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A THREE-LAYER BLOCKCHAIN FRAMEWORK FOR SMART COLD CHAIN TRACEABILITY OF FRESH AGRICULTURAL PRODUCTS

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Abstract:

Ensuring end-to-end traceability in fresh agricultural product cold chains remains a persistent challenge, as existing systems suffer from centralised data vulnerability, absence of automated enforcement mechanisms, and disconnection between traceability records and analytical decision-support tools. This paper proposes a three-layer blockchain architecture based on Hyperledger Fabric. The system integrates smart contracts and big data analytics to strengthen traceability and supply chain transparency. It is designed to address operational inefficiencies in the distribution of temperature-sensitive perishable goods. The framework structures cold chain management into three layers: Data, Contract, and Application. The Data Layer adopts a hybrid on-chain/off-chain storage mechanism with hash anchoring to ensure integrity and scalability. The Contract Layer deploys three specialised smart contracts for quality certification, transaction settlement, and cross-organisational information sharing. The Application Layer integrates a big data analytics module that performs parameter optimisation and feeds the results back into the contract layer, forming a closed-loop system. Comparative analysis against four representative existing approaches demonstrates that the proposed architecture offers broader smart contract coverage and deeper analytical integration than current solutions. The closed-loop feedback mechanism transforms the traceability system from a static recording tool into an adaptive management platform. It is capable of continuous operational refinement. The contribution of this paper lies in the design and conceptual evaluation of the proposed architecture rather than in an empirically validated implementation, and prototype deployment together with quantitative performance assessment is planned as a subsequent research stage. Limitations concerning the dependency of

the framework on Internet of Things (IoT) infrastructure, the scalability of transaction throughput under high-frequency monitoring conditions, and the governance of automated parameter updates are acknowledged as directions for further investigation.

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Big Data Analytics, Blockchain Traceability, Cold Chain Management, Fresh Agricultural Product Supply Chain, Hyperledger Fabric Smart Contracts



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Introduction

Fresh agricultural products like fruits, vegetables, and aquatic products are naturally perishable products. Their quality and safety are directly related to the provision of uninterrupted temperature-controlled environments throughout the entire distribution chain, from farm to consumer (Han et al., 2021). The cold chain distribution of these products is subject to stringent time and environmental conditions. Any break in the cold chain can accelerate product deterioration, leading to significant economic losses that constitute a major portion of post-harvest waste in developing countries (Hodges et al., 2011). Compounding these physical challenges, the globalisation of agricultural trade has transformed the traditional supply chains into complex multi-stakeholder models. These models comprise geographically dispersed producers, processors, distributors, and retailers. Each is subject to unique sets of regulations and quality management systems. Growing global awareness of food safety and the demand for end-to-end traceability places significant pressure on all stakeholders to adopt transparent and reliable monitoring systems.

The existing traceability systems for fresh agricultural products have three major limitations, which make it difficult for these systems to be effectively applied in practice. The centralised traceability systems create a single point of failure, where any attempt to manipulate the central server undermines the entire traceability record. This problem is even worse when multiple independent entities have to rely on a single source of information, which they have no control over (Bai et al., 2023). The manual verification approach to quality and contractual compliance creates a number of problems, including delays and the potential for fraud, which could otherwise be prevented by automated systems. Most critically, traceability systems are poorly integrated with analytical decision-support tools. Consequently, the huge volumes of environmental and transactional data collected during the cold chain are not effectively utilised

to improve the decision-making process for the supply chain, resulting in a predominantly reactive approach to risk management, without any predictive capabilities to anticipate quality issues before they arise (Kshetri, 2025).

A clear understanding of how these constraints persist is possible in light of two complementary theories which are used to justify the architectural design principles that this paper aims to promote. As posited in the theory of Transaction Cost Economics (Williamson, 1985), the inefficiencies arising from a many-to-many model of supply chains can be traced to the costs of searching, negotiating, monitoring, and enforcing agreements between independent parties, resulting from the exchange of information and value across organizational borders. By eliminating the need for multiple forms of verification of facts on the ground and instead relying on a single authoritative source of information, the cost of transactions is reduced. In Agency Theory (Eisenhardt, 1989), the significance of automatic execution of contractual obligations is explained by the fact that a situation where the agent possessing the knowledge of operations differs from the principal that depends on the agent can lead to opportunism and information asymmetry. This in turn can result in non-compliance with agreed rules and regulations, especially given that monitoring in many cases may prove to be costly and infeasible. Thus, automating contractual logic becomes critical for overcoming the identified constraint.

