

“A Blockchain-Driven Traceability Framework for Transparent Food Supply Chains”

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Abstract - In the contemporary global market, the opacity of food supply chains has emerged as a significant challenge, leaving consumers with limited insight into the provenance and handling of their purchases. This research presents a robust traceability framework powered by blockchain technology, engineered to document the lifecycle of food products—from initial cultivation and industrial processing to logistics, storage, and retail. By utilizing a decentralized, immutable ledger, the proposed architecture ensures that all longitudinal data remains secure, verifiable, and resistant to unauthorized tampering.

The technical core of this system involves assigning each food batch a unique QR code that serves as a gateway to its digital twin on the blockchain. Throughout the supply chain, authorized stakeholders input data at specific milestones, which is then validated and archived through automated smart contracts. This allows consumers, regulatory bodies, and auditors to reconstruct the entire history of a product via a mobile or web interface, facilitating instant verification of origin and safety protocols. Developed using high-performance platforms such as Hyperledger Fabric or Polygon, the system prioritizes practical scalability and user experience. Ultimately, this study demonstrates how blockchain integration can mitigate food fraud, streamline recall procedures, and restore consumer confidence in the global food ecosystem.

Key Words: Blockchain, Food Supply Chain, QR Code, Hyperledger, Polygon.

1.INTRODUCTION

Modern food supply chains involve multiple stakeholders, including farmers, processors, distributors, retailers, and consumers. Although this multi-stage structure supports large-scale food distribution, it also creates significant challenges related to transparency, data integrity, and traceability. Consumers often have limited access to reliable information regarding the origin of food products, processing conditions, and handling practices during transportation and storage. This lack of visibility can result in issues such as food fraud, product mislabeling, delayed recall procedures, and reduced consumer trust.

With the globalization of food markets and increasing consumer awareness about food safety and quality, the need for an efficient and reliable traceability system has become more important than ever. Traditional food traceability systems are generally centralized and rely heavily on manual record-keeping or isolated digital databases. Such systems are vulnerable to data manipulation, unauthorized access, and single points of failure. Furthermore, inconsistent information sharing among supply chain participants makes it difficult to identify contamination sources or verify product authenticity quickly and accurately.

In recent years, blockchain technology has emerged as a promising solution to overcome these limitations. Blockchain is a decentralized and immutable digital ledger that enables secure and transparent data sharing among multiple parties without the need for a central authority. Once data is recorded on the blockchain, it cannot be modified or deleted, thereby

ensuring data integrity, security, and accountability. In addition, smart contracts can automate validation processes and enforce predefined rules, reducing human intervention and minimizing operational errors.

In the context of food supply chain management, blockchain technology can significantly improve traceability by recording critical events such as harvesting, processing, transportation, storage, and retail delivery on a distributed ledger. This creates a verified and tamper-resistant history of food products throughout the supply chain. Moreover, the integration of QR codes enables consumers and regulatory authorities to easily access product information through mobile or web-based applications, thereby enhancing transparency and supporting informed decision-making.

This paper proposes a blockchain-based food traceability framework designed to provide end-to-end visibility across the food supply chain. The proposed system focuses on securely recording product information at every stage of the supply chain while ensuring usability for both supply chain participants and end users. The remainder of this paper is organized as follows: Section II reviews related work in food traceability and blockchain applications; Section III describes the proposed system architecture and methodology; Section IV discusses the benefits and analysis of the system; and Section V concludes the paper with future research directions.

2. LITERATURE SURVEY:

Food traceability has become an increasingly important topic in recent research due to growing public concern regarding food safety, product quality, and authenticity. Traditional food supply chains mainly rely on centralized databases and manual record-keeping methods to store and manage product information. Although these systems support basic information management, they are often criticized for their limited transparency, vulnerability to data manipulation, delays in information sharing, and difficulties in accurately tracing contamination sources. These limitations make it challenging for consumers and regulatory authorities to verify the origin, quality, and handling history of food products effectively.

To overcome these challenges, numerous studies have explored the use of blockchain technology in food

supply chain management. Blockchain provides a decentralized and tamper-resistant platform where recorded data cannot be modified or deleted once stored. Research findings consistently indicate that blockchain technology improves data integrity, transparency, and trust among supply chain stakeholders. In most proposed frameworks, blockchain is used to record important events such as harvesting, processing, transportation, storage, and retail distribution, ensuring that all participants have access to the same reliable and verified information.

Several research works have focused on permissioned blockchain platforms, particularly Hyperledger Fabric, which offer controlled access, enhanced security, and improved privacy for supply chain participants. These platforms are especially suitable for consortium-based environments where farmers, processors, distributors, and retailers collaborate under predefined governance policies. On the other hand, some studies have investigated public blockchain platforms such as Ethereum to achieve greater decentralization and transparency. However, public blockchains often face challenges related to scalability, transaction costs, and data privacy.

Literature also emphasizes the integration of blockchain with complementary technologies such as QR codes, RFID tags, and IoT sensors to connect physical food products with their digital records. Among these technologies, QR code-based systems have gained significant popularity because of their low implementation cost and ease of use. Consumers can quickly access detailed product information, including origin, processing history, and transportation details, simply by scanning a QR code using a mobile device. Nevertheless, several studies highlight that many existing systems focus primarily on technical architecture while neglecting user-friendly interfaces and practical usability.

Despite the considerable progress reported in recent research, several challenges remain unresolved. One major issue is data authenticity, as blockchain technology can secure stored data but cannot guarantee the accuracy of the information entered initially. In addition, integrating blockchain systems with existing supply chain infrastructures and encouraging participation from small-scale producers continue to be difficult tasks. Many blockchain-based food traceability models presented in the literature remain conceptual or prototype-based, with limited

research addressing large-scale real-world implementation and adoption.

3. METHODOLOGY:

This research embraces a System Development Life Cycle (SDLC) framework uniquely tailored for the dynamic realm of blockchain technology. Our primary goal is to seamlessly bridge the gap between the tangible movement of food products and the unwavering integrity of digital data through an innovative, multi-stage development journey.

3.1 Stakeholder Mapping and Requirement Specification

The proposed system begins with clearly defining the boundaries of the food supply chain ecosystem by identifying three major categories of stakeholders: upstream participants, including farmers and producers; midstream participants, such as processors and logistics providers; and downstream participants, including retailers and consumers. This classification helps in understanding the specific roles and responsibilities of each stakeholder within the supply chain. The primary functional objective of the system is to develop a reliable mechanism for tracking product provenance while ensuring the immutability and integrity of recorded data logs. In addition to functional requirements, important technical constraints are also considered during the design process. Key performance benchmarks, such as system throughput measured in transactions per second and network latency, are established to ensure that the blockchain platform can efficiently handle the high-frequency data generated throughout logistics and supply chain operations.

3.2 Multi-Layered System Architecture

The proposed system architecture is designed as a modular and multi-layered framework to ensure high maintainability, scalability, and flexibility. The perception layer is responsible for collecting and entering data into the system through advanced IoT sensors and QR code scanning technologies, enabling seamless and accurate data acquisition from different stages of the food supply chain. The network or blockchain layer utilizes a permissioned consortium blockchain platform, such as Hyperledger Fabric, where only verified and authorized participants are allowed to take part in the consensus process, thereby enhancing trust, security, and collaboration among

stakeholders. The contract layer contains the core business logic of the system and operates through smart contracts that automate validation processes, transaction execution, and compliance with predefined rules. Finally, the presentation layer provides stakeholders with an intuitive and user-friendly front-end dashboard through which they can monitor product information, access traceability records, and make informed decisions efficiently.

3.3 Digitization assets (Tokenization)

To create a cohesive link between the physical and digital realms, each product batch transforms into a Digital Twin. A distinct cryptographic identifier, embedded within a QR code, acts as the "Primary Key" within the distributed ledger, effectively connecting physical movements to digital timestamps.

3.4 Data Automated Ingestion and Smart Contract Logic

Unlike traditional systems that depend heavily on manual data entry, the proposed system utilizes smart contracts as autonomous mechanisms for managing and validating data within the blockchain network. Smart contracts automatically enforce predefined validation rules before any information is recorded on the blockchain, thereby ensuring greater accuracy, consistency, and reliability of the stored data. For example, environmental conditions such as temperature readings during transportation and storage must remain within specified thresholds before the transaction is accepted into the system. Furthermore, all transactions are verified through a consensus mechanism involving multiple blockchain nodes. This distributed verification process prevents any single participant from altering or manipulating the origin, status, or history of food products, thereby enhancing transparency, trust, and data integrity throughout the supply chain.

