



TraceRoot: A Blockchain-Based Traceability Framework for Enhancing Transparency and Trust in Rice and Essential Goods Supply Chain

Md. Safaet Hossain¹, Mohammad Shakibul Hasan Sakib², Md. Rayhan Ahmed Shis^{3*}, Md. Sakib Ahmed⁴, Md. Fudail⁵

¹ Associate Professor. Department of Computer Science and Engineering. Director, IQAC, University of Information Technology and Sciences, Bangladesh

²³⁴⁵ Department of Computer Science and Engineering. University of Information Technology and Sciences. Bangladesh

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ABSTRACT

Modern food supply chains, particularly those involving essential commodities like rice, often suffer from major challenges such as product fraud, inefficient record-keeping, and a lack of consumer trust. Traditional centralized systems are prone to data tampering, limited transparency, and poor traceability, making it difficult to verify the authenticity and origin of goods. To address these issues, our research introduces TraceRoot, a blockchain-based traceability framework designed to enhance transparency, accountability, and trust in agricultural supply chains. TraceRoot leverages the immutability and decentralization of blockchain technology to maintain a secure, distributed ledger that records every transaction and movement of goods across the supply chain. Each stakeholder including farmers, distributors, retailers, and consumers has role-based access to authenticated data through a user-friendly interface. The framework integrates smart contracts to automate transactions and digital signatures to verify the integrity of the data being uploaded, minimizing the risk of human error or manipulation

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* Corresponding author: sakibulh13345@gmail.com

INTRODUCTION

The global agri-food supply chain faces significant challenges, including food adulteration, data manipulation, and insufficient transparency. To address these issues, this study presents TraceRoot, a blockchain-based framework engineered to enhance traceability and accountability within rice and essential goods supply chains. Leveraging the decentralized

and immutable characteristics of blockchain technology serves to bolster trust and mitigate fraud. Fundamentally, blockchain functions as both a data repository and a secure transaction ledger; each block comprises a series of validated transactions, which, upon completion, are integrated into a permanent, cryptographically linked chain, facilitating the secure exchange of assets and contracts as a distributed software protocol.

This research was specifically developed to bridge critical practical gaps identified in existing literature. An optimized single-blockchain architecture was selected to avoid the excessive costs and deployment complexities associated with multi-blockchain systems (Peng et al., 2022), thereby ensuring economic viability for local deployment. This framework extends beyond general supervision models (Rashid et al., 2024) by integrating mandatory digital signatures, ensuring that accountability is cryptographically guaranteed for every record entry. Furthermore, a customizable Smart Contract framework was designed to align with local stakeholder requirements, facilitating a user-friendly implementation that reconciles policy frameworks with grassroots agricultural practices (Awaludin et.al., 2025). Additionally, end-to-end visibility is provided via QR codes and mobile applications to enable instant consumer verification. Finally, the blockchain storage paradox is addressed through a Hybrid Model, which offers a more practical approach for managing massive supply chain data compared to full on-chain storage (Rashid et al., 2024). The subsequent section presents a comparative analysis of related literature.

Table 1: Comparison with Related Work

Feature	TraceRoot (Our Project)	(Peng et al., 2022)	(Farooq et al., 2023)	(Rashid et al., 2024)
Architecture	Permissioned (Hyperledger Fabric)	Multi-Blockchain (Complex)	Single/Hybrid Framework	Single, Practical Application
Core Security	Digital Signatures + Validation Logic	Data Isolation	Sensor Data Hashing (Conceptual)	Multi-Party Governance
Scalability/ Cost	High (Targeting L2/Permissioned)	Low (Expensive)	Moderate-High (Data Volume)	Moderate
Primary Focus	Authenticity & Grassroots Adoption	Regulatory Oversight	Framework & Reliability	Fair Pricing & Traceability
Storage Model	Hybrid (On-chain Hash + Off-chain RDB)	Multi-mode (Chain + Sub-Chain + Cloud)	Centralized/Off-chain for full data	On-chain storage of all data

Agricultural producers face significant occupational challenges, as highlighted in Ref. (Hegde et al., 2020). A primary issue is the proliferation of intermediaries, which facilitates the dissemination of misinformation and leads to economic losses. Traditional supply chain structures, reliant on such intermediaries, exhibit inherent deficiencies in transparency, accountability, and auditability (Shahid et al., 2020). These conventional systems undermine stakeholder trust and impede efficient supply chain management (Abdullayev et.al, 2025; Mulyana et.al., 2024; Rochim et.al., 2024; Aufo et.al., 2024; Ismail et.al., 2024).

Blockchain technology offers a viable solution to these systemic issues. As an immutable, tamper-evident ledger, it fosters transparency and decentralization in data exchange (Hegde et al., 2020). Integrating this technology into the agricultural sector enhances food product traceability, aligning stakeholders—from producers to consumers—within a unified system for managing ownership and scalability. This paradigm is poised to revolutionize e-commerce, facilitate startup growth, and improve the accessibility of agri-food

products (Demestichas et al., 2020). Baralla et al. (Baralla et al., 2019) developed a blockchain-based traceability system utilizing Hyperledger Sawtooth, focused on the "farm-to-fork" model currently implemented in the European Union; their system enables consumers to trace product provenance and verify quality via QR codes while restricting access through a permissioned membership model. Cocco et al. (Cocco et al., 2021) examined the use of Self-Sovereign Identity combined with blockchain and the Interplanetary File System to manage food certifications in a decentralized manner, ensuring compliance with technical standards through Ethereum. Additionally, Cocco et al. (Cocco et al., 2021) presented a case study employing blockchain and IoT to ensure the traceability of the Carasau bread supply chain in Italy, utilizing RFID tags and sensors to automate data collection and mitigate data tampering risks.