Blockchain technology, which has the inherent properties of decentralisation, immutability, and cryptographic verifiability, has been identified as a promising solution in addressing the trust deficit in the traceability of the agricultural supply chain (Y. Zhang et al., 2022). It eliminates the need for a central authority by distributing a synchronised ledger across all network participants, while a consensus algorithm ensures the immutability of the data once it has been recorded on the ledger. Smart contracts, which are self-executing contracts on the blockchain, enable the automation of quality verification, transaction settlement, and information sharing according to the specified parameters, thus reducing the need for inter-organisational trust. While the potential of the integration of big data analytics and blockchain-based traceability presents a promising opportunity to transform the raw supply chain data into meaningful intelligence, the exploration of the same in the specific context of fresh agricultural products in cold chains remains a relatively unexplored research domain in the existing literature.

To address the identified gaps, this study proposes a three-layer blockchain architecture based on Hyperledger Fabric, which incorporates chaincode-based smart contracts and a big data analytics module. The primary contributions of this study are threefold. The work introduces a layered architecture that provides a systematic approach to data collection, contract execution, and application services. It develops three smart contracts, namely Quality Certification Contract, Transaction Contract, and Information Sharing Contract, which are designed to execute critical business processes in blockchain-based architecture. It also implements a closed-loop big data analytics module that incorporates parameter optimisation results into the smart contract layer to enable continuous improvement.

For an in-depth understanding of the theoretical and technological underpinning of the framework proposed in this study, the next section reviews the literature relating to traceability systems, blockchain technology, and smart contracts within the supply chain management field. Then, the framework proposed is discussed in detail, while its strengths and weaknesses are analyzed comparatively with respect to other architectures.

Literature Review

Traceability Systems for Fresh Agricultural Products

Several changes can be seen in the structure of the traceability system. From basic product identification using barcodes, the traceability system design has now developed into advanced architectures, utilizing different kinds of sensors as well as different methods for managing data. A combined approach involving the use of blockchain and Radio-Frequency Identification (RFID) tagging has also been studied recently. Under these conditions, the optimisation of the SM3 cryptographic hash function, a hashing standard issued by the State Cryptography Administration of China, has been observed to improve the efficiency of data summarisation by approximately thirty per cent, reducing the execution time of the algorithm in processing 192-byte messages to approximately 210 microseconds (Li et al., 2024). These observations indicate the importance of cryptographic efficiency in the context of traceability system architecture, particularly in conditions where data from multiple nodes in the supply chain is input at a high frequency.

In the specific domain of cold chain logistics, the need for addressing the temperature and time constraints of the distribution of perishable goods has prompted researchers to design specific systems to address this need (X. Zhang et al., 2022). The development of blockchain-based traceability systems for agricultural products demonstrates how sensor data can be structured and stored to enable batch-level tracking, while ensuring secure and tamper-resistant data access for all participants (Yao & Zhang, 2022). Building on this capability, the development of anomaly detection systems based on Internet of Things (IoT) technology has been designed to detect temperature changes in the environment of the products during transportation, which could compromise the safety of the products, meeting the need for immediate action in the face of extreme environmental conditions (Gillespie et al., 2023).

In this regard, the issue of privacy protection is a major factor to be considered in traceability, as the sharing of information across organisational boundaries in a supply chain has implications for commercial confidentiality and leakage of business information that can be used to gain a competitive edge. A proxy re-encryption scheme using a blockchain-based approach has been put forth for protecting biological risk privacy in traceability, indicating that access control must be integrated into traceability architecture rather than being an afterthought (S. Wang et al., 2024). In a broader sense, traceability architecture must be able to achieve a balance between transparency for verification and confidentiality for business information, a factor that has not been adequately addressed by conventional architectures that consolidate data storage, contract logic, and application services within a single undifferentiated layer. In this context, blockchain technology has emerged as a promising solution to reconcile these competing requirements within cold chain logistics.

Blockchain Technology in Cold Chain Logistics

The applications of blockchain technology in the field of agri-food supply chain management have become increasingly common over the years. With the advent of blockchain platforms, there is always an underlying trade-off between decentralization, performance, and security. One of the permissioned blockchain systems that have been considered suitable for use in traceability of agri-food products includes the Hyperledger Fabric framework. Through this platform, authorized users will be able to record their product information while ensuring

transparency (Marchese & Tomarchio, 2022). Furthermore, one of the strengths of the Hyperledger Fabric system is its transactional speed and data privacy features, making it appropriate for enterprise use cases that need identity management capabilities (Rahaman et al., 2024). Apart from selecting the right blockchain platform, it is also important to consider other aspects of architecture. One of the considerations that have been made in relation to the implementation of blockchain-based supply chain management framework involves recognizing the differences between on-chain and off-chain data storage. The reason for this is because of the trade-off that exists between data immutability and storage of large volumes of data in relation to the monitoring of the environment (El Mane et al., 2022). In this regard, there have been efforts to explore the potential of developing a multi-mode blockchain data management strategy through combining consortium-chain and private-chain structures alongside IPFS off-chain storage (Si, 2022).

