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Blockchain for Transparency and Traceability in Agri-food supply chain

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ABSTRACT

Transparency and traceability remain major challenges in conventional agri-food supply chains due to fragmented information flow, manual record keeping, centralized data storage, and limited stakeholder accountability, leading to risks such as food adulteration, data tampering, delayed recalls, and reduced consumer trust. This paper proposes a blockchain-based transparency and traceability framework that securely records supply-chain events on a decentralized and immutable ledger, covering production, inspection, processing, transportation, and distribution stages. Smart contracts automate data validation and enforce business rules, while QR code–based product identification enables stakeholders and consumers to access complete product provenance in real time. Experimental evaluation indicates that the proposed system improves data integrity, tamper resistance, and traceability accuracy compared to traditional centralized approaches, demonstrating its suitability for practical deployment in modern agri-food supply chains.

INDEX TERMS INTRODUCTION, RELATED WORK, SYSTEM ARCHITECTURE OVERVIEW, IMPLEMENTATION, RESULTS, CONCLUSION AND FUTURE WORK.

1. INTRODUCTION

The agri-food supply chain plays a critical role in ensuring food safety, quality, and availability. However, most existing agri-food systems rely on manual documentation and centralized databases, which are vulnerable to data tampering, errors, and lack of transparency. Consumers often have limited knowledge about the origin, quality, and handling process of the food products they purchase, leading to reduced trust.
With increasing cases of food fraud, adulteration, and supply-chain inefficiencies, there is a strong need for a secure and transparent tracking mechanism. Blockchain technology has emerged as a promising solution due to its decentralized nature, immutability, and secure data-sharing capabilities. By recording supply-chain events on a distributed ledger, blockchain ensures that once data is stored, it cannot be altered without network consensus. The proposed project introduces a blockchain-based system that records every agri-food transaction in a secure and transparent manner. The system eliminates dependency on intermediaries, improves data authenticity, and enables real-time traceability using QR-based identification. The simplicity and reliability of the system make it suitable for real-world agri-food applications.

2. RELATED WORKS

In recent years, the application of blockchain technology in agri-food supply chains has attracted considerable research interest due to growing concerns over food safety, traceability, and consumer trust. Researchers have explored blockchain as a means to overcome the limitations of traditional supply-chain systems, such as data silos, lack of transparency, and susceptibility to fraud.

Early research on blockchain-based food traceability systems concentrated on recording product origin, transaction history, and ownership transfer in an immutable ledger. Tian et al. (2017) proposed a blockchain-based food safety system that enhanced traceability by ensuring tamper-proof storage of food production and inspection data. While the system improved data integrity, it offered limited support for direct consumer interaction and real-time accessibility.
Similarly, Caro et al. (2018) introduced a blockchain framework for agricultural supply chains aimed at improving transparency and trust among stakeholders. Their approach demonstrated the feasibility of

decentralized traceability but highlighted challenges related to scalability, data storage overhead, and integration with existing supply-chain infrastructure. Other studies have explored blockchain platforms such as Ethereum and Hyperledger for tracking food products; however, many of these solutions remain at a conceptual or prototype level, with limited validation in real-world agricultural settings. Overall, existing blockchain-based traceability systems successfully address data immutability and provenance tracking but often fall short in terms of usability, scalability, and consumer-facing accessibility.

Smart contracts have been widely studied as a mechanism to automate and enforce supply-chain operations, including compliance verification, quality assurance, access control, and payment settlement. By encoding predefined rules into executable contracts, these systems reduce reliance on intermediaries and minimize human intervention. Several researchers have demonstrated that smart contracts can improve efficiency and trust by automatically validating transactions and enforcing regulatory requirements. However, many smart contract–enabled supply-chain solutions are complex, resource-intensive, and difficult to deploy, particularly in small-scale or resource-constrained agricultural environments.

Despite the advantages offered by blockchain-based solutions, most existing systems suffer from high implementation costs, scalability constraints, lack of real-world deployment, and minimal consumer engagement.

3. SYSTEM ARCHITECTURE OVERVIEW

The proposed blockchain-based agri-food traceability system follows a layered and modular architecture to ensure security, transparency, scalability, and interoperability among multiple stakeholders. The architecture separates concerns across different layers, allowing independent development, maintenance, and future enhancements. This structured approach improves system robustness while enabling seamless integration between user interfaces, application logic, blockchain infrastructure, and data storage mechanisms.