Smart contracts extend blockchain capabilities by automating transactions and enforcing agreements without the necessity for intermediaries, enabling parties without established trust to engage in secure transactions (Hegde et al., 2020). Within agricultural supply chains, Ref. (Shahid et al., 2020) advocates for utilizing the Ethereum blockchain to develop traceability systems and smart contracts, facilitating transaction recording and data storage on the Interplanetary File System. A novel methodology introduced in Ref. (Marchesi et al., 2022) expedites the creation and customization of Ethereum-based smart contracts for the agri-food industry, supporting modular code reuse to reduce development time while maintaining security standards. The objective is to implement a semi-automated system capable of generating user interfaces for interacting with smart contracts. Furthermore, Prashar et al. (Prashar et al., 2020) proposed a blockchain-based system that eliminates reliance on intermediaries, utilizing smart contracts to manage transactions and ensure a cost-effective, secure traceability process; the system achieved a throughput of 161 transactions per second, demonstrating its efficacy in ensuring food safety in India.

The TraceRoot framework leverages smart contracts implemented as Hyperledger Fabric Chaincode to enforce operational rules and validate product movement. For example, when Farmer Sultana transfers 200 kg of paddy, the Chaincode initiates sequence verification by mandating a digital signature to authenticate identity and the transfer activity. Following successful authentication, the system records the transaction with a timestamp and geolocation data, ensuring the transfer remains traceable and transparent. This procedure fosters participant confidence by systematically recording every transactional stage.

1. The Core Asset Model

The smart contract utilizes two data types on the ledger to track the lifecycle of critical goods:

- a. Product Batch Registration: This functions as a "birth certificate" for a batch, storing the productId, issuer identity, creation timestamp, initial geolocation coordinates, and metadataHash.
- b. Historical Event Tracking: These are the "historical footprints" generated as the product circulates. Each event is tagged with a composite key comprising the productId and timestamp, recording the event type, the actor's unique identifier, and the relevant physical coordinates.

2. Functional Operations

The smart contract manages the ledger through specific functions invocable only by authorized parties via the API gateway:

- a. Asset Creation: This function initializes a new product on the blockchain, requiring a cryptographic signature from the farmer to link the physical crop to a digital identity.

- b. State Transition: This function is invoked when the product changes ownership or status; the contract logic employs sequence validation to ensure events follow a logical chronological order.
- c. Auditability: This allows for immediate auditing. By querying a productId, the contract retrieves all state changes recorded on the ledger, providing consumers with a verifiable farm-to-table chronology.

3. Hybrid Data Strategy

The contract handles extensive datasets via a hybrid approach. Rather than storing large files—such as quality certificates or high-resolution images—directly on the blockchain, this contract facilitates off-chain storage. It includes a SHA256 metadataHash, while comprehensive details are preserved in a relational MongoDB database. The smart contract retains the digital fingerprint; should any off-chain data be altered, the hash will fail to match, signaling a compromise in integrity.

4. Enforcement and Security

The smart contract acts as a proactive security layer. Validation logic identifies 100% of tested fraudulent transactions, such as unauthorized role-based actions. The contract's internal rules reject invalid inputs and inconsistent dates during review. Furthermore, the contract utilizes coordinates from the Browser Geolocation API to establish a durable link between the digital transaction and the physical location of the products. Regarding non-repudiation, once a smart contract is signed and committed, the actorId and timestamp cannot be modified, preventing stakeholders from denying their involvement in a specific event. Consequently, the TraceRoot smart contract architecture evolves from a simple logging utility to a self-governing ecosystem that prioritizes transparency and accountability.

Issues such as rice adulteration, mislabeling, and inequitable pricing have significantly eroded consumer trust. Farmers frequently face reduced profitability due to opaque procedures. A transparent blockchain framework can empower local producers, improve governance, and bolster food safety. Blockchain provides a reliable mechanism to document every stage of the production and distribution process, facilitating the rapid identification and resolution of issues such as contamination or mislabeling. Furthermore, regulatory bodies and consumers can verify the safety and quality of food products, substantially enhancing food security. Real-time data provided by blockchain technology supports improved planning and response to supply chain disruptions—a resilience crucial for maintaining a stable food supply, particularly during natural disasters or market volatility (Hassan, 2024).

This initiative aims to establish a secure, efficient, and egalitarian supply chain ecosystem. Our objective is to enhance food security by addressing governance and accountability deficiencies within agricultural logistics using blockchain technology. The primary aims are:

- a. Economic Equality for Local Producers: Foster equitable conditions for local producers.
- b. Localized Adoption: Develop a single-blockchain supply chain model optimized for local adoption and efficiency, serving as a substitute for cost-prohibitive multi-chain alternatives.
- c. Data Authenticity: Implement cryptographic digital signatures and smart contracts to ensure data authenticity throughout the product's lifecycle.

- d. **Practical Viability:** Assess the solution's practical viability, emphasizing an intuitive User Experience to facilitate adoption by non-technical stakeholders, such as farmers and field workers.
- e. **Consumer Verification:** Demonstrate the system's ability to provide a rapid, verifiable, and consumer-facing product history via a simplified interface.

This project offers three distinct contributions:

- a. **Enhanced Accountability:** We propose a design where data authentication is a mandatory prerequisite for logging, providing a stronger cryptographic guarantee of accountability compared to the general supervision models discussed in existing literature (Rashid et al., 2024).
- b. **Scalable and Economical Framework:** Our system provides a scalable, single-blockchain framework that strategically avoids the complexity and high cost associated with multi-blockchain models (Peng et al., 2022), rendering it accessible and economically viable for national or regional deployment.
- c. **Accessible Decentralized Application:** We contribute a functional, simplified DApp interface, specifically addressing the critical adoption barriers faced by new technology in low-resource environments.

