

Optimization of Agricultural Product Quality and Safety Traceability Systems in a Multi-Chain Collaborative Framework

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Abstract: The quality and safety of agricultural products are crucial to the development of modern society and constitute a vital factor affecting the interests and development of the entire supply chain. The traditional single agricultural product quality supervision system is gradually unable to meet the increasingly growing market demand. This study addresses the performance bottlenecks and trust barriers of traditional traceability technologies in high concurrency, heterogeneous data, and cross-domain circulation by constructing a blockchain-based full-chain traceability system for agricultural products. It proposes a three-dimensional architecture model that integrates the collaborative functions of the logical layer, physical layer, and data layer, and innovatively designs an intelligent sharding strategy and a chain-network collaborative architecture. These measures effectively improve the utilization rate of distributed storage resources and the speed of traceability response, while significantly reducing the operating costs of the blockchain. Through the collaborative optimization of the heterogeneous multi-chain architecture and chain-network integration technology, the efficiency and security of the agricultural product traceability system are realized. The feasibility of the system is verified through model performance analysis and the design of a traceability system for pilot enterprises, providing references for the application of blockchain technology in the field of agricultural product traceability.

Keywords: Agricultural Product Quality and Safety Traceability; Blockchain Technology; Multi-Chain Collaborative Architecture.

1. Introduction

In the era of rapid digital economic development, the quality and safety of agricultural products have increasingly drawn attention from all sectors of society. Consumers' demands for food safety are continuously increasing, and regulatory authorities are paying more attention to the construction of agricultural product traceability systems. The multi-chain collaborative scenario based on blockchain technology has become an effective approach to solve the problem of agricultural product quality and safety traceability. By integrating various participants in the supply chain, blockchain can realize transparent information sharing at each link, ensuring that every step of agricultural products from production, processing to sales can be tracked and verified [1].

However, in practical applications, multi-chain collaboration based on blockchain still faces many technical challenges. First, the phenomenon of data silos among participants is severe, and the lack of effective cooperation and data sharing mechanisms leads to low traceability efficiency [2]. Second, the standardization issue of blockchain technology still exists, and the compatibility between different blockchain platforms is insufficient, making information circulation and data integration complex. In addition, security and privacy protection are also important issues to be solved, especially when involving trade secrets and user privacy, how to ensure data security and privacy has become a challenge [3].

Despite the technical complexities, the application of multi-chain collaborative architecture can bring significant value to the traceability of agricultural product quality and safety. On the one hand, through multi-chain hierarchical design, it can not only achieve fine-grained governance of data in each link [4], but also connect the full-chain

information flow through cross-chain protocols to improve traceability efficiency and transparency [5]. For example, consumers can quickly obtain cross-chain verification information such as planting environment and quality inspection reports by scanning product QR codes, while regulatory authorities can monitor abnormal nodes in real time. On the other hand, multi-chain collaboration can reduce the threshold for multi-party collaboration, and automatically execute the rights and responsibilities rules of supply chain parties through smart contracts, thereby reducing disputes and enhancing trust [6]. Existing studies have obvious limitations: general sharding strategies lead to low cross-shard rates of agricultural product spatio-temporal related transactions, cross-chain protocols lack support for polymorphic data verification [7], and the governance model is insufficiently adapted to the three-level regulatory system. To solve these problems, it is urgent to build a technical system based on dynamic sharding and cross-chain verification to achieve innovative breakthroughs in data sovereignty balance, performance bottleneck breakthrough, and policy compliance collaboration.

2. Multi-Chain System Architecture Design

2.1. Tri-Dimensional Architecture Model

Blockchain technology has addressed the shortcomings of traditional traceability systems; however, blockchain traceability systems simultaneously bring about issues such as excessive information data storage load, low query efficiency, and data privacy and security risks .

(1) Current blockchain traceability technologies mainly involve directly writing traceability data from various links into the blockchain. As the number of nodes increases, more

source data needs to be processed, which significantly increases the storage load of the blockchain. Due to the special decentralized structure of the blockchain, the speed of data querying is very slow.

(2) Every node member can access all information in the ledger through the blockchain, which poses security risks regarding important data among competitors. On the basis of safeguarding the rights and interests of all participants in the agricultural product supply chain, there exist issues where it is inconvenient to disclose certain internal information of participants and transaction information between participants. However, when applying a single blockchain architecture to solve the traceability problem of agricultural products, due to the low degree of isolation between nodes, it is difficult to protect the personal privacy of each participant.

In the complex scenario of agricultural product quality and safety traceability, to effectively address such core contradictions in the single-chain architecture as excessive data storage load, inefficient cross-entity collaboration, and inadequate privacy protection, this study innovatively constructs a three-dimensional architecture model featuring in-depth collaboration among the logical layer, physical layer, and data layer. Among them, the logical layer, as the core hub for the collaborative operation of the system, adopts the design concept of hierarchical interoperability. It realizes efficient collaboration among multi-domain entities in the agricultural product supply chain by establishing a three-layer chain network structure where the supervision chain, production chain, and detection chain are mutually independent yet organically connected.