The efficient utilization of resources is one of the key factors to consider while evaluating the potential for using the technology. The findings of the study conducted on Hyperledger Fabric prove that the endorsement and ordering procedures are resource-intensive, which highlights the importance of designing the architecture of the system effectively without compromising its consensus mechanism (Yang et al., 2022). In addition, practical studies conducted on agricultural supply chains reveal that the channel-based architecture of the platform allows its users to maintain their confidentiality while disseminating the necessary data (Balasubramanian & Akila, 2022).

Recent empirical analysis, on the other hand, has commenced providing quantifiable insight into the operation of Hyperledger Fabric implementations in the field of food and cold chains, thus complementing architectural analyses discussed above. According to Aydoğan (2025), an IoT-sensor-enabled fabric-based implementation of a cold chain solution achieved a throughput of approximately 442 TPS at a send rate of 500 TPS, and 818 TPS at a send rate of 1,000 TPS, with the former resulting in average latencies of 0.21 seconds and latter in average latencies of 0.26 seconds. It appears from the aforementioned performance statistics that the maximum possible throughput of Hyperledger Fabric solutions in food and cold chains is obtained when the load is heavily write-heavy, but not particularly intensive traceability-query-oriented. Using a combination of IoT sensors and Fabric under the Raft consensus algorithm, Oh et al. (2025) observed a maximum throughput of 230.2 TPS, latencies varying from 259 to 279 milliseconds for a range of experiments on two- to four-nodes configurations, and consistently less than 3.2 seconds block-finalisation times for over 114,000 transactions, indicating that even with very frequent data integrity events, integrity is not affected. Moreover, Zhou et al. (2026) illustrated that by means of channel splitting and trust and incentives encoded in the chaincode, confidentiality of sensitive data could be maintained even across rival organisations without sacrificing the throughput, and, importantly, that the process of updating chaincode in Fabric served as a governance layer of its own because the contract logic and endorsement policies were modified only upon approval from multiple parties. The results presented by the authors also indicate that the tradeoff between payload anchors and raw data significantly affects the performance of the solution.

These studies collectively highlight the viability of the blockchain technology, and the Hyperledger Fabric system in particular, for the implementation of cold chain traceability. More importantly, however, these studies reveal that the overwhelming emphasis in the current implementation of the system has been on data recording and access control, with little

attention devoted to the integration with data-driven analytical optimisation, which could greatly enhance the overall efficiency of the system.

Smart Contracts and Big Data in Supply Chain Management

Smart contracts have been identified as one of the primary vehicles for the automation of supply chain activities, especially those that traditionally involve manual verification, negotiation, and enforcement. The implementation of blockchain-based smart contracts in the logistics and supply chain industry has been identified as having the ability to decrease the time taken for transactions and eliminate conflicts resulting from contradicted manual agreements (Alqarni et al., 2023). In addition, the implementation of a blockchain-based framework, focusing on the use of smart contracts for supply chain collaboration, identified the ability of chaincode logic to define complex agreements among different parties in the supply chain in a transparent manner, as well as its ability to be executed automatically upon the satisfaction of specific trigger conditions (Agrawal et al., 2023).

In conjunction with the developments in the automation of contracts, the fusion of artificial intelligence and machine learning with cold chain logistics has revealed new avenues for predictive optimisation. AI and machine learning approaches have been explored to address capacity constraints in cold chain logistics. By forecasting demand fluctuations, these predictive models support more efficient resource allocation, reducing waste and improving service performance (Jackson et al., 2025). When combined with blockchain-based traceability systems, such models can rely on trustworthy and consistent data, further enhancing decision-making capabilities. In the overall context of Industry 4.0, the fusion of blockchain technology, IoT technology, and big data analytics has revealed avenues for the development of holistic systems for the management of food supply chains that encompass the use of real-time monitoring systems, automated decision-making systems, and blockchain-based record-keeping systems as part of an overarching system (Kayikci et al., 2022).