RESEARCH METHOD

TraceRoot was developed using an iterative Agile methodology, balancing the creation of robust, verifiable security mechanisms with an intuitive user experience. The system governs supply chain operations across four distinct stakeholder roles—Farmer, Supplier, Processor, and Retailer—each of whom is authenticated and granted specific permissions alongside defined data entry responsibilities. Access control is rigorously enforced through Next.js API routes and an integrated authentication framework.

TraceRoot adopts a three-tier architecture designed to optimize performance, security, and data immutability. A mobile-first web application serves as the primary interface for all stakeholders, facilitating both data input and traceability verification. The centralized Node.js/Next.js backend manages user authentication, data validation, and off-chain database interactions, serving as the trusted gateway to the blockchain network. Hyperledger Fabric is utilized for immutable transaction recording, while MongoDB facilitates the storage of voluminous, rich data.

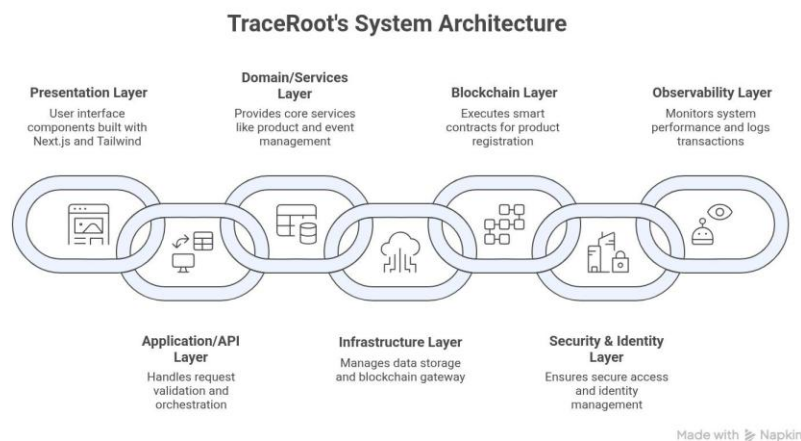


Figure 1: TraceRoot's System Architecture

Component Breakdown

1. TraceRoot Technology Stack:

The proposed architecture utilizes a hybrid data management strategy to balance security with operational efficiency. Hyperledger Fabric serves as the primary blockchain framework, providing a private, permissioned environment that ensures ledger immutability and enterprise-grade scalability. To complement the on-chain logic MongoDB is employed as an off-chain database to handle high-speed querying and complex user management tasks that would otherwise be computationally expensive on the ledger.

The user interface is built on Next.js 16 (App Router) and React 19, leveraging server-side rendering for optimal performance. The front-end is styled with Tailwind CSS to ensure a mobile-first, responsive experience. Furthermore, the system integrates the Browser Geolocation API to capture and timestamp verifiable coordinates, ensuring the geographical integrity of every recorded event.

2. Blockchain and Smart Contract Layer:

The Hyperledger Fabric platform was chosen due to its permitted framework, which is crucial for regulated businesses within supply chains. This permitted format guarantees adherence to regulations by restricting access solely to authorized individuals, thus safeguarding confidentiality and sensitive data. It also enhances the ability to conduct audits, facilitating the clear and secure validation of transactions.

The Smart Contract (Chaincode) Model identifies two primary assets: the Traceable Item and the Transaction Event. The Traceable Item is characterized by its unique product identifier and initial geographic location. It records the transfer of the product's state. Immutable fields include ProductId, eventType (for instance, Register, Transfer, Process), actorId, timestamp, necessary location (latitude, longitude, precision), and metadataHash (SHA256) for external data. The API Gateway creates and updates assets on the ledger by invoking chaincode functions (registerProduct, addEvent). The chaincode only keeps the necessary data to verify physical movement and its respective location.

3. Off-Chain API and Application Layer:

This layer, developed using Next.js, is designed to optimize performance, enhance usability, and ensure secure integration. The application employs a functional component architecture and leverages the browser's native Geolocation API to automatically capture coordinates upon submission, thereby associating the physical location with each transaction. Tailwind CSS is implemented to provide a highly responsive design compatible with both desktop and mobile devices. This architecture forms the transactional engine of TraceRoot. Upon user action submission, the API route initiates the following secure, sequential workflow:

The API confirms user authentication and authorization. It receives and validates the Geolocation data from the frontend. Rich product information to the MongoDB database, including a placeholder for the txId. The API generates a cryptographic hash of the newly saved MongoDB record's details to create the metadataHash. It then assembles the minimal canonical payload for Fabric. Submit the transaction via the Fabric Gateway and wait for block confirmation. The received immutable txId is used to update the corresponding record in MongoDB. This anchors the rich data to the blockchain, making it verifiable.

Implementation

The design of the system was established as a practical prototype to confirm the Hybrid Storage and Trusted Gateway concept. The execution was carried out in four main areas:

1. Network Structure and Chaincode

A multi-entity Hyperledger Fabric setup was initiated with Docker, including Certificate Authorities (CAs), Orderer nodes, and Peers that represent important participants (for instance, FarmerOrg and RetailerOrg). The smart contracts (Chaincode) delineate the framework for Product and SupplyChainEvent assets. The rules guarantee data integrity by requiring that later state modifications refer to earlier records while safeguarding unchangeable fields like metadataHash and geospatial coordinates.

2. Trusted Gateway and Dual-Storage Process

The integration component, constructed on Next.js, directs a synchronized two-phase commit mechanism between the off-chain MongoDB database and the on-chain ledger:

- a. Data Collection: The API captures event information along with geolocation verified by a browser.
- b. Off-chain Storage: Comprehensive records are authenticated and saved in MongoDB.
- c. Cryptographic Association: The system creates a SHA256 hash of the MongoDB entry and sends it, together with the geolocation data, to the Fabric network.
- d. Finalization: Once the transaction is verified, the resulting txId is added to the MongoDB entry, creating a verifiable connection between the two tiers.

3. Frontend and Verification Interface

A mobile-friendly React interface was created to enhance user engagement. This incorporates a dedicated registration module equipped with automated geolocation gathering and a Traceability Lookup function. By scanning a product's QR code, users can access the entire supply chain record from MongoDB, where each event features a direct link for cryptographic verification through a blockchain explorer.

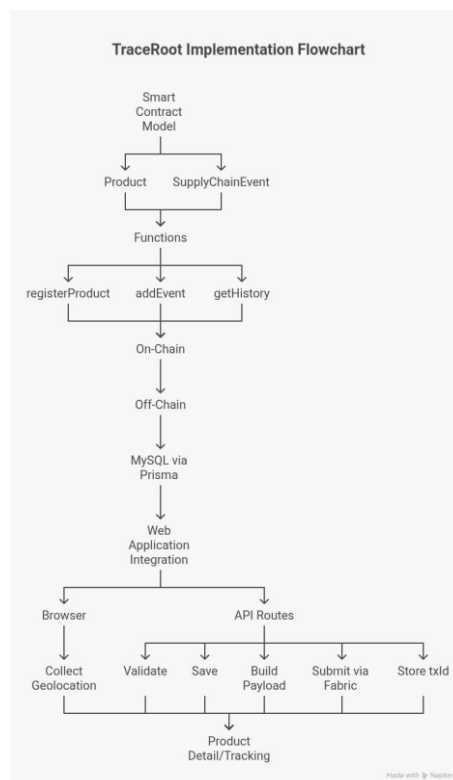


Figure 2: TraceRoot System Implementation Workflow

a. TraceRoot Features

To provide safe and context-aware user experiences, the developed platform uses a multi-role routing design. Once authorized, the system automatically guides users to specialized dashboards ranging from administrative overviews to particular interfaces for consumers, retailers, distributors, and farmers while keeping a constant loading state to guarantee seamless state changes.

The product onboarding module is only accessible to certified farmers in order to preserve data integrity at the source. Critical metadata recorded by this module include harvest dates and geographical provenance protected by multi-layer guardrails that confirm identity and certification status. The system uses gated visibility; guest users see high-level marketing content, while authenticated stakeholders view minute data like pricing trends and supply-chain status, even if the general product catalog stays available for market transparency.

The Product Detail and Provenance module forms the heart of the provenance engine. This system combines a non-destructive, append-only price history ledger with real-time QR code generation and blockchain references. The system uses mapping APIs to display registration coordinates together with a chronological supply-chain timeline, improving spatial transparency. Moreover, the platform gives investors strong price analysis that includes trend projections and volatility measures.

b. Web application

In order to facilitate communication and networking among the end users of our system, we have developed a front-end interface. The protocol is shown in Figure. The homepage of TraceRoot, a blockchain-powered supply chain tracking system that features options to register products, track movement, and verify authenticity via a secure and transparent web interface.

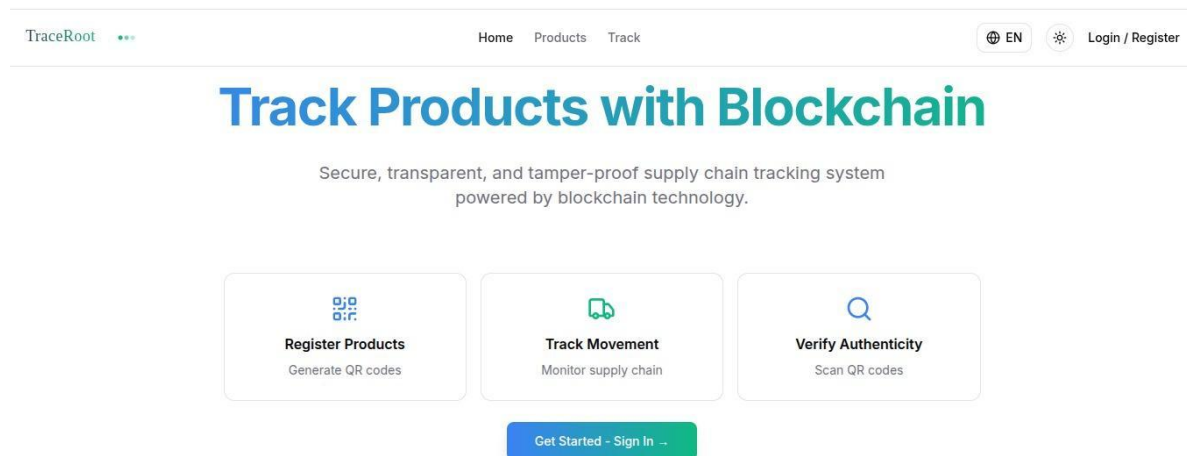


Figure 3: TraceRoot Home interface

The user interface of the TraceRoot web application, showcasing the secure dashboard where users can register/login as ADMIN/FARMER/DISTRIBUTOR/RETAILER/CONSUMER.

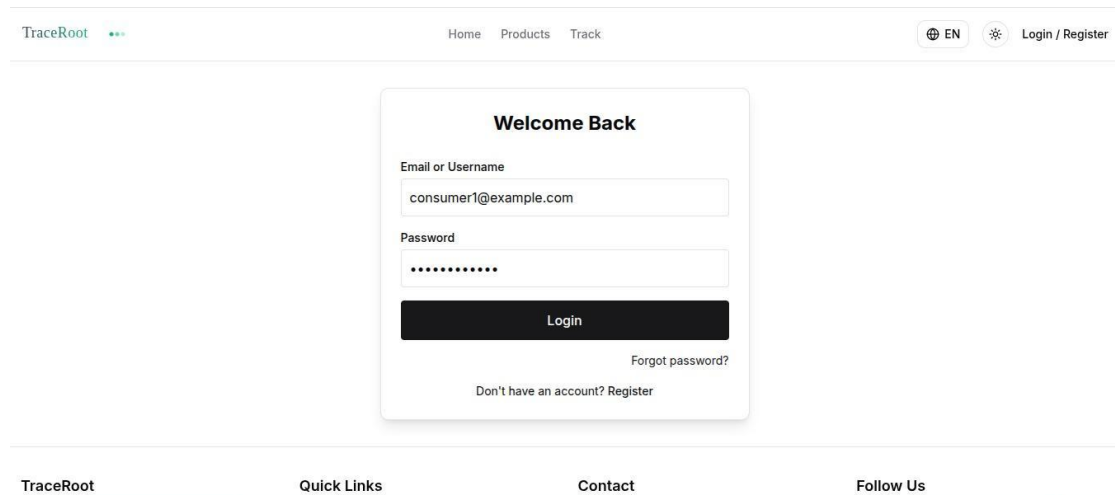


Figure 4: TraceRoot user login interface

In this interface users can find product detail or track using name or product ID.

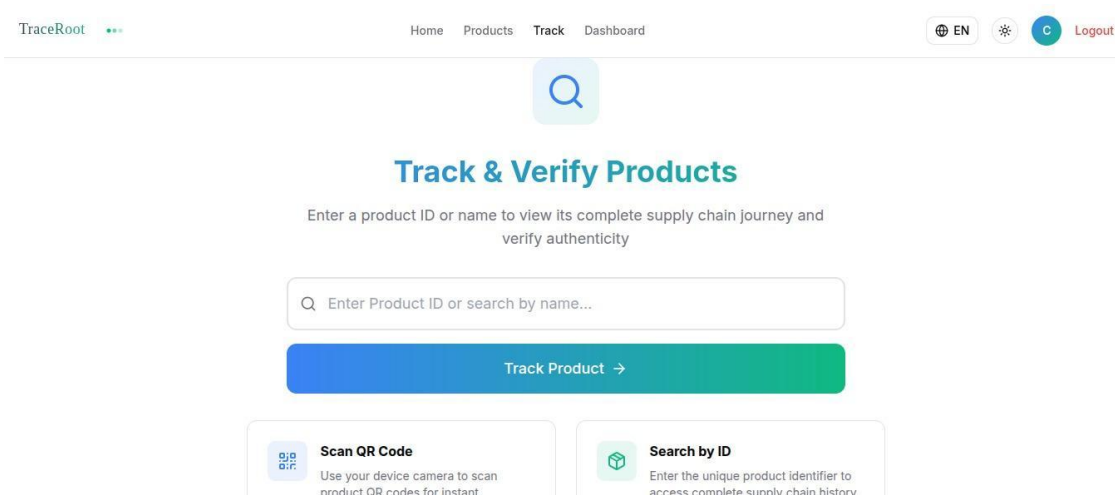


Figure 5: TraceRoot Products verify interface

In this interface the user can see all products Product Information like Origin, Manufacture Date, Registration Date, Price, all Supply Chain History. When FARMER, DISTRIBUTOR, RETAILER given information about products there generate a Qr code.

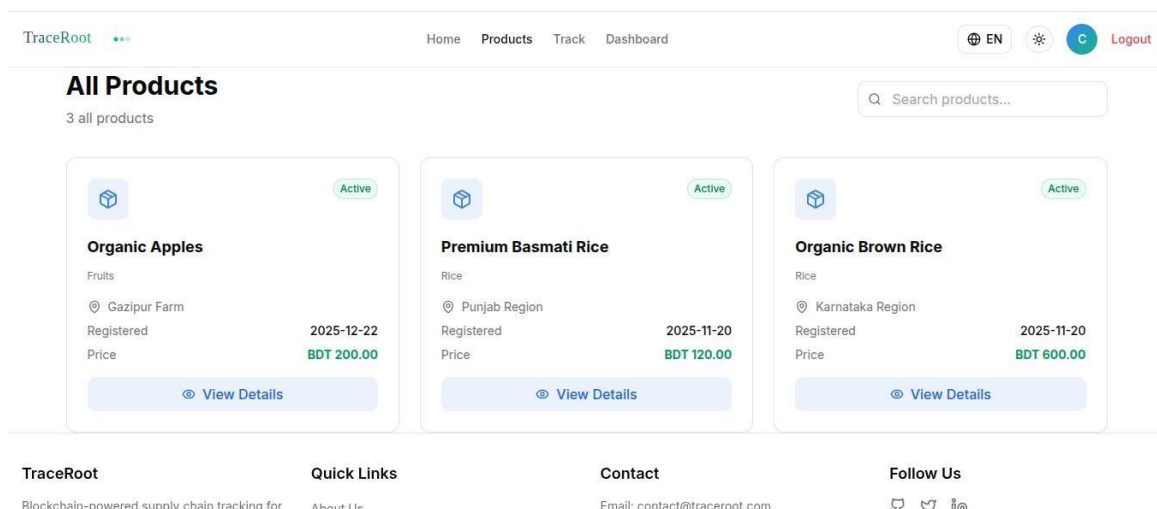


Figure 6: TraceRoot registered Products view interface

This interface visualizes the complete journey of agricultural products across the supply chain, enabling transparent tracking from farmer to end consumer.

