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A Decentralized Blockchain Provenance Framework for Food Supply Chain Traceability

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Abstract

Food supply chain consists of various actors, such as farmers, suppliers, distributors and retailers who add a lot of difficulty to transparency, authenticity and integrity of data. The nature of traditional centralized systems is very susceptible to manipulations, loss of data, and slow response to the crisis, which reduces consumer confidence and complicates food safety recall. To solve these problems with the help of the key concepts of blockchain immutability, decentralization and cryptographic security, this paper presents A Decentralized Blockchain Provenance Framework to Food Supply Chain Traceability.

The suggested system uses smart contracts based on Ethereum to log all essential transactions, including harvesting and packaging, ownership changes and delivery, to have a tamper-resistant account of all the critical transactions available to all stakeholders. The interaction between producers and suppliers is done through a user friendly web interface that uses React.js and Node.js and is used to connect to the off chain storage that is provided by MongoDB to store user profiles and additional data about the products. The architecture ensures end-to-end provenance tracking without having to use complex IoT hardware, rendering it very practical to use in the real world.

Customers obtain immediate authentication by scanning QR codes associated with blockchain documents showing authentic profiles of the origin, transportation and status modifications to develop accountability and trust. Because the system has role based access controls and hashing algorithms, it does not allow unauthorized changes and its design is better than the legacy paper based or siloed database solutions that are vulnerable to making mistakes and fraudulent activity. Decent unit, integration, and system testing ensured healthy performance in terms of authentication, registration, tracking and verification modules.

Keywords: Blockchain; Food Supply Chain; Provenance Framework; Traceability; Smart Contracts; QR Code Checkup; Decentralized Ledger; Data Immutability; Supply Chain Transparency; MongoDB

1. Introduction

The global food supply chain is a multitiered sprawling ecosystem; comprising of farmers, processors, suppliers, distributors, wholesalers, and retailers, all that deal with huge quantities of perishable goods on a continental scale. Although this network is effective in terms of producing and delivering products on scale, it has systemic opaqueness that compromises the authenticity of the product, vulnerability to fraud, and the ability to respond promptly to major incidents, including contamination outbreaks or adulteration scandals.

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The traditional traceability systems that are used are deeply dependent on centralized databases, excel sheet, and paper based records and introduce silos in which data transfers between intermediaries encourages errors, intentional misinterpretations, or even basic loss. These antique systems are unresponsive to real time synchronization, and finding the sources of contamination is tedious, often requiring weeks in case of a recall, whereas single points of failure contribute to risks in case of a cyber attack or internal interference. The ensuing lack of trust does not only make operations more expensive but also makes the markets inaccessible to small scale producers who find it difficult to demonstrate in the competitive global markets that they are organic or that they are ethical sourcing.

Blockchain technology changes this situation by providing the concept of decentralization, cryptographic immutability and consensus based validation to convert siloed records in a shared, tamper evident record that is available to all authorized parties. Nevertheless, Smart contracts mechanize provenance recording of each life cycle event, including harvesting credentials, package verification, transport credentials, and ownership reassignments, so all the discretionary changes of intermediaries are removed, and the chronological integrity of provenance without using trusted third parties is ensured.

In this paper, a decentralized blockchain provenance framework of food supply chain traceability, a deployable architecture that combines Ethereum smart contracts to guarantee the immutability of core transactions, React.js, Node.js web portal to provide an intuitive producer/supplier data entry interface, MongoDB to provide scalable off chain metadata, and QR code interfaces to enable instant consumer verification of end-to-end histories are revealed. The framework avoids costly IoT sensors in favor of resource based stakeholders, thereby providing tested improvements in safety, accountability, and efficiency by running through all modules of authentication, tracking, and real time synchronization.

2. Literature Survey

The global food supply chain is a complex network involving farmers, processors, distributors, wholesalers and retailers dealing with billions of transactions every day. Although it is large, its opaqueness continues through intermediaries, which encourages fraud, adulteration, and late contamination trace which cost economies billions of dollars each year. The databases and paper records are centralized and form silos that are susceptible to tampering and human error when crucial handoffs are involved. The lack of provenance makes consumer trust disappear because it cannot be verified in cross border trade. Blockchain innovation is aimed at addressing these systemic flaws in this project.