However, a significant research gap has been identified in the current literature in terms of the integration of smart contract automation and big data analytics in a cohesive architectural framework, especially in the context of cold chains of fresh agricultural products. Although the potential of blockchain technology in the agricultural supply chain has been identified in terms of the improvement of traceability and reduction of information asymmetry (Mukherjee et al., 2022), most of the current frameworks consider smart contracts and big data analytics as independent blocks of the overall system rather than as a cohesive part of the system. The proposed framework aims to address this research gap by considering a three-layered system in which the outputs of big data analytics are fed into the smart contract layer through a parameter optimisation process.

Proposed Framework

Overall Architecture Design

At the heart of the proposed framework is a three-layered blockchain architecture, which groups the functional components of the fresh agricultural product cold chain traceability system into three layers, namely the Data Layer, the Contract Layer, and the Application Layer. The suggested three-layer blockchain framework follows the system architecture concepts where the process of data collection and software development is separated from each other.

This makes it possible to develop, test, and maintain every layer of the framework individually while making sure there are proper interfaces that ensure communication between the layers. Moreover, the framework complies with certain architectural patterns used in recent blockchain-based solutions for food traceability (Ellahi et al., 2023). It is built on top of Hyperledger Fabric due to the permissioned nature of the network, channel-based data segregation, and chaincode environment which can ensure complex business logic implementation and access control (AlSallut et al., 2023).

Figure 1 illustrates the overall architecture of the proposed framework, presenting the three-layer structure along with the key components within each layer and the data flow pathways that connect them.

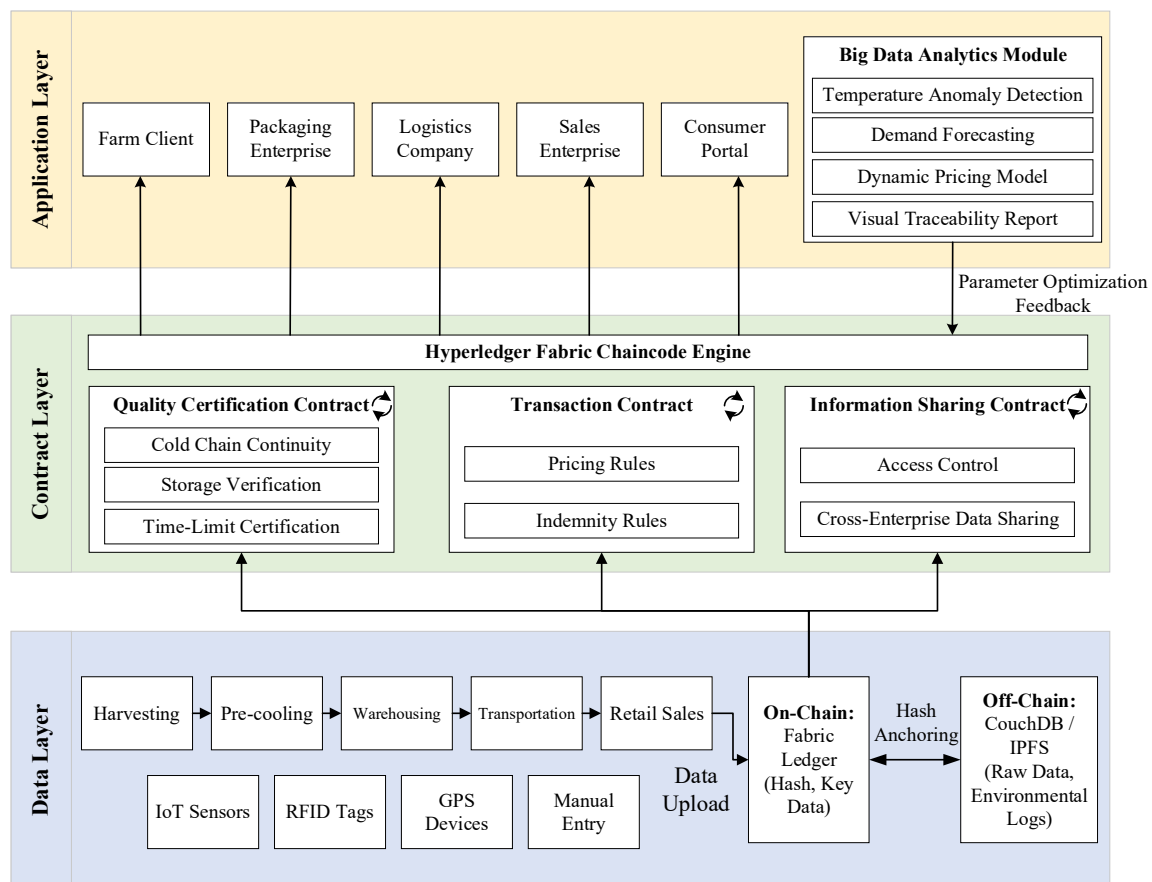


Figure 1: Three-Layer Blockchain Architecture For Fresh Agricultural Product Cold Chain Traceability