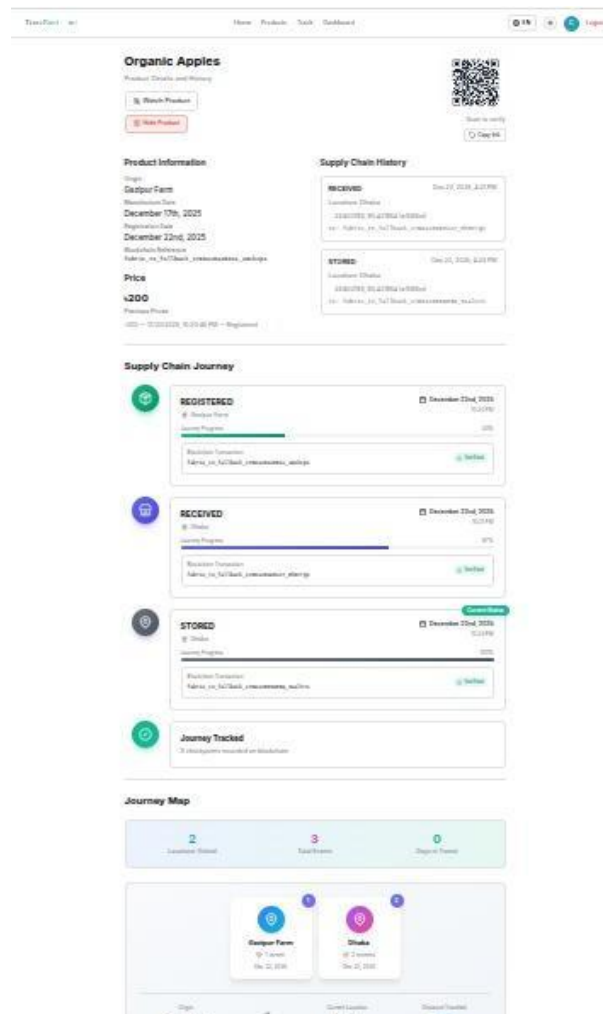


Figure 7: TraceRoot Supply Chain Journey or History interface

This interface allows authorized users to register new agricultural products by entering essential product name, origin, manufacture date, price, category, and description.

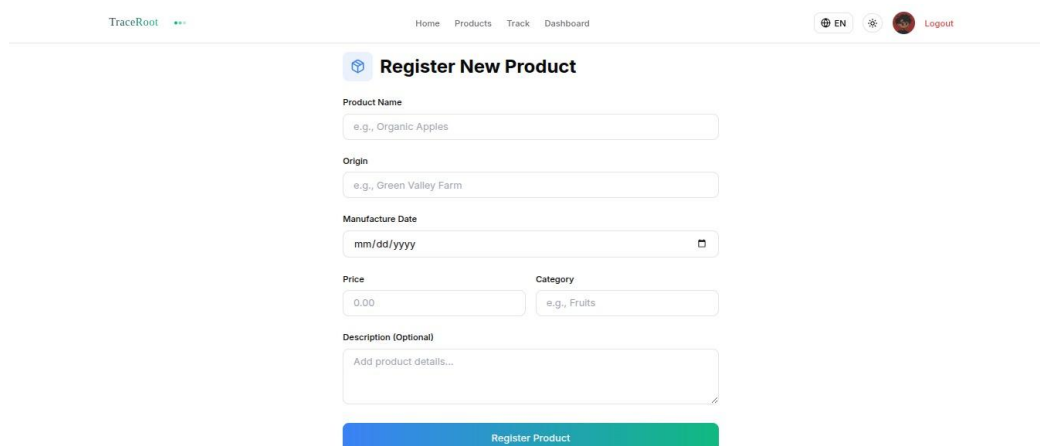


Figure 8: TraceRoot Product Register Interface

This interface enables stakeholders to update and manage product pricing dynamically based on market conditions and supply chain stages.

Previous Prices
₹120 — 11/21/2025, 2:41:36 AM — Registered

Update Price

New Price

Notes (optional)

✓ Update Price

Edits are appended on-chain; previous prices remain visible for audit trail.

Figure 9: TraceRoot Product Price update interface

This dashboard provides farmers with an overview of their registered products, pricing status, and supply chain progress in a centralized view.

TraceRoot Home Products Track Dashboard EN Logout

Farmer Dashboard

Welcome back, Kamal

+ Register Product

2
Total Products

₹320.00
Total Value

1
Added This Week

Your Products

Organic Apples

Gazipur Farm • ₹200.00 • 2025-12-22

Figure 10: TraceRoot Farmer Dashboard interface

This dashboard allows retailers to monitor available products, pricing details, and transaction history for efficient retail management.

TraceRoot Home Products Track Dashboard EN Logout

Retailer Dashboard

Welcome back, City Grocers

0
Products Received

0
In Stock

0
Items Sold

Active
Store Status

Recent Activity

No transactions yet

Your store activity will appear here

Figure 11: TraceRoot Retailer Dashboard interface

This dashboard enables distributors to track product distribution status, manage logistics, and coordinate supply chain operations effectively