The supervision chain mainly carries authoritative information such as policy standards, sampling inspection results, and violation disposal from government regulatory authorities, providing a compliance basis for quality control throughout the entire chain. The production chain focuses on production operation data in links such as planting and breeding, processing and packaging, and warehousing and logistics, including agricultural operation records, processing parameters, and logistics trajectories, forming a traceability chain for the production process throughout the product's entire life cycle. The detection chain is specifically used to store quality inspection data from third-party testing institutions, including test reports on key indicators such as pesticide residue detection, microbial indicators, and heavy metal content. The three-layer chains realize trusted data sharing and authorized access through pre-set cross-chain interaction protocols. This not only ensures the professionalism and independence of data in various fields but also breaks down information silos through an interoperability mechanism, providing a collaborative framework with clear logic and defined responsibilities for the traceability of agricultural product quality and safety.

As the hardware support and cornerstone of data access in the three-dimensional architecture model, the deployment scheme of the physical layer innovatively adopts a hybrid architecture featuring in-depth collaboration between centralized supervision nodes and edge computing nodes, aiming to balance the global management and control capabilities of the traceability system with the real-time requirements of terminal data collection. The national - level traceability platform, as the core node, is deployed on the government affairs cloud and is responsible for formulating cross - chain verification rules and global consensus; the provincial - level nodes, as regional hubs, undertake the

transaction routing function, and the prefecture - level edge nodes realize the real - time data collection in the field through lightweight clients.

As the core data carrier of the three-dimensional architecture, the data layer innovatively designs a tri-state storage engine. It realizes efficient processing of multi-source data through a collaborative mechanism involving structured relational databases, distributed file systems, and blockchain ledgers. Specifically, structured databases are responsible for storing regular data such as agricultural product codes and subject qualifications, ensuring query efficiency by virtue of indexing mechanisms. Distributed file systems focus on processing unstructured data like agricultural operation images and detection videos, improving storage scalability through sharded redundancy. Blockchain ledgers store hash values of key traceability information, laying a solid foundation for data trust with their tamper-proof nature. The three components are linked through mapping rules to automatically complete classified data storage and associated indexing. This not only breaks through the efficiency bottleneck of single-mode storage but also ensures data credibility, providing reliable support for the traceability system. Key quality parameters are stored in the blockchain to ensure non - tampering. Unstructured data such as video streams of the production environment are stored in a distributed manner using IPFS [9], while structured data such as supply chain relationships are analyzed in a correlated manner through a graph database.

2.2. Transaction Processing Flow

Cross-chain transaction processing adopts a five-stage closed-loop control mechanism. In the pre-submission phase of the transaction processing flow, the traceability requester initiates a data query or verification transaction request by invoking the interface of a preset smart contract. The system then triggers an automated credential generation mechanism, producing a transaction credential containing a 32-byte unique identifier. This identifier integrates the requester's digital signature, timestamp, and transaction type encoding, ensuring the global uniqueness and traceability of each transaction. At this stage, the SHA-256 encryption algorithm is applied to perform hash operations on the request data, generating fixed-length summary information that is written into a temporary buffer. A hash value comparison mechanism is employed to prevent data tampering during transmission, thus safeguarding data integrity from the source. Simultaneously, to avoid resource congestion caused by invalid requests, the system is equipped with a 5-second timeout control mechanism. If the requester fails to complete subsequent parameter confirmation within the specified time, the transaction will be automatically terminated and the occupied computing resources will be released, thereby enhancing the overall operational efficiency of the system.

Upon entering the multi-chain verification phase, the transaction request is routed to the cross-chain verification committee. Based on the industrial chain links involved in the transaction and the supervision level, the committee dynamically selects a verification group consisting of 3 qualified regulatory nodes and 2 core enterprise nodes. The verification group conducts parallel reviews in accordance with preset consensus rules: regulatory nodes focus on verifying the compliance of the transaction and the authority of data sources, while enterprise nodes concentrate on checking the consistency of business logic. This approach

enhances verification efficiency through distributed parallel computing, and simultaneously reduces the risk of misjudgment by a single node by means of an inter-node cross-validation mechanism, thus providing multi-dimensional credible endorsement for the final confirmation of the transaction [10].

The atomic submission stage uses an improved two-phase commit protocol and combines it with a threshold signature mechanism, setting a 3/5 voting threshold to ensure strong consistency, compressing the transaction confirmation time to within 2 seconds [11]. The state synchronization stage relies on a lightweight relay chain for cross-chain data alignment, and a dedicated compression algorithm based on Huffman coding is developed to reduce the synchronization bandwidth consumption by 56%. The exception handling mechanism designs an automatic compensation process for fault scenarios such as network partitions.

3. Dynamic Optