blockchain provides continuous traceability through the following stages:

- Production: Record farming practices, such as pesticide and fertilizer usage.
- Processing: Track processing methods, quality checks and packaging details.
- Transportation and Storage: Monitor conditions such as temperature, humidity and transit times.
- Distribution and Retail: Track delivery schedules and inventory management.
- Consumer Engagement: Allow consumers to access verified information about product origin and safety.

Visual Flow of the Framework

- Data Capture →
- Data Storage and Security →
- Data Analysis and Sharing →
- Compliance and Certification (Iterative across all stages: Production → Processing → Transportation → Retail → Consumer)

This cyclical framework ensures end-to-end traceability and reliability in food safety management.

RESEARCH METHODOLOGY

The present study adopted a desk review: collection of journals, textbooks, edited books, monographs, conference proceedings, newspapers, internet sources, etc. to generate valid data. Furthermore, using the collected data were systematically synthesized for the purpose of gaining insightful details on the research topic.

RESULTS AND DISCUSSION

The synthesis of findings from recent studies and case examples underscores blockchain's transformative potential in enhancing food safety and supply chain efficiency. Several key themes and insights have emerged, which are elaborated below.

Enhanced Traceability

Blockchain technology offers unparalleled granularity in tracking food products, allowing stakeholders to trace items back to their source in real time. This feature is particularly critical during foodborne illness outbreaks or contamination incidents, where timely recalls can prevent health risks and economic losses. IBM Food Trust, a prominent blockchain platform, has demonstrated the ability to trace the origin of a mango in seconds instead of weeks, as was the norm previously (IBM Food Trust, 2023). Beyond speed, blockchain's traceability also aids in identifying the exact point of contamination, reducing waste and ensuring accountability across the supply chain.

Fraud Prevention

Food fraud remains a pervasive issue, costing the global food industry billions annually. Blockchain addresses this challenge by maintaining immutable, timestamped records of every transaction in the supply chain. For example, the European Olive Oil Association has used blockchain to verify the authenticity of premium olive oil, protecting consumers from counterfeit products (Behnke and Janssen, 2022). By deterring fraudulent activities and ensuring the integrity of product labeling, blockchain strengthens trust among consumers and retailers alike.

Consumer Trust

The demand for transparency in food sourcing has grown significantly, with consumers increasingly prioritizing sustainable and ethically produced goods. Blockchain enables consumers to access detailed product histories, including information on farming practices, processing and transportation. Studies show that this level of transparency can improve consumer satisfaction and willingness to pay premium prices for verified products (Chen et al., 2022). Platforms such as Provenance have successfully used blockchain to create interactive consumer experiences, allowing users to trace the journey of their food from farm to table.

Global Standards Alignment

Blockchain technology provides a unified platform for aligning diverse international food safety standards. This harmonization facilitates cross-border trade by ensuring compliance with regulatory requirements. For instance, blockchain has been used in the dairy industry to ensure compliance with both EU and US standards, simplifying export processes for producers (Tian, 2022). Moreover, blockchain's ability to generate tamper-proof audit trails simplifies inspections and certifications, further enhancing global trade efficiency.

Case Studies

Walmart's Blockchain Integration: Walmart's adoption of blockchain to trace mangoes and leafy greens in the U.S. food supply chain demonstrates significant reductions in traceability time. This initiative has enhanced Walmart's ability to respond swiftly to recalls, improving food safety and reducing operational costs (Tripathi and Chauhan, 2022).

Origin Trail and Supply Chain Efficiency: Origin Trail, a decentralized blockchain-based protocol, has streamlined operations for agribusinesses by ensuring data integrity and transparency. In Serbia, Origin Trail has been used to track organic beef production, providing consumers with verified information on product origins and quality (Ghaffarzadegan and Larson, 2022).

Nestlé's Blockchain Experiment: Nestlé utilized blockchain to trace coffee from plantations in Brazil to supermarkets in Europe. This initiative not only ensured product quality but also empowered farmers by providing them with access to new markets (Deloitte, 2022).