FIGURE 1. Architecture of Blockchain-Enabled Agri-Food Supply Chain

The User Interface (UI) Layer serves as the primary interaction point between the system and its users. It provides web-based access for supply-chain stakeholders such as farmers, processors, distributors, retailers, and administrators. Each user interacts with role-specific dashboards that allow them to perform authorized operations, including product registration, process updates, and transaction verification.

For consumers, the UI layer enables QR code–based access through mobile devices. By scanning the QR code attached to an agri-food product, consumers can instantly view verified product information retrieved from the blockchain.

The UI layer is designed to be intuitive and responsive, ensuring ease of use for both technical and non-technical users while maintaining secure communication with the application layer.

The Application Layer acts as the logical backbone of the system, handling core business operations and enforcing system rules. This layer manages user authentication, role-based access control, input validation, and transaction processing. It ensures that only authorized users can submit data and that all submitted information adheres to predefined validation rules.

Additionally, the application layer facilitates interaction with smart contracts deployed on the blockchain. It prepares transaction data, invokes smart contract functions, and processes responses returned from the blockchain network. By abstracting blockchain complexity from the UI layer, this layer improves system maintainability and allows future upgrades without impacting end users.

The Blockchain Layer provides a decentralized and immutable ledger for recording all critical agri-food supply-chain events. Each transaction is cryptographically secured and linked to previous records using hash values, ensuring data integrity and tamper resistance.

Smart contracts deployed within this layer define the rules and conditions for data submission, verification, and access. Once validated and recorded, blockchain entries cannot be altered or deleted without consensus from the network. This layer eliminates reliance on centralized authorities and establishes trust among stakeholders by ensuring transparent and verifiable recordkeeping throughout the supply chain.

The Database and Storage Layer is responsible for managing off-chain data storage to address scalability and performance limitations associated with on-chain storage. Large or non-critical data—such as images, certificates, and detailed reports.

To maintain data integrity, a cryptographic hash of each off-chain record is generated and stored on the blockchain. During data retrieval, the system recalculates the hash and compares it with the blockchain-stored hash to verify authenticity. Any mismatch indicates data tampering. This hybrid storage approach balances efficiency with security while preserving blockchain-based trust guarantees.

4. IMPLEMENTATION

The proposed system is implemented using a modular architecture to ensure scalability, security, and maintainability. Each module operates independently while seamlessly integrating with the blockchain network. The implementation emphasizes data integrity, controlled access, and transparent traceability across the agri-food supply chain. All critical transactions are recorded on the blockchain to prevent unauthorized modification and to ensure end-to-end visibility for all stakeholders.

The User Authentication Module is responsible for verifying the identity of all stakeholders participating in the system, including farmers, processors, distributors, retailers, and administrators. Secure login credentials are provided to each user based on their role.

Role-Based Access Control (RBAC) is implemented to restrict system operations according to user privileges. For example, farmers can register product origin data, processors can update processing details, and distributors can add transportation records. Unauthorized users are prevented from accessing restricted functionalities. Passwords are stored in encrypted form to protect against credential theft, ensuring a secure and reliable authentication mechanism.

The Product Registration Module enables the entry of essential product information at the source level. This includes product name, origin location, batch number, production date, and quality parameters.

Each product batch is assigned a unique identifier to distinguish it throughout the supply chain.

Once registered, the product details are converted into a blockchain transaction and permanently recorded. This ensures that the origin data cannot be altered or deleted at later stages. The module establishes the foundation for complete traceability by linking all subsequent supply-chain events to the original product registration.

The Blockchain Transaction Module forms the core of the system by maintaining an immutable ledger of all supply-chain events. Every transaction—such as harvesting, processing, packaging, transportation, and delivery—is recorded as a new block or blockchain entry.

Each block contains the transaction data, timestamp, cryptographic hash, and the hash of the previous block. This chaining mechanism ensures data integrity and tamper resistance. Any attempt to modify stored records results in a hash mismatch, immediately revealing data manipulation. The decentralized nature of blockchain eliminates reliance on a central authority and enhances trust among stakeholders.

The QR Code Generation and Tracking Module provides an interface for consumers and stakeholders to verify product authenticity and history. A unique QR code is generated for each product batch after successful registration on the blockchain.

By scanning the QR code using a mobile device, users can access complete product information, including origin, processing stages, transportation details, and timestamps. The retrieved data is fetched directly from the blockchain, ensuring accuracy and transparency.

This module improves consumer trust by enabling instant verification of agri-food products without requiring specialized technical knowledge.