As depicted in Figure 1, the Data Layer is the foundation of this architecture, and it consists of five nodes representing a series of physical operations in a supply chain, namely Harvesting, Pre-cooling, Warehousing, Transportation, and Retail Sales, which represent the physical operations of a cold chain for the transportation of fresh agricultural products. The environmental and operational data is collected using four different data collection mechanisms, namely IoT sensors for monitoring temperature and humidity, RFID tags for tracking products, GPS for tracking transportation, and human entry for recording quality inspection data, which requires human intervention. The collected data is stored using a twofold data storage system, namely an on-chain Fabric Ledger for recording hashes and key data for

immutability, and an off-chain data storage system using CouchDB and IPFS for storing raw data files and environmental data, respectively.

Situated above the Data Layer, the Contract Layer includes the Hyperledger Fabric Chaincode Engine and three distinct smart contracts, each of which manages the main operations of the cold chain. Data flowing upward from the on-chain ledger feeds these contracts, allowing them to access the verified information to execute their respective operations. Situated at the top of the structure, the Application Layer provides role-based interfaces for the five distinct categories of users, namely Farm Client, Packaging Enterprise, Logistics Company, Sales Enterprise, and Consumer Portal, and a Big Data Analytics Module to process the aggregated information to produce valuable insights. One of the most important architectural characteristics is the parameter optimisation feedback flowing downward from the Big Data Analytics Module to the Chaincode Engine, thus creating a closed-loop system.

Data Layer Design

As the main interface between physical cold chain operations and the digital traceability system, the Data Layer must support the heterogeneity of the data sources, the high frequency of sensor readings, and the varying criticality of the data for different stages of the supply chain. There is considerable variation in the structure and volume of data collected at each stage of the supply chain process. Data from harvesting will normally be event-driven in nature and relates to the location and the quality of the produce. Pre-cooling and warehousing are two supply chain processes where environmental monitoring is conducted, and the readings may be taken at frequent intervals, including thirty seconds. Temperature monitoring coupled with Global Positioning System (GPS) location data is collected during the transportation phase (Singh & Raza, 2023).

The main conflict in blockchain-based traceability stems from the requirement of verifying the vital pieces of information in an immutable way and the impossibility of recording vast amounts of data collected by sensors. This problem can be addressed by the approach presented based on storing data in two different locations. As per the solution offered here, the Fabric Ledger blockchain contains only hashes, metadata and information related to the transactions. On the contrary, CouchDB/IPFS system includes all data collected – from environment data logging to the highest resolution data coming from sensors as well as additional documentation, e.g., pictures taken during the quality check procedures.

To maintain consistency between these two layers, hash anchoring is employed. This mechanism enables bidirectional verification between the two systems, so that any attempt to alter the off-chain data set will be revealed through a mismatch in hashes when the data is verified against the blockchain-based record (Liu et al., 2022). Under the dual system architecture, the system is designed to support a throughput of approximately 10,000 to 15,000 data records per day across a medium-scale supply chain network consisting of 50 to 80 nodes. However, these parameters are also subject to empirical validation in future system prototypes. Having a reliable data foundation in place, the next question then becomes what form business decisions can be made based on the verified supply chain data, a process handled in the Contract Layer described next.

Contract Layer Design

The Contract Layer forms the core of the business logic of the proposed framework, where three distinct chaincode-driven smart contracts are executed. Each smart contract corresponds to one of the three essential processes in cold chain management: quality certification, commercial transactions, and inter-organisational information sharing. These contracts are executed within the Hyperledger Fabric Chaincode Engine and are automatically triggered by events generated from the Data Layer, thus obviating the need to manually initiate verification, settlement, or authorisation processes (Valencia-Payan et al., 2025). By employing the endorsement policy mechanism of Hyperledger Fabric, the chaincode implementation ensures that the outcome of the execution of each contract is validated by a group of endorsing peers before it is committed to the ledger, thus providing an additional layer of institutional control in addition to the algorithmic logic underlying each contract (Chen et al., 2023).

To illustrate the internal decision logic of each contract, Figure 2 presents a swim lane diagram depicting the execution flow of all three smart contracts in parallel.