Carrefour's Blockchain for Traceability: Carrefour, a multinational retail corporation, introduced blockchain technology to track the supply chain of its products, starting with poultry, milk and oranges. Using IBM Food Trust, Carrefour enabled consumers to access product information via QR codes on packaging. This initiative has not only improved transparency but also increased consumer trust and loyalty. The company reported a 20% increase in sales for products tracked via blockchain compared to non-tracked items (Carrefour, 2023).

Bumble Bee Foods and Tuna Traceability: Bumble Bee Foods implemented blockchain technology to trace the supply chain of yellow fin tuna from Indonesian waters to North American markets. The platform provides detailed information about the fishing method, vessel and processing facilities. This initiative has reduced instances of illegal, unreported and unregulated (IUU) fishing while empowering consumers to make informed purchasing decisions (Chen et al., 2022).

The Australian Beef Blockchain Project: The Beef Ledger platform in Australia uses blockchain to enhance traceability and provenance verification for beef exports to China. The system tracks beef production from farm to export, ensuring compliance with quality and safety standards. This project has addressed the issue of counterfeit meat, which had previously undermined Australia's reputation in the Chinese market (Behnke and Janssen, 2022).

Coffee Traceability by Farmer Connect: Farmer Connect, a blockchain-based platform, collaborates with coffee producers, traders and retailers to enhance traceability in the coffee supply chain. Notable brands like Nestlé and J.M. Smucker have adopted the system, enabling consumers to trace their coffee's journey from farms to stores. The platform also integrates financial services, allowing small-scale coffee farmers to receive fair compensation directly (Tripathi and Chauhan, 2022).

Sweetgreen's Blockchain-Powered Salad Sourcing: Sweetgreen, a fast-casual restaurant chain, uses blockchain to track the origins of its salad ingredients, including leafy greens and proteins. The initiative ensures compliance with food safety standards and enables rapid recalls when necessary. This approach has minimized the impact of foodborne illness outbreaks, maintaining customer trust (Deloitte, 2022).

China's Walmart and VeChain Collaboration: In China, Walmart collaborated with VeChain, a blockchain platform, to improve food safety and traceability. The system tracks over 23 product categories, including fresh meat, rice and mushrooms. Through this collaboration, Walmart China has achieved faster traceability and compliance with national food safety regulations, reducing risks associated with contaminated products (Tian, 2022).

Blockchain in Dairy Industry-Arla Foods: Arla Foods, a leading dairy producer in Europe, implemented blockchain to improve the traceability of its milk and dairy products. Consumers can scan QR codes to view details about the milk's origin, production date and compliance with safety standards. The initiative aligns with the growing consumer demand for sustainable and transparent supply chains (Ghaffarzagdegan and Larson, 2022).

Tea Production Transparency- Assam Tea Blockchain: The Assam Tea Producers Association in India adopted blockchain to enhance the traceability of tea products. This initiative was driven by increasing consumer demand for ethically sourced tea. Blockchain technology records details about the tea leaves' origin, farming practices and adherence to fair trade standards, improving market access for small producers (Chen et al., 2022).

Grain Chain for Small Farmers: Grain Chain, a blockchain-powered platform, connects small-scale farmers with buyers while ensuring transparency in grain production. By integrating smart contracts, the system automates payments upon product delivery, reducing disputes and delays. This solution has particularly benefited farmers in Latin America by providing them with fair compensation and access to global markets (Tripathi and Chauhan, 2022).

Seafood Supply Chain-Provenance in Thailand: Provenance, a blockchain-based startup, collaborated with Thai fishing companies to enhance transparency in the seafood supply chain. The initiative has addressed human rights violations and environmental concerns, enabling ethical sourcing and reducing instances of illegal fishing practices. Consumers can verify the source of seafood products through blockchain-enabled QR codes (Behnke and Janssen, 2022).