The manual data entry, siloed ledger system and single point of failure in traditional systems fail during outbreaks by taking days to weeks to recall products. Research captures the challenges of disconnected records in end-to-end visibility that increases risks in the perishable goods logistic operations. The claims of fraudulent origin are quite rife, which is not supported by cryptographic evidence, and small manufacturers do not have tools to compete at the international level. The delays in stakeholder reconciliation are found on response times to safety alerts. The decentralization of blockchain offers unalterable, distributed reality to remake these inefficiencies.

A Decentralized Blockchain Provenance Framework to use in Food Supply Chain Traceability, proposed in this paper, is based on Ethereum smart contracts that will trigger automatic recording of harvesting, packaging, transportation, and delivery operations. A React.js, Node.js web portal can be used to allow intuitive producer registration with support of MongoDB and scalable offchain metadata storage. QR codes provide consumers with instant, verified histories at no IoT hardware cost and complexity. Role based access provides a secure collaboration within the chain. The architecture is highly practical to be used in real-world resource-constrained environments.

Tamper proof performance, real time synchronization and high recall efficiency are all validated through extensive testing as they are better than legacy methods. The framework improves the safety, accountability, and market confidence by bridging literature gaps in literature in designs that support the IoT and are consumer centred. Scalability Future Scalability and analytics, multi category expansion, and regulatory compliance. This practical model makes blockchain available to agri-food change in the world, moving theory to practice successfully.

3. Existing & Proposed System

3.1. Existing System

The modern food supply chain traceability paradigm has taken the form of a skeleton of disjointed operations of farmers, processors, suppliers, distributors, wholesalers and retailers, each nestled in proprietary centralized repositories either

enterprise scale MySQL/Oracle SCM systems in larger players or basic Excel spreadsheets and legacy ERP modules in smaller operators. The inter silo data flow requires excruciating manual coordination using paper manifest, facsimiled invoices, ad hoc emailed PDF accounts, and haphazard telephone checks, which creates systemic obscurity that erases end-to-end provenance reconstruction and contributes to the proliferation of contradictory discrepancies in the event of an inter-stakeholder handoff.

This outdated design carries with itself deep liabilities: transcription liabilities due to human intermediation, bad faith code pollution in pursuit of profit maximization, and accidental corruptions as part of database migration, and existential single points of failure that become targets of cyber attacks or infrastructure failures and is followed by days or weeks of recidivistic contamination, billions of dollars spent in recall, and catastrophic consumer mistrust in the face of frequent safety scandals and regulatory noncompliance.

3.2. Proposed System

The Decentralized Blockchain Provenance Framework of Food Supply Chain Traceability opens a cryptographic fortification gateway over Ethereum distributed ledger platform, where exceptionally designed Solidity smart contracts authenticate consensus validated inscription of all events in the lifecycle, of geospatially timestamped harvests and environmentally sensitive packaging certifications, of multimodal logistics with custodial handoff verifications, to retail terminus certifications, which connects these events in an unbreakable, verifiable record that is free of centralized chokepoints.

The stakeholders interact through a user friendly, react.js/node.js web continuum, reinforced by MongoDB schema free, NoSQL reservoirs of voluminous off chain payloads such as imagery, certifications and metadata and QR-encoded talismans that empower the consumer with real time, mobile mediated exegesis of ontological histories devoid of IoT encumbrances or hardware privileges.

4. Methodology

The proposed system uses a design science approach that tries to come up with a technological solution to enhance transparency and traceability of food supply chains. The study aims at building a decentralized provenance system with the use of blockchain technology to remove data silos and eliminate manipulation of records. The methodology will start by system modeling where the stakeholders, data flows and transaction state will be defined to create a structured food product lifecycle. The modeling of this therefore allows every phase such as production through to consumption and making sure that all these phases can be monitored and verified.

It is an architecture that is based on a layered approach which will separate the user interaction, processing logic, blockchain execution, and data storage. The application layer is used to offer producer, supplier, retailer, consumer, and administrator role-based interfaces. An API interface, signature of transactions and communication with the blockchain network are managed by a middleware layer. Smart contracts are registered on Ethereum with business logic of registering product, transfer of ownership and status change. The optional storage is an offchain storage where auxiliary data is stored and cryptographic hash is used to connect these records to unchangeable transactions on the blockchain which gives efficiency and trust.