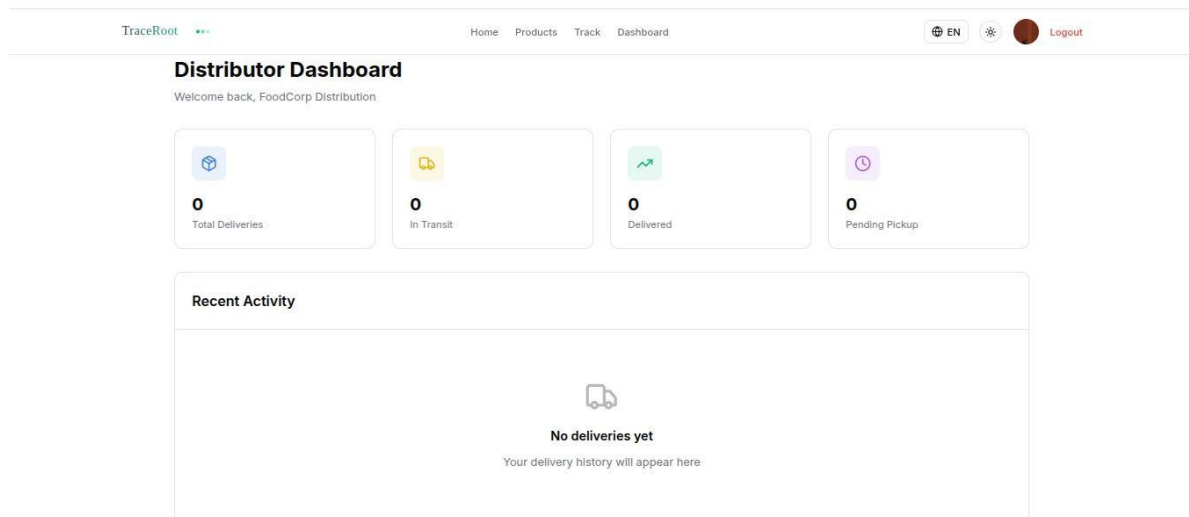


Figure 12: TraceRoot Distributor Dashboard interface

This interface provides administrators with full system control, including user management, product oversight, and overall platform monitoring.

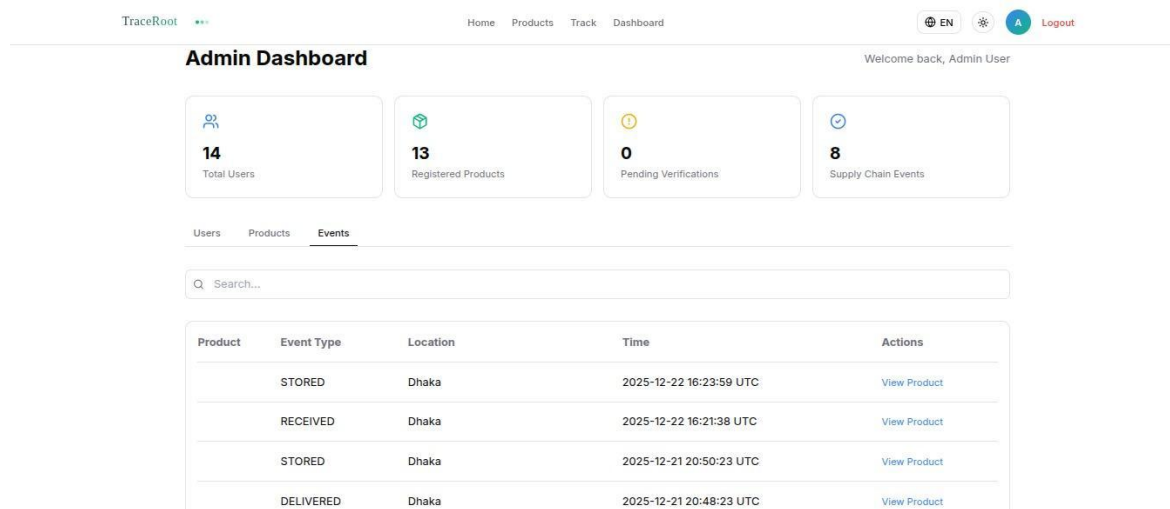


Figure 13: TraceRoot Admin Dashboard interface

RESULT AND DISCUSSION

The evaluation of the system's operational efficiency was conducted by assessing the latency of full-path traceability characterized as the duration from the start of a QR code scan to the ultimate data display. The experimental findings demonstrated an average response time of less than 3 seconds. This performance indicator signifies a significant enhancement when compared to conventional manual auditing methods, ensuring that the system satisfies the stringent time constraints necessary for executing swift regulatory recalls in actual supply chains.

To evaluate the security framework, the system underwent stress testing that involved the introduction of fraudulent transactions, which included chronological anomalies (illogical dates), unauthorized access to roles, and discrepancies in quantities. In every scenario, the Smart Contract layer maintained a complete rejection rate of 100% for invalid information. When paired with obligatory digital signature protocols, these results indicate that the

architecture offers a strong defense against prevalent data manipulation techniques, thereby guaranteeing a high level of immutable data integrity.

An essential aspect of the study involved the validation of the decentralized application (DApp) interface with a group of non-technical users. Despite the inherent complexities of blockchain technology, the user experience design was simplified, effectively allowing for wallet connection and transaction signing without any external help. These findings suggest that a design strategy focused on grassroots aspects can substantially lower the barriers associated with limited digital literacy, indicating a feasible approach for the widespread adoption of blockchain solutions across various socio-economic contexts.

Table 1: Comparison to Existing Models

Finding	Impact on Project Value	Comparison to Literature
Instant Fraud Rejection	Proves the system's resilience and accountability at the source	Offers stronger security than general consensus models (Rashid et al., 2024) because the logical rules are enforced before the data is permanently recorded.
Single-Chain Low Overhead	Ensures economic viability for a low-margin essential good.	Successfully counters the cost and technical barrier of the complex multi-blockchain approach proposed by Peng et al. (Peng et al., 2022).
UX Focused	Increases the probability of successful adoption by farmers and small retailers.	Addresses the critical adoption gap not prioritized by highly technical frameworks (Farooq et al., 2023).

By implementing TraceRoot, we acquired practical knowledge regarding how decentralized technologies can address existing challenges in the agricultural supply chain. In contrast to previous research that emphasizes the theoretical benefits of blockchain, our initiative illustrates that its primary advantage lies in the enforcement of business rules among various actors.