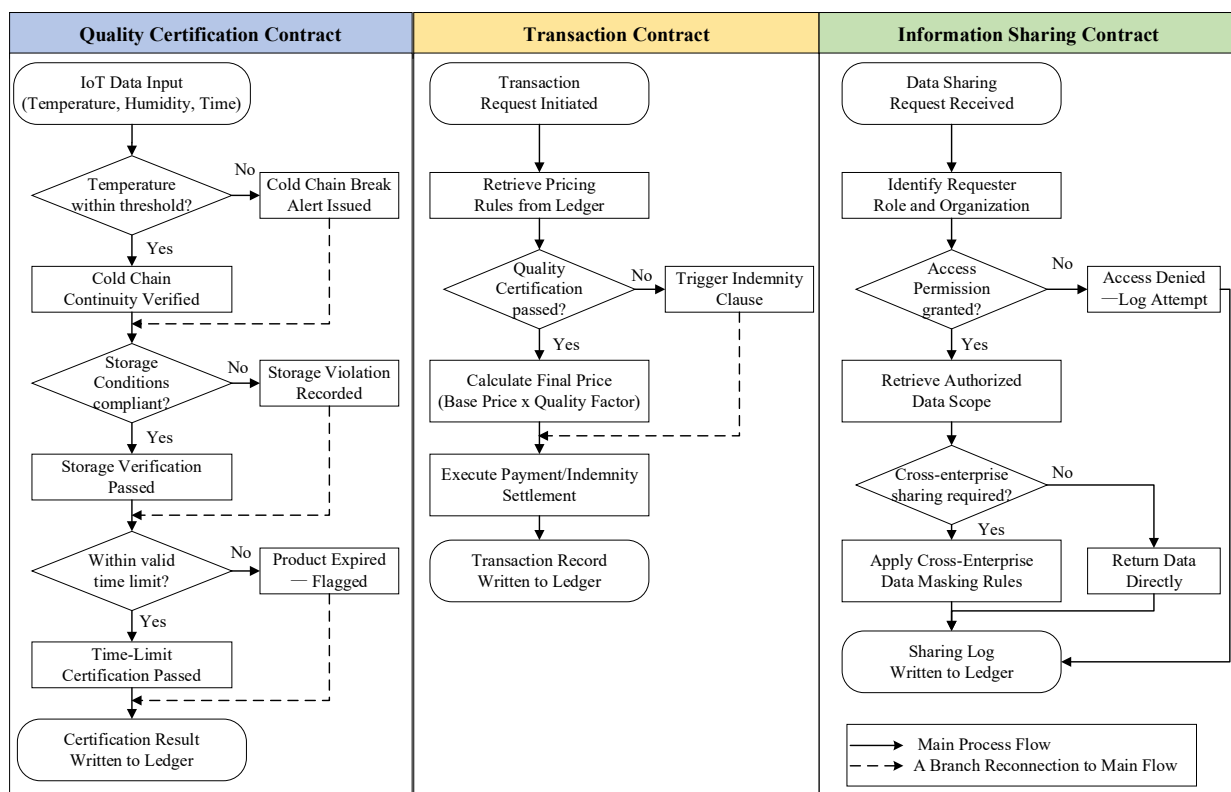


Figure 2: Execution Logic of Three Types of Chaincode-Driven Smart Contracts

Figure 2 illustrates how the Quality Certification Contract performs validation of the IoT inputs of temperature, humidity, and time. The smart contract first determines whether the measured temperature is within the threshold value for the relevant type of products. Should the reading meet the threshold value, it indicates that there is no violation in the cold chain process. Otherwise, there is a violation, which will be permanently documented into the blockchain. It then moves on to performing verification of the storage condition by assessing whether the temperature falls within the required range. If there is a discrepancy, it will be flagged as a

violation and recorded on the blockchain. Lastly, it verifies the time limit, and should the period since harvest exceed the allowed duration, the product will be marked as expired.

It should be noted, however, that the dashed arrows used in the flowchart, denoted by the reconnection lines, illustrate the process advancing even if the checks are not entirely successful, thus providing a holistic evaluation of the product.

In a different logical approach, the Transaction Contract is responsible for the commercial resolution of the transactions by performing the following two functions automatically: firstly, collecting the price formula from the ledger in the beginning of the transaction process; and secondly, cross-checking the quality certification status of the product batch. Upon the successful acquisition of the product's quality certification, the transaction contract computes the final price based on the quality factor of the product through multiplication of the base price with the quality factor, and thus taking into account the discount or premium attached to the product's quality. In case the product does not receive quality certification, the contract implements the indemnity function and resolves the transaction process automatically. All information related to the transaction, including the method of computation of the price, the quality factor used, and the end results, are recorded in the ledger.