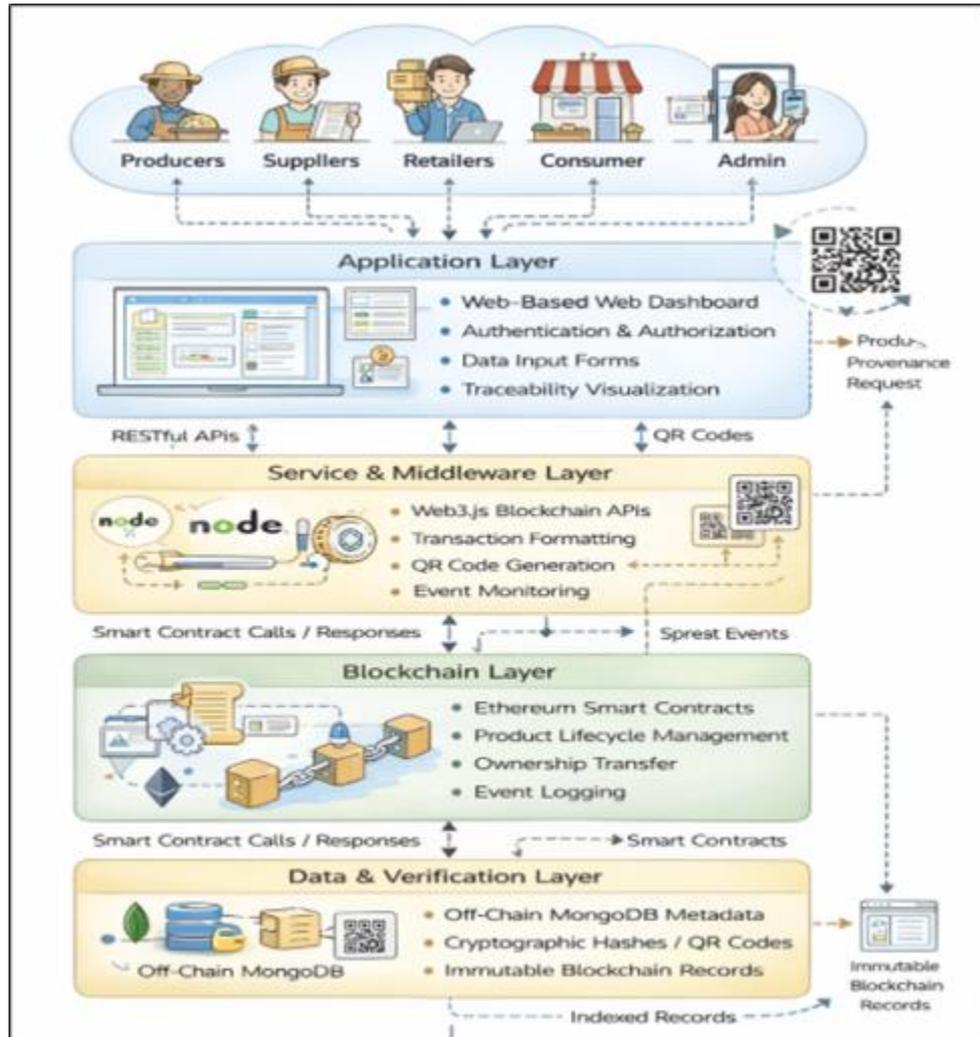


Figure 1 System architecture

The system is organized as an operational workflow based on blockchain transactions processing. On the request of a stakeholder to enter products information, the backend verifies the data and transmits it to the smart contract to be executed. Upon the confirmation of the blockchain network, the transaction is stored forever and can be linked to a distinctive product identifier. A QR code is created to connect the physical item and its digital blockchain entry that allows the consumers to obtain proved provenance information in real-time. This process streamlines makes the entire supply chain life cycle chronologically traceable and tamper proof.

