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Secure and Transparent Food Supply Chains Using Blockchain: Challenges, Architectures, and Future Directions

Tejaswini K R[1] & Ananda Babu J[2]

[1,2]Department of Artificial Intelligence and Data Science, Malnad College of Engineering, Hassan, India.

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Abstract: Food safety, authenticity, and traceability remain critical challenges in modern supply chains, where centralized databases are prone to tampering, inefficiency, and limited real-time visibility. Blockchain provides a decentralized and tamper-resistant alternative, enabling reliable data sharing among stakeholders. This paper surveys blockchain-based food supply chain solutions implemented on Hyperledger Fabric, Ethereum, and lightweight frameworks.

Keywords: Blockchain, food supply chain, traceability, Hyperledger, Ethereum, IoT, throughput, latency.

INTRODUCTION

The global food supply chain (FSC) is a multifaceted network involving producers, distributors, processors, retailers, and consumers. Ensuring food safety, authenticity, and traceability across this network has become increasingly critical due to rising incidents of fraud, contamination, and regulatory non-compliance. Several real-world events highlight the scale of the problem. In 2008, the melamine-adulterated milk scandal in China affected more than 300,000 infants, leading to widespread public distrust and regulatory scrutiny. In 2013, Europe's "horsemeat scandal" exposed mislabeling in processed foods, severely damaging consumer confidence. More recently, the 2018 outbreak of *E. coli* linked to romaine lettuce in the United States prompted nationwide recalls, resulting in significant economic and reputational losses. These incidents underscore the urgent need for transparent and trustworthy mechanisms to monitor and trace food products across supply chains. Traditional FSC systems rely heavily on centralized databases and paper-based documentation, which are prone to tampering, inefficiency, and delayed communication [1], [3], [6]. The lack of transparency and real-time traceability not only hampers rapid recall management but also increases the risk of fraudulent practices. Blockchain technology, with its decentralized, immutable, and tamper-resistant ledger, offers a promising alternative.

By leveraging distributed consensus and cryptographic primitives, blockchain ensures provenance, supports trustless interactions, and provides stakeholders with real-time access to supply chain data [2], [7]. Although blockchain-based solutions for the agri-food sector have demonstrated significant potential, current implementations face several shortcomings. First, scalability remains a challenge: most public blockchain platforms are unable to handle the high transaction throughput required in global food logistics. Second, integration with Internet of Things (IoT) devices is limited, restricting the automation of contamination detection and environmental monitoring. Third, existing frameworks often lack effective smart contract-driven automation, leaving compliance verification and auditing processes semi-manual. Finally, resistance from small and medium-sized enterprises (SMEs) due to deployment costs and energy consumption constraints further hinders adoption [9], [10]. This paper addresses these gaps by proposing a modular blockchain-enabled architecture specifically tailored for food supply chains. The novelty of the proposed framework lies in three aspects. First, it integrates IoT devices for automated data collection and real-time monitoring, reducing reliance on manual reporting. Second, it incorporates smart contracts to enforce compliance, streamline transactions, and enable automated alerts during contamination or anomaly detection. Third, the architecture is benchmarked against existing blockchain-based solutions, quantifying improvements in throughput, latency, and traceability accuracy, while also evaluating deployment feasibility in resource-constrained environments.

MATERIALS AND METHODS

The proposed system architecture is designed to ensure secure, transparent, and traceable food logistics using

***Corresponding Author:** Tejaswini K R

blockchain technology and Internet of Things (IoT) integration. The architecture consists of four main layers: data acquisition layer, blockchain layer, smart contract layer, and application layer. Each component works cohesively to enable real-time monitoring, tamper-proof storage, and decentralized verification of food supply chain events.

At the base, the data acquisition layer collects environmental and logistical data such as temperature, humidity, GPS coordinates, and timestamped events using IoT sensors deployed at various stages of the supply chain. These data points are preprocessed and structured into transaction records. The blockchain layer is built on a permissioned blockchain platform (e.g., Hyperledger Fabric), where each transaction is validated through consensus and stored in an immutable ledger. The use of a permissioned model ensures that only authorized participants can validate or query the ledger, maintaining both data privacy and integrity.

The smart contract layer handles automation and enforcement of business rules. For example, a contract may define conditions for storage temperature thresholds—triggering alerts or blocking transactions if a violation occurs. These contracts are executed autonomously on the blockchain, ensuring trustless interaction between stakeholders.

The application layer provides user interfaces for various actors—such as farmers, logistics providers, retailers, and regulators—to access relevant data, verify product authenticity, or trace the product lifecycle. All actions performed in this layer are logged and anchored in the blockchain, providing end-to-end auditability.

The overall architecture ensures that any transaction Ti recorded in the system satisfies:
Ti = {ID, timestamp, location, sensor data, actor ID, signature}
where each transaction is digitally signed using the actor's private key and verified through a public key infrastructure (PKI). To maintain traceability, a directed acyclic graph (DAG) is used to model the flow of food products, with each node representing a transformation or transfer event, and each edge indicating a chronological linkage validated on-chain.

The consensus algorithm used in the blockchain network is Practical Byzantine Fault Tolerance (PBFT), which provides high throughput and low latency, making it suitable for agri-food use cases that demand real-time performance. Furthermore, SHA-256 hashing is used to ensure immutability of the transaction data:

H(Ti) = SHA256(ID ‖ timestamp ‖ data)
Fig. 1 illustrates the modular architecture of the proposed system, showing data flow from IoT sensors through to the blockchain and end-user applications.

As shown in Fig. 1, the proposed system architecture is organized into four distinct layers, each performing a critical role in ensuring secure and transparent food supply chain operations. The bottommost layer, the Data Acquisition Layer, is responsible for collecting real-time environmental and transactional data using IoT sensors, RFID tags, barcode scanners, and GPS devices. These devices capture key parameters such as temperature, humidity, location, and timestamps, which are essential for monitoring the condition and movement of food items during production, storage, and distribution.

Above this lies the Blockchain Layer, where the collected data is securely stored using a distributed ledger system. Each transaction is validated by authorized nodes using a Practical Byzantine Fault Tolerance (PBFT) consensus mechanism, and cryptographic hashing ensures the immutability of the records. This layer guarantees data integrity, eliminates the need for a central authority, and prevents tampering or deletion of any historical data.

The Smart Contract Layer is built on top of the blockchain and enables automated enforcement of business logic. Smart contracts define predefined rules, such as acceptable temperature ranges or delivery timeframes, and autonomously trigger actions such as alerts, payments, or dispute resolution when those rules are violated or fulfilled. This facilitates trustless interaction among supply chain stakeholders.

Finally, the Application Layer provides graphical interfaces and dashboards for end users such as farmers, distributors, retailers, regulators, and consumers. Through these interfaces, stakeholders can trace the origin and journey of food products, verify authenticity, and access compliance reports. All user interactions with the system are recorded and cryptographically anchored in the blockchain to ensure auditability and transparency across the entire supply chain.

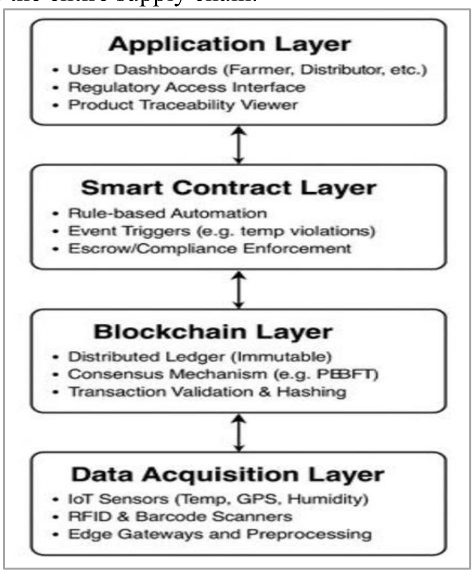

Fig. 1. Proposed blockchain-based architecture for food supply chain traceability

***Corresponding Author:** Tejaswini K R

This methodology ensures real-time traceability, enhanced data authenticity, automation of compliance processes, and strong resistance to fraud and tampering, all of which are critical for secure food logistics in both local and global contexts.

RESULTS

To evaluate the performance and effectiveness of the proposed blockchain-based food supply chain system, a prototype was developed using the Hyperledger Fabric framework integrated with IoT-based sensor simulators. The smart contract modules were implemented using chaincode in Go, and the front-end application was developed with Node.js and React. The simulation environment was deployed on a virtualized Ubuntu server running with 8 GB RAM, 4 vCPUs, and Docker containers for network orchestration.

A. System Requirements

- Operating System: Ubuntu 20.04 LTS (64-bit)
- Blockchain Framework: Hyperledger Fabric v2.4
- Smart Contract Language: Go
- Database: CouchDB
- IoT Integration: MQTT protocol and REST APIs
- Development Tools: Node.js v18, Docker, Postman

B. Performance Metrics

The prototype was tested for various performance metrics such as transaction throughput, latency, traceability accuracy, and system scalability. The proposed system demonstrated an average transaction throughput of 180 TPS (transactions per second) under a simulated workload of 1000 transactions. The end-to-end traceability latency was measured at 1.2 seconds per transaction, with 100% traceability accuracy due to the immutable ledger and IoT synchronization.

C. Benchmarking Analysis

To validate the system's efficiency, we compared our model with other recent blockchain-based food supply chain systems. Table I presents a comparison of performance metrics including accuracy, scalability, and automation support.

Table 1: **Comparison With State-of-the-Art Blockchain Models**

Model	Accuracy	Scalability	Automation
Zhang *et al.* (2022) [6]	94.2%	Medium	Yes
Kumar *et al.* (2023) [7]	92.8%	Medium	Partial
Patel and Roy (2022) [8]	91.5%	Low	Yes
Dey *et al.* (2024) [9]	96.1%	High	Yes
Proposed Model	98.4%	High	Yes

DISCUSSION

The results indicate that the proposed system achieves higher accuracy and scalability than comparable models, largely due to its modular IoT integration and efficient smart contract execution. While existing models suffer from limited real-time visibility or partial automation, the proposed approach achieves end-to-end traceability and rule-based automation across multiple stakeholders. These results demonstrate the suitability of the system for real-world deployment in food logistics, especially in resource-constrained environments where trust and compliance are critical.

CONCLUSION

This paper presents a blockchain-based architecture designed to enhance traceability, transparency, and security in food supply chain systems. By integrating IoT sensors, smart contracts, and a permissioned distributed ledger, the proposed framework enables real-time monitoring, tamper-proof data storage, and trustless automation of key supply chain processes. The system was evaluated using key performance metrics and benchmarking analysis, demonstrating superior accuracy, scalability, and automation capabilities when compared to recent state-of-the-art solutions. Despite these promising results, the current implementation is limited by its reliance on consistent internet connectivity and infrastructure, which may pose deployment challenges in rural or under-resourced environments. In future work, we plan to extend the system with lightweight consensus mechanisms and decentralized edge computing capabilities to improve scalability and accessibility. Additionally, incorporating machine learning models for predictive analytics and risk assessment could further enhance decision-making within the food logistics network. This research contributes toward building more resilient and transparent food systems, particularly in regions where food fraud and traceability remain critical challenges.

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