The Information Sharing Contract regulates data access by implementing a permission verification system based on role assignment. This ensures that the identity and organizational affiliation of the requesting entity are verified before any access to traceability data is allowed. When the data sharing request is received, the contract verifies the role and organization of the requesting entity, and then it checks whether data sharing is permissible according to the scope of that particular role. In case the answer is negative, the result is stored on the ledger, while otherwise, an additional verification check is performed to determine whether data sharing among different enterprises should be authorized. If not, then data masking is performed so that sensitive data is kept confidential, yet traceability data remains available for verification purposes. Otherwise, the data will be shared directly, without being masked at all. The data sharing events are recorded in the sharing log on the ledger regardless of the outcome of the check. As a result, the combination of these three contracts represents an automated layer that includes quality assurance, financial settlement, and data governance, forming the backbone for the application layer development.

Application Layer and Big Data Analytics Module

The differentiated user interfaces, which meet the needs of five different user categories, represent the front-end part of the Application Layer. The farmer users utilize the interface to provide their data on harvest as well as quality assessment and follow up on the further processing of their produce. The packaging firms enter data related to pre-cooling and packaging of produce, attach RFID tags, and check the quality of the products received so that they meet all required criteria before being processed. The logistics companies provide real-time data on GPS and temperatures during transportation, are automatically notified of any deviation from acceptable levels, and supply proof of delivery statements. The sales enterprises use the interface for transaction, stock, and traceability report generation for customers while Consumer Portal allows customers to read a graphical traceability report.

One unique aspect about the proposed architecture when compared to typical blockchain-powered traceability systems is that it features the Big Data Analytics Module that allows for four different analytics features to turn stored information about supply chains into practical intelligence. In particular, the Temperature Anomaly Detection feature helps detect any anomalies in the temperature patterns through the use of pattern recognition methods and statistical analysis; in case there are any anomalies, it can help take immediate actions so as to prevent any potential impact on the quality of products. As for the Demand Forecasting functionality, it allows predicting future demand levels for products by analyzing past sales information and environmental factors. Additionally, the Dynamic Pricing Model helps update pricing recommendations based on real-time information such as the remaining shelf life of products, their quality and demand patterns. This feature makes it possible to incorporate the inherently time-dependent nature of products' values (Y. Wang et al., 2024). Lastly, the Visual Traceability Reports feature makes it possible to collect data from various points in the supply chain and create an easily understandable visualization report to be viewed both by regular consumers and professional system users. As a typical example of its implementation, one should mention the use of information collected during the first 90 days of operation together with updating data once a week thereafter.

The other important element of this innovation is the presence of closed loop feedback, depicted by Parameter Optimisation Feedback in the diagram (Figure 1). It is not enough for it to act only as an auxiliary analytics function; rather, the Big Data Analytics Module would process past data to look for certain trends or correlations that could impact optimisation of contract parameters: in the Quality Certification Contract case, it could include optimisation of the temperature threshold taking into account the correlation between weather conditions and product quality; in the case of Transaction Contract, it could refer to the pricing factors based on reaction of the market and analysis of price-quality elasticity; and in the case of Information Sharing Contract, optimisation of access control measures based on changes in inter-organisation relations and regulations. As a result, the system would evolve from a simple documentation keeping tool into an effective management tool that learns from itself.

Comparative Analysis and Discussion

Comparison With Existing Approaches

In order to understand the contribution made by this new framework, a comparative study is carried out with other traceability systems using the blockchain technology discussed in various literatures. Five significant criteria have been evaluated in this comparison, which include blockchain technology, smart contract, database, big data, and applicability. These criteria are presented in Table 1.

Table 1: Comparative Analysis of Proposed Framework with Existing Blockchain-Based Traceability Systems

Dimension	Yao and Zhang (2022)	Marchese and Tomarchio (2022)	Rahaman et al. (2024)	Si (2022)	Proposed Framework
Blockchain Platform	Ethereum	Hyperledger Fabric	Hyperledger Fabric	Consortium chain + private chain	Hyperledger Fabric
Smart Contract Coverage	Traceability recording and privacy protection	Product lifecycle tracking	Food processing quality assurance	Data sharing and access control	Quality certification, transaction settlement, and information sharing
Data Storage	Ethereum + IPFS dual storage	On-chain (Fabric with CouchDB state database)	On-chain with CouchDB	Consortium/private chain with IPFS off-chain	Hybrid on-chain/off-chain with hash anchoring (Fabric Ledger + CouchDB/IPFS)
Big Data Integration	Not addressed	Not addressed	Not addressed	Efficiency evaluation only, via Data Envelopment Analysis (DEA)	Closed-loop module with feedback optimisation
Applicability	General agricultural products	Generic agri-food supply chain	Food processing industry	Agricultural cold chain logistics	Fresh agricultural product cold chain with temperature-sensitive requirements

Some points can be drawn from the above comparison. The existing methodologies present varying degrees of complexity in the use of blockchain technology, but no one manages to combine the two seamlessly. While the methodology presented by Yao and Zhang (2022) provides an enhanced data structure for blockchain-based traceability of agricultural products that have both forward and backward tracing abilities, it fails to incorporate the necessary permission network control and privacy data gathering requirements needed for enterprise cold chain logistics.