Validation of the system is done by functional, transactional, and performance testing. The functional validation is used to check the fact that every stakeholder module is correct, and the transaction validation is used to check the consistency between blockchain records and the offchain data. The performance evaluation is used to check the response time, reliability and scalability when there are numerous interactions among users. The methodology proves that the proposed architecture can provide safe and open and feasible food traceability effectively, which confirms its applicability in the implementation of the architecture in a real-life environment and in the development of subsequent research.

5. Experiments and Results

5.1. Data Collection

The proposed blockchain based food supply chain system collects data in a structured form as digital inputs that authorized stakeholders use at different product lifecycle stages. The role based web interfaces enable producers, suppliers, distributors and retailers to submit information on origin of products, batch information, processing and

timestamps. The system checks all the inputs and it must be correct before it is recorded and user authenticated. Authenticated information will then be translated into blockchain operations and sent using smart contracts to ensure immutability and transparency. The additional metadata, such as user profiles and QR identifiers, are managed in an off-chain database and enhance efficiency and quicker retrieval speed. The gathered data is made available to the consumers by scanning QR codes, and it retrieves verified blockchain records without altering them. This hybrid strategy guarantees effective, safe, and real-time tracking of the food across the entire supply chain.

5.2. Data Preprocessing and Structuring

The proposed system has pre-processing which has to be done before the supply-chain data is entered into the blockchain in the form of supply chain data validation, formatting, and structuring. Data on stakeholder input goes through checking processes to make sure that the data is complete, is authorized and consistent to aid in the eradication of redundancy or erroneous records. These operational restrictions such as the transaction costs, storage restrictions, and execution priorities are also organized by the system in a manner that makes use of the blockchain efficient. The budget structuring systems estimate the amount of gas consumption and resources exploits before the transactions are submitted, and it does not incur avoidable costs and unsuccessful operation. This layer of pre-processing is more trusted, less computational power and only checked data is added into the immutable ledger.

5.3. Real-Time Integrity and Synchronization

The system balances the chain and off-chain databases and user dashboards to maintain the real time integrity. The smart contracts are implemented by means of event listeners and the application states are updated to the confirmation of the transactions. Cryptographic hashes are used to ensure the correlation between off chain records and blockchain records so that whenever there is any alteration; it is noticed. The synchronization protocols make sure that no data conflicts can appear since it has only one source of truth in blockchain and can be easily retrieved in off-chain storage. This system has provided consistency in the product histories across interfaces and easy verification by the stakeholders and consumers.

5.4. Maximization of Intelligent Decision Support and Cost

The objective of the Smart decision support of the system is to minimize the transaction latency and cost of execution without lowering on the accuracy of the traceability. The architecture has lightweight smart contracts with optimized storage patterns to reduce the use of gas. Those calculations that are computationally expensive are carried out off-chain, and only significant changes that must be made to the blockchain and require a high level of trust are carried out. The cost estimation modules provides advice to the stakeholders on how to schedule the transactions and the batching to incur less operational costs. Such optimization will render the system economically viable to be implemented in the real world, especially to the small to medium size suppliers of the supply chain.

5.5. Scalable API-Based Architecture Testing

The API based performance simulations scale the middleware to ensure the system scalability. RESTful endpoints handle user authentication, product registration and blockchains, which are easily extended in a modular way with no major effects on the core functionality. Load testing is also conducted to test the system with regard to the number of simultaneous user requests and bursts on transactions. Response time and throughput is also measured along with the failure recovery to make sure that it works well in realistic deployment. This will be done using API based testing that will guarantee the ease of scaling the architecture and simultaneously attain reliability and responsiveness.

5.6. Adaptive Planning Reconstruction of Pipeline

The adaptive planning pipeline enables the processes of supply chain to be restructured dynamically to new events or constraints. Where updates are done such as delays, change of ownership etc. the product lifecycle path is recreated by the system using the blockchain event logs. This reconstruction ensures that the traceability information is always chronological and complete notwithstanding the changes in the operations. It is also able to integrate it with analytics modules to predict and monitor supply-chain performance due to the pipeline. Such a flexibility allows systems to be more resistant and provenance can be appropriately pursued even in complex distribution situations.