An important discovery from our research is the effectiveness of the Hybrid Data Model. We maintain cryptographic hashes on the Hyperledger Fabric ledger while managing detailed metadata within a relational database. This strategy enables us to achieve a balance between security, scalability, and cost, a concept often referred to as the "blockchain trilemma." In practical terms, especially in underdeveloped regions, the expense of storing extensive data on a blockchain can be prohibitively high. Our findings indicate that the hybrid model ensures data security. For example, consider a situation in which a farm logs information regarding the cultivation and transportation of a rice batch within the off-chain relational database. If someone attempts to modify these details, such as the pesticide levels, the hash stored on the blockchain will quickly reveal a mismatch, signaling potential tampering. This rapid detection safeguards the integrity of the digital fingerprint and illustrates the effectiveness of our hybrid model.

The transition to traceability below three seconds is revolutionary. Following a batch of rice in a conventional setup requires sorting through physical logs and disjointed databases, a laborious process that may consume days or even weeks. TraceRoot condenses the timeline into mere seconds. This advancement is not solely about acceleration; it represents a significant achievement for public health. In the event of a safety recall or contamination scare,

the ability to swiftly identify the source can literally save lives and avert local issues from escalating into larger economic disasters.

When compared to existing studies, our research distinguishes itself by emphasizing a permissioned network as opposed to a public one. Although public blockchains like Ethereum offer substantial decentralization, the permissioned aspect of Hyperledger Fabric better suits the regulatory demands of food safety authorities. By utilizing Hyperledger Fabric, we can incorporate sophisticated governance features such as identity verification and access management, ensuring that every member of the network is recognized and authenticated, which greatly improves oversight relative to conventional auditing techniques in public chains. In a public blockchain, identity management tends to be less regulated, often resulting in difficulties in establishing accountability.

The permissioned architecture of Hyperledger Fabric enables us to oversee who can access data and the actions they can take, thus providing a balance between openness and confidentiality. This unique combination of known yet transparent participants aligns well with the rigorous requirements of food safety regulators. The capability to perform thorough and effective audits within this structure guarantees a high degree of trust and compliance, creating what we consider to be the most feasible path forward for the digital transformation of supply chains for essential goods. Despite its advantages, the TraceRoot framework contains built-in restrictions that should be recognized for future academic enhancement:

While blockchain guarantees that data remains unchanged once documented, it cannot inherently confirm the authenticity of the initial manual data entry by a human referred to as the Garbage In, Garbage Out dilemma. The dependence on the Browser Geolocation API presupposes reliable GPS signals and internet access. In remote rural farming areas, limitations in equipment or connectivity may obstruct the accuracy of real-time data. While the hybrid model is effective, it creates a reliance on the off-chain database (MongoDB). If this database experiences a localized malfunction, the extensive metadata becomes temporarily inaccessible, even though the blockchain hash stays secure.

CONCLUSION

Blockchain technology has revolutionized the agricultural supply chain by providing a decentralized, transparent, and secure data management system. Traditional supply chain systems are inefficient, lack traceability, and rely on intermediaries, resulting in higher costs and decreased stakeholder confidence. Blockchain addresses these difficulties by ensuring data immutability, security, and transparency during transactions. This paper proposes a blockchain-based agri-supply chain model using smart contracts to automate procedures and improve transactional reliability. The system promotes direct relationships between farmers, suppliers, distributors, and customers, reducing the need for intermediaries. We created a user-friendly web application for easy access and use by all network participants. The smart contract is the key component of the proposed system, controlling data flows and enforcing norms for transparency and accountability. This framework attempts to improve operational efficiency, trust, and sustainability in the agricultural supply chain ecosystem.

LIMITATIONS AND FUTURE RESEARCH RECOMMENDATIONS

Although the proposed system demonstrates the feasibility of integrating blockchain technology into supply chain monitoring, several limitations should be acknowledged. *First*, the current prototype has not yet incorporated a fully integrated Internet of Things (IoT)

infrastructure capable of automatically collecting environmental parameters such as temperature, humidity, and geolocation throughout the logistics process. Consequently, data acquisition still depends on limited system inputs rather than continuous real-time sensing, which may reduce monitoring accuracy and operational responsiveness under dynamic transportation conditions.

Second, the blockchain implementation remains at the prototype level and has not been evaluated within a production-scale environment. The current architecture has not addressed challenges associated with high transaction throughput, network scalability, latency, and permission management that typically arise in commercial supply chain operations. These limitations restrict the practical applicability of the proposed framework for large-scale industrial deployment.

Third, the financial settlement mechanism is not yet fully automated. Although the proposed framework demonstrates the potential of blockchain-enabled verification, payment execution and stakeholder reconciliation have not been integrated into a decentralized smart contract ecosystem capable of supporting autonomous financial transactions based on verified delivery and quality compliance.

Future research should therefore focus on extending the proposed framework through the integration of real-time IoT sensing technologies to enable continuous monitoring of environmental conditions across the entire supply chain. The incorporation of secure IoT gateways and cryptographic data authentication mechanisms would further improve data integrity, traceability, and trust among supply chain participants.

Furthermore, future studies are encouraged to investigate the implementation of enterprise-grade permissioned blockchain platforms, such as Hyperledger Fabric, to evaluate system performance under commercial operating conditions. Comparative analyses between public and permissioned blockchain architectures would provide valuable insights into scalability, transaction efficiency, privacy protection, and implementation costs for industrial applications.

Finally, future research should develop and validate automated settlement protocols based on smart contracts that enable decentralized payment execution following multi-party verification of delivery completion and product quality compliance. Integrating autonomous financial settlement with trusted monitoring infrastructure has the potential to improve transparency, reduce administrative costs, minimize disputes among stakeholders, and strengthen the overall efficiency and reliability of blockchain-enabled supply chain management systems.

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