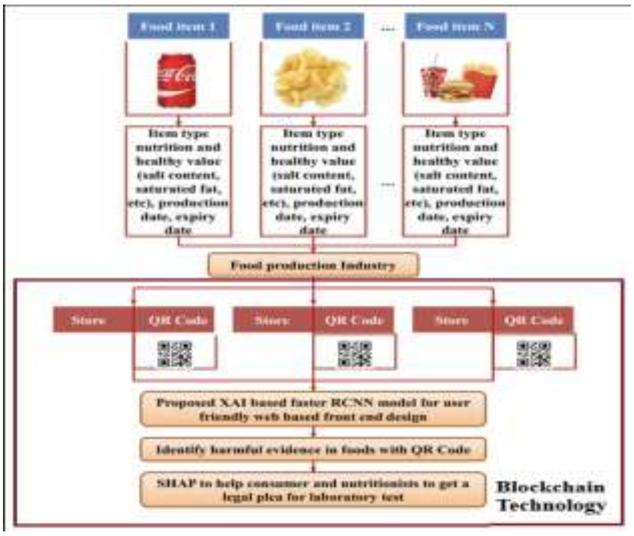

FIGURE 1. QR Code–Enabled Blockchain Framework for Food Item Traceability and Consumer Safety Analysis

5. RESULTS

The proposed blockchain-based agri-food traceability system was successfully implemented and evaluated to assess its effectiveness in ensuring transparency, security, and data integrity. The results demonstrate that the system provides reliable end-to-end traceability while preventing unauthorized data modification. All functional modules operated as intended under controlled testing conditions.

The system successfully recorded and displayed complete product histories across all stages of the agri-food supply chain. Each product batch was uniquely identified and linked to its corresponding blockchain transactions, enabling accurate retrieval of origin, processing, transportation, and distribution details.

Upon scanning the generated QR code, users were able to access verified product information in real time. The retrieved data was consistent with the records stored on the blockchain, confirming the correctness of transaction logging and traceability mechanisms. No data inconsistencies were observed during repeated retrieval tests.

Performance analysis showed that blockchain transactions were executed and stored without data loss or duplication. Transaction confirmation times remained within acceptable limits for supply-chain operations, indicating the system's suitability for real-world usage.

Security evaluation focused on data integrity and tamper resistance. Any attempt to modify stored records—either in the database or during transmission—resulted in a cryptographic hash mismatch when verified against the blockchain. These mismatches were immediately detected by the system, confirming the effectiveness of blockchain-based immutability and hash verification in preventing undetected data tampering.

User evaluation was conducted with stakeholders representing different roles in the supply chain. Participants reported improved confidence in product authenticity due to the availability of transparent and verifiable product histories. The role-based dashboards were found to be intuitive, and the QR code–based verification process was considered simple and efficient by consumers.

Overall feedback indicated enhanced trust, improved usability, and increased acceptance of blockchain-based traceability compared to traditional centralized systems.

6. CONCLUSION AND FUTURE WORK

This work presented a blockchain-based system for enhancing transparency and traceability in agri-food supply chains. By integrating role-based access control, immutable blockchain transactions, QR code–enabled consumer verification, and hash-based tamper detection, the proposed system addresses critical challenges associated with data integrity, trust, and accountability in traditional supply-chain models.

The implementation demonstrates that blockchain technology can effectively prevent unauthorized data modification while providing end-to-end visibility of product history. Off-chain storage combined with on-chain hash verification ensures scalability without compromising security. Experimental results confirm reliable traceability, tamper resistance, and improved user confidence, validating the suitability of the proposed approach for real-world agri-food applications.

Overall, the system establishes a secure and transparent framework that strengthens trust among stakeholders and empowers consumers with verifiable product information. The proposed architecture can serve as a foundation for future advancements in digital supply-chain management.

Although the proposed system demonstrates effective transparency and traceability, several enhancements can further improve its functionality and real-world applicability. One major extension involves the integration of Internet of Things (IoT) devices such as temperature, humidity, and location sensors. These devices can enable automated and real-time data capture during storage and transportation, reducing manual input errors and improving data reliability.

Advanced data analytics and machine learning techniques can be incorporated to analyze historical supply-chain data for quality prediction, demand forecasting, and anomaly detection. Such insights can support proactive decision-making, reduce wastage, and improve operational efficiency across the agri-food ecosystem.

Interoperability with existing enterprise systems and cross-platform blockchain networks represents another important direction for future development. Supporting standardized data formats and multiple blockchain frameworks can facilitate broader adoption and seamless information exchange among heterogeneous supply-chain participants. These enhancements will strengthen scalability, adaptability, and long-term sustainability of the proposed traceability system.

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