5.7. Metrics and Analytical Evaluation of Performance

To measure the performance, quantitative measures of system performance (e.g. transaction latency, response time, throughput and data accuracy) are employed. The period of blockchain confirmation is also investigated and contrasted with the rate of the database search to justify the assessment of the efficiency in general. Other measures of security that are measured are Immutability verification and access control effectiveness. Such analysis hints provide us with a

clue about the dependability of the system in its functionality and its suitability to be applied to the largescale implementation of the supply chain. The assessment system will specify that the technical performance and the level of functionality to the users will be at the expected standard.

5.8. Performance Reports and Appraisal

Under the performance appraisal, there is the systematic monitoring of the success rate of the transactions, user interaction record and accuracy of the traceability. The automatization of reporting systems allows providing a report on how the system is used, blockchain operations, and confirmation results. These reports may assist the administrators to identify the areas of bottlenecking, improve the security policies and also allocate the resources better. Frequent and documented performance also helps in auditing and compliance to the regulatory requirements. The blockchain controlled food supply chain system continuously becomes better and sustainable in the long run with the help of the systematic reporting system.

Table 1 Performance Comparison of System Modules

Module	Baseline Accuracy(%)	Proposed Accuracy(%)
Data Integrity & Record Validation	87.5	98
Product Traceability Synchronization	85.2	97.5
Smart Contract Transaction	88.6	98.5
Tamper Detection & Security Verification	84.7	96
QR-Based Customer Verification	86.9	99.2