The two hyperledger fabric-based systems mentioned above have advanced enterprise capabilities but restrict the smart contracts to perform single tasks, namely tracking the lifecycle of a product and the quality of food processing, respectively. They do not cover the full spectrum of activities in the cold chain industry, which include quality verification, commercial transactional activities, and information management simultaneously. Despite the multiple modes architecture introduced by Si (2022), whose design is flexible enough for being implemented as both a consortium network and a private chain using IPFS off-chain storage, the analytical dimension was restricted only to efficiency analysis.

The two interlinked improvements in the suggested system that set it apart from other approaches involve, firstly, the comprehensive nature of smart contracts, which facilitates the parallel execution of three interrelated cold-chain processes within the same chaincode system; and secondly, the closed-loop integration of big-data analysis, which makes it possible for the system to gain new experience based on what it learns and optimize its contractual terms accordingly. These improvements help overcome the main drawback in current approaches – failing to appreciate the true nature of blockchain traceability as a platform for dynamic management (X. Zhang & Ling, 2022).

Advantages And Limitations

These are some of the key benefits provided by this architectural approach. The first benefit is that of modularity, with the use of the three layers enabling easier scaling since extra nodes can be added to the network without changing the contract code. The second is that of system flexibility since separate layers are responsible for data handling and analysis. In addition to that, the use of dedicated smart contracts for such purposes as quality certification, transactions processing, and information exchange makes the proposed architecture more automated and transparent compared to conventional approaches.

However, some of the implementation concerns remain. This model requires data collection through IoT devices and therefore the reliability of sensors plays an important role in determining contract accuracy. Moreover, scalability might require optimization to retain high transaction efficiency.

Furthermore, the effectiveness of the feedback optimization method will depend on the reliability of historical data available, which may be constrained at the early stages of the application. Governance regarding the changes to the contract parameters and especially the authority to change them according to analysis results can be seen as a sociotechnical problem that goes beyond the design aspect. Finally, the compatibility of the Hyperledger Fabric-based solution with existing enterprise resource planning applications in agricultural companies also requires additional development work. None of these problems undermine the theoretical value of the model but point out potential areas for research (Tokkozhina et al., 2023).

Conclusion And Future Work

This research presents a three-tiered architecture of blockchain technology that will be used to implement smart contracts based on chaincodes to improve traceability of perishable agricultural goods through cold chains by utilizing big data analytics. This proposed architecture incorporates hybrid storage techniques, customized smart contracts for authentication and transactions management, and an analytical feedback process to evolve traditional traceability systems into management systems.

The introduction of quality validation, transaction procedures, and information exchange into the blockchain infrastructure in combination with the principles of analytics optimization adds to the traceability architecture by providing more comprehensive application of distributed ledger technology and analytics-based decision making. Nevertheless, it needs to be pointed out that the current contribution reflects a conceptual architecture backed up by comparative analysis, which is why the assertions put forward in this paper cannot be interpreted as performance metrics. Testing the performance in terms of throughput, latency, efficient

storage, and cost of consensus processing will become the focus of the next phase of the research.

Future studies will emphasize the design and development of a prototype based on Hyperledger Fabric test network in order to perform a realistic assessment of system performance characteristics, such as transactional throughput, querying latency, and consensus processing times. Pilot implementations in real-world use cases of fresh agricultural produce supply chains will also provide insights regarding practical application viability. The Big Data Analytics module will also be enhanced using machine learning methods for performing predictive modeling of quality degradation. In addition, governance models for adjusting the parameters of the smart contracts will also be implemented.

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Ethics Statement: This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.

Author Contribution Statement: The contributions made by Huixiang Ruan included the conceptualization of the research work, the design of the three-layer architecture model, the development of the logic behind the smart contracts, the comparative analysis of the proposed system against other systems, and the preparation of the first draft of the manuscript. On the other hand, Zainura Idrus contributed in the form of general academic supervision, the enhancement of the architectural model design, the positioning of the methodology used in the research, and the critical review of the manuscript.

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