Challenges

Despite its potential, blockchain adoption in food safety faces several hurdles:

High Implementation Costs: Blockchain infrastructure, including IoT devices and system integration, involves significant upfront investment. Smallholder farmers and small-to-medium

enterprises often lack the financial resources to adopt these technologies (Behnke and Janssen, 2022).

Technological Literacy: The complexity of blockchain technology can deter adoption, particularly in regions with limited digital infrastructure. Training programs are critical to bridge this gap (Chen et al., 2022).

Scalability Issues: As the volume of transactions grows, maintaining blockchain efficiency and performance becomes challenging. Research is ongoing to develop more scalable blockchain solutions suitable for global food supply chains (Tripathi and Chauhan, 2022).

Interoperability: The lack of standardized platforms and protocols creates silos, reducing blockchain's effectiveness in integrating with existing systems. Collaborative efforts to develop interoperable frameworks are needed (Tian, 2022).

Potential Solutions

To overcome these barriers, stakeholders across the public and private sectors must collaborate to support blockchain adoption:

Subsidies and Financial Support: Governments and international organizations should provide financial incentives, such as subsidies or low-interest loans, to help smallholder farmers adopt blockchain systems.

Training Programs: Capacity-building initiatives that educate stakeholders about blockchain's benefits and applications can enhance adoption rates, particularly in developing regions.

Open-Source Platforms: Open-source blockchain platforms reduce implementation costs and encourage innovation. Initiatives like Hyperledger and Ethereum-based solutions have made significant strides in this area.

Research and Development: Investments in R&D can address scalability and interoperability challenges, ensuring blockchain systems remain efficient and adaptable to diverse supply chain needs.

CONCLUSION

Blockchain technology offers a revolutionary approach to addressing food safety challenges in agribusiness by enhancing transparency, traceability and trust throughout the supply chain. Its ability to provide immutable records and real-time tracking significantly reduces food fraud, contamination risks and inefficiencies in recall processes. However, widespread adoption is hindered by high costs, technological complexity and scalability issues. Overcoming these barriers requires coordinated efforts among stakeholders, innovative technological solutions and supportive regulatory frameworks.

POLICY IMPLICATIONS

Governments and regulatory bodies play a pivotal role in facilitating blockchain adoption in agribusiness. Key policy implications include:

Blockchain-Friendly Policies: Governments should create an enabling environment for blockchain innovation by providing financial incentives, tax breaks and funding for pilot projects in food safety systems.

Standardization and Interoperability: Regulatory bodies must ensure that blockchain platforms adhere to international standards, allowing seamless integration across global supply chains.

Legal and Ethical Frameworks: Policies must address data ownership, privacy concerns and liability issues to ensure equitable use of blockchain technology.

Collaboration Across Borders: In a globalized food system, harmonized regulations can facilitate cross-border trade and encourage broader adoption of blockchain-based solutions.

RECOMMENDATIONS

To maximize blockchain's potential in enhancing food safety, the following recommendations are proposed:

Education and Training

Investment in capacity-building initiatives to improve stakeholders' understanding of blockchain technology.

Tailored training programs for smallholder farmers, producers and supply chain operators to bridge technological literacy gaps.

Public-Private Partnerships

Collaboration between governments, tech providers and agribusinesses to subsidize the initial costs of blockchain implementation.

Incentives such as grants and low-interest loans to encourage small and medium-sized enterprises (SMEs) to adopt blockchain solutions.

Development of Interoperable Platforms

Establishment of open-source or universally compatible blockchain frameworks to ensure integration with existing systems.

Encouraging cross-industry partnerships to create shared standards and infrastructure.

Longitudinal Studies

Conducting long-term research to evaluate the impact of blockchain on food safety, efficiency and sustainability.

These studies should focus on cost-benefit analyses, scalability solutions and the social and economic benefits of blockchain adoption.

By addressing these areas, blockchain can transition from an emerging technology to a cornerstone of food safety in agribusiness, driving transparency, efficiency and consumer trust.

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