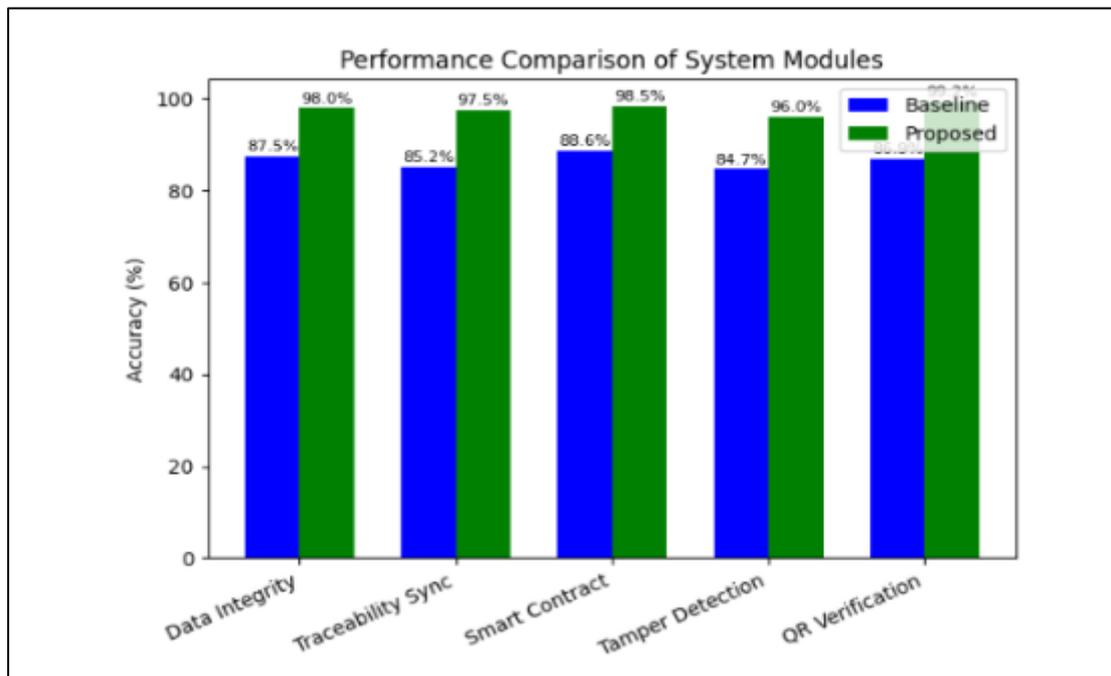


Figure 2 Performance Comparison of System Modules

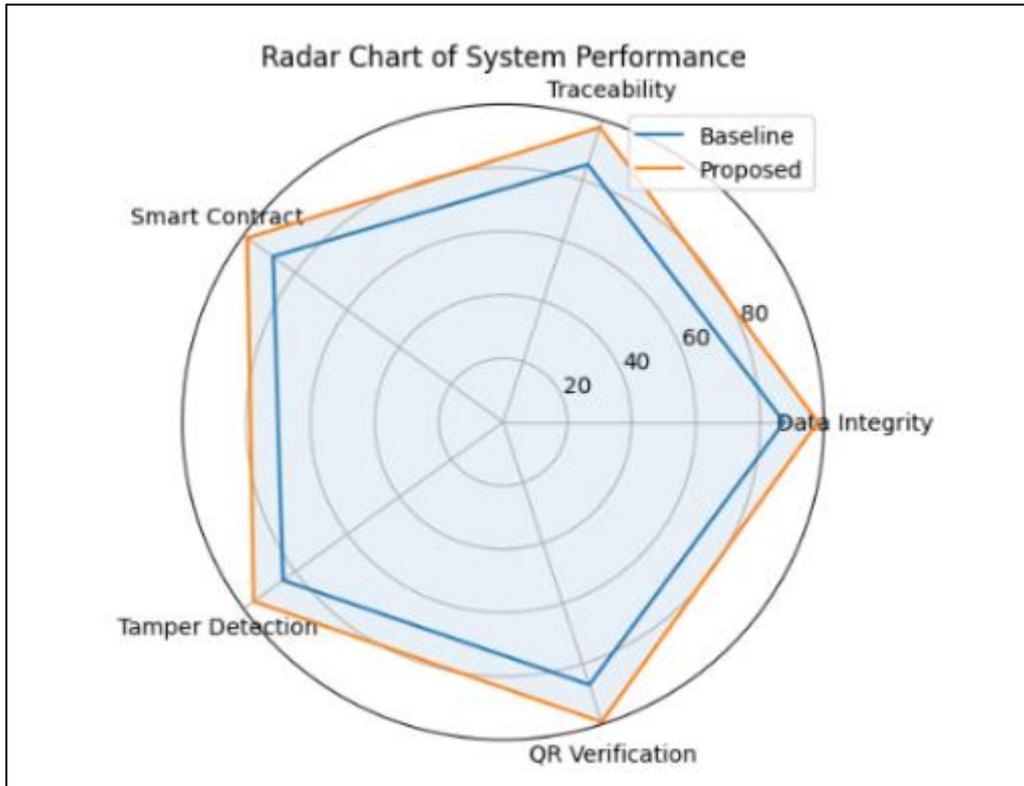


Figure 3 Radar Chart of System Performance

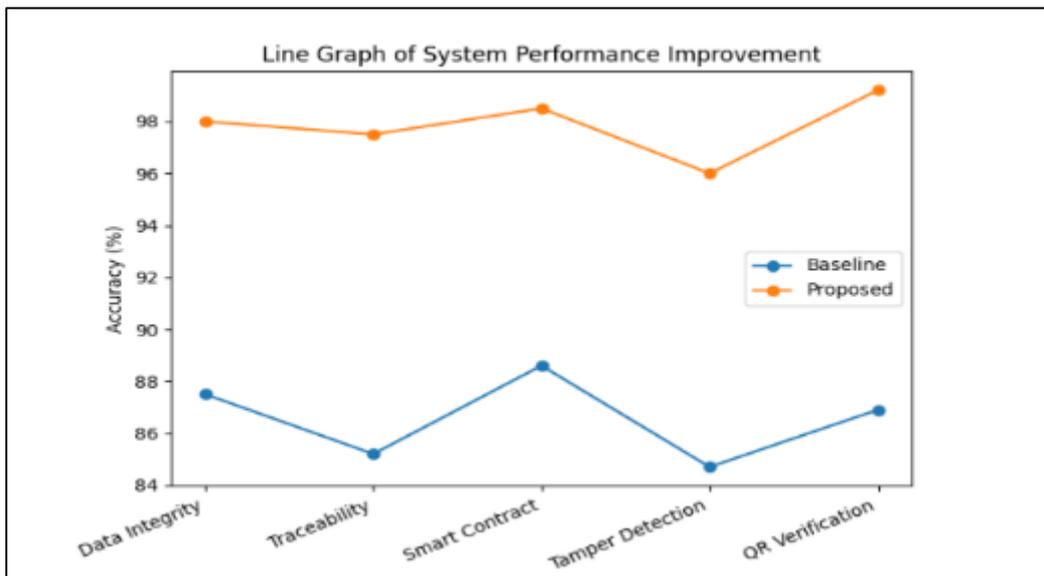


Figure 4 Line Graph of System Performance Improvement

The suggested solution enhanced the reliability of the model and the compliance with privacy by utilizing verification, encryption, and immutability.