3.5 Role-Based Access Control (RBAC) and Security

The proposed system incorporates a dual-layered security approach to ensure the protection, integrity, and reliability of supply chain data. The first layer focuses on on-chain security, where advanced

cryptographic hashing algorithms are used to secure blockchain records. Once data is recorded on the blockchain, it becomes immutable and cannot be altered or deleted, thereby maintaining the integrity and authenticity of the information throughout the product lifecycle. The second layer involves access management through Role-Based Access Control (RBAC). This mechanism assigns different levels of access permission to stakeholders based on their roles within the supply chain. Consumers are permitted to view product histories and traceability information, while data verification and input privileges are restricted to authorized producers, regulators, and certified participants. This controlled access structure enhances security, accountability, and quality control across the system.

3.6 System Prototyping and UI Design

The user interface is meticulously designed to align with user intent. The Operational Interface is optimized for rapid data entry by warehouse personnel, while the Consumer Interface presents an engaging and simplified visualization of the "Product Journey," evoked by a quick mobile scan.

3.7 Stress Testing and Comparative Analysis

The final phase of the proposed system involves extensive evaluation and testing across two critical dimensions: system performance and traceability efficiency. System stress testing is conducted to analyze the blockchain network's ability to handle increasing transaction volumes and maintain stable performance under high operational loads. This ensures that the system remains reliable, scalable, and resilient in real-world supply chain environments. In addition, traceability efficiency is evaluated through a mock recall process, where the time required to identify and trace a contaminated food batch is measured and compared with traditional paper-based and centralized database systems. The results help assess the effectiveness of the proposed blockchain framework in improving response time and supply chain transparency. Overall, this comprehensive and structured approach enhances the reliability, security, and transparency of food supply chains while demonstrating the potential of blockchain technology to play a significant role in ensuring food safety, quality, and integrity in the future.

4. Specifications

The proposed framework establishes a unified digital ecosystem designed to provide complete visibility across the entire food supply chain, from initial production to final retail delivery. By utilizing a decentralized blockchain ledger, the system records every logistical event in a chronological and tamper-proof manner. The framework primarily employs a permissioned or hybrid blockchain platform, such as Hyperledger Fabric or Polygon, selected for their enterprise-level performance, high transaction throughput, and low latency. This infrastructure supports a consortium-based model in which all authorized participants share a common and verified version of information while sensitive business data remains protected through cryptographic security mechanisms. Unlike traditional centralized databases, the immutable nature of blockchain ensures that once information is validated and recorded, it becomes a permanent part of the audit trail. This feature significantly strengthens trust among producers, regulators, distributors, retailers, and consumers.

The operational functionality of the system is driven by smart contracts, which act as autonomous protocols responsible for managing data validation, integrity, and access control. These programmable contracts enforce predefined business rules and ensure that data is recorded on the blockchain only when it originates from authorized sources and satisfies specified quality standards. Through automated verification and validation, the system minimizes the risk of human error, fraud, and intentional data manipulation. To efficiently manage the large volume of data generated within modern supply chain operations, the framework adopts hybrid storage architecture. Critical transaction metadata and cryptographic hashes are stored securely on the blockchain for verification purposes, while larger files such as compliance certificates, inspection reports, and high-resolution images are maintained in secure off-chain storage systems. This dual-storage approach improves system scalability and performance while preserving the ability to verify the authenticity and integrity of every document using its digital fingerprint.

The connection between physical food products and their corresponding digital records is maintained through a unique digital twin identity assigned to each product batch. This identity is represented through a QR code generated at the point of origin and remains

associated with the product throughout its lifecycle. The QR code serves as a gateway for real-time data entry, tracking, and retrieval at every stage of the supply chain. At the user level, the framework provides specialized interfaces tailored to the requirements of different stakeholders. Producers and supply chain operators interact with a comprehensive management dashboard for recording and monitoring product data, while consumers and regulatory inspectors use a simplified mobile or web-based application to instantly access verified product provenance and traceability information through QR code scanning.