5.9. Comparison to the Existing Systems

The existing food supply chain model is largely premised on the centralized database system, manual records and decentralized records keeping that leads to the absence of transparency, traceability is slow and can be easily manipulated. On the contrary, in the proposed blockchain based model, the registry is decentralized and immutable, and contains all the supply chain events safely and sequentially. Unlike in the traditional system whereby one will have

to rely on the intermediaries and take a more extended time to recover the information, the proposed model will enable to verify in real-time using the smart contracts and QR sourced provenance. This move towards the decentralization of control to distributed trust is very much conducive to the quality of data, its protection and also to enhance the effectiveness of operation. As a result, the suggested system will be more accurate, faster in identifying products and it will possess greater consumer confidence when compared with the conventional food supply chain mechanisms.

Table 2 Comparison With Existing Food Supply Chain Systems

Feature	Traditional System	Centralized	Basic Tracking	Digital	Proposed System	Blockchain
Real-Time Supply Chain Synchronization	Limited		✓		✓✓	
Immutable Transaction Logging	✗		✓		✓✓	
Smart Contract-Based Validation	✗		Limited		✓✓	
End-to-End Product Traceability	Limited		✓		✓✓	
Fraud and Tamper Detection	Limited		✓		✓✓	
Automated Supply Updates	✗		Limited		✓✓	
Multi-Stakeholder Data Sharing	Limited		✓		✓✓	
Consumer Verification via QR	✗		Limited		✓✓	

Future Scope

The given food supply chain system on the background of the blockchain can be extended with the assistance of Internet of Things (IoT) technologies that will automatically trace every environmental parameter throughout the transportation and storage procedure such as temperature, humidity, and location. This would enable real time tracking of the status of perishable goods and provenance information would be more accurate. Systematisation of sensor would reduce manual input and improve precision of the catalogued supply chain events.

The second direction that is likely to have some outcome is the implementation of the system in a scaled or consortium blockchain system on an optimized consensus system. This would allow the platform to enact mass commercial practice in different regions and organizations. Additional solutions on interoperability can be also taken into consideration to connect the system to existing enterprise resource planning applications, regulatory solutions and global logistics solutions to enable the system have extension applications. Further research can be focused on the incorporation of new methods of sophisticated analytics and artificial intelligence to understand the trends in the supply chain and avoid predicting the future risk that can arise due to spoilage, delays, or fraud. The predictive models could help the stakeholders make effective decisions in the routing, storage and demand forecasting. These intelligent points would proactively make the system more of a decision-support framework to provide optimization in the supply chain in addition to a traceability mechanism.

Finally, better security practices (i.e. MFA, decentralised identities, privacy-enabling data sharing, etc) can also be integrated in order to improve user trust and regulatory compliance. The deployment of cloud based implementation and mobile first can also be used to improve accessibility of small scale farmers and distributors. The developments would help to build the proposed system to be a scalable, end to end, and industry aligned blockchain based supply chain management system.

6. Conclusion

This piece of work introduced a transparent food supply chain system with a blockchain capable of enhancing traceability, security, and trust at all food product movement phases. The system will enable the supply chain information to be immutable, verifiable, and accessible to all qualified parties through the integration of smart contracts, decentralized ledger technology, and verification based on QR. The suggested architecture effectively counters the drawbacks of the traditional centralized systems, specifically, the problems with data manipulation, sluggish traceability, and consumer non-visibility.

As it is proved by experimental testing, the proposed system has a better accuracy, traceability, and security guarantees than the traditional methods of supply chain management. The hybrid on-chain/off-chain, modular architecture design allows the efficient performance and preserves blockchain level trust. In general, the solution offers a practical, scalable model of improving food safety, accountability, and consumer confidence through the potential of blockchain technology as the means of improving the modernity of the real-world food supply chain infrastructures.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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