By replacing isolated and centralized databases with a distributed blockchain architecture, the proposed framework eliminates single points of failure and enhances resilience against cyber threats, unauthorized modifications, and data loss. Furthermore, the system offers a scalable and standardized solution capable of supporting global food safety regulations and industry standards. Overall, the framework promotes greater transparency, accountability, security, and trust within the food supply chain ecosystem, thereby contributing to improved food safety and consumer confidence in the global food trade.

5 PROPOSED FRAMEWORK

The architecture of the proposed system is designed to establish seamless synchronization between physical food logistics and a digital monitoring layer, thereby creating a transparent, secure, and accountable food supply chain ecosystem. By connecting real-world supply chain activities with a decentralized blockchain ledger, the framework ensures that data is not only stored securely but also continuously verified through distributed consensus mechanisms. This approach replaces traditional isolated information systems with a shared and trusted source of information that records the complete journey of food products, from their origin at the production stage through processing, transportation, storage, and finally to consumer delivery.

At the core of the framework is a distributed blockchain network that maintains a permanent and chronological registry of all supply chain events. The process begins with asset digitization, where each food batch is assigned a unique cryptographic identity, commonly referred to as a digital twin. This digital identity acts as the foundation for storing and linking

all related information, including processing activities, transportation conditions, cold-chain monitoring, storage durations, and delivery records. By integrating these events into a unified blockchain ledger, the system enables complete provenance reconstruction, allowing stakeholders to trace and audit the entire lifecycle of a product accurately and efficiently. Furthermore, the decentralized nature of blockchain eliminates dependency on a single centralized authority, thereby reducing the risk of loss, manipulation, or system failure.

The governance and validation of digital transactions within the framework are managed through autonomous smart contracts, which function as the logical backbone of the system. These programmable contracts automatically enforce predefined validation rules and role-based permissions for every transaction and data entry operation. Information is permanently recorded on the blockchain only after the smart contract verifies that the participant possesses the necessary authorization and that the submitted data satisfies predefined safety, operational, and quality standards. This automated validation mechanism significantly reduces the trust gap commonly associated with manual reporting processes and minimizes the risks of human error, fraud, and data tampering during high-frequency logistics operations.

To support real-time interaction and accessibility, the framework incorporates a QR code-integrated portal system that bridges the connection between physical food products and their corresponding digital records. Each product batch carries a unique QR code that can be scanned through mobile or web-based applications to instantly retrieve cryptographically verified information stored on the blockchain. This feature enables consumers, retailers, and regulatory authorities to access real-time details regarding product origin, handling conditions, certifications, and compliance status. At the same time, the framework follows a privacy-by-design approach by utilizing a permissioned or hybrid blockchain model, such as Hyperledger Fabric or Polygon. This approach ensures that while transparency is maintained for relevant stakeholders, sensitive operational and business data remains accessible only to authorized entities through secure role-based access control mechanisms.

Overall, the proposed architecture provides a scalable, resilient, and highly transparent solution for modern food supply chain management. By integrating

blockchain technology, smart contracts, QR code systems, and secure access control mechanisms, the framework enhances traceability, data integrity, accountability, and consumer trust while supporting compliance with global food safety standards and regulations.

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7. CONCLUSION:

This study introduces a ground breaking architecture that enhances transparency and accountability within global food networks. By connecting the physical supply chain movements to a decentralized digital ledger, the framework establishes a lasting, chronological record of a product's journey. The innovative use of cryptographic batch identification through QR codes ensures that every transition—from raw material sourcing to final retail is captured in an immutable format, effectively reducing the risks associated with data silos and outdated manual logging.

The system's strength lies in its dual-layer security and automation strategy. Smart contracts replace human oversight with autonomous enforcement, committing only data that meets stringent validation criteria. This automation preserves information integrity and accelerates response times during food safety emergencies, enabling nearly instantaneous trace-backs and targeted recalls that protect public health.

Additionally, the design balances public transparency with corporate data privacy. Using a permissioned or hybrid blockchain structure, along with role-based access controls, the framework allows for a "tiered disclosure" model, empowering consumers with verified provenance data while safeguarding sensitive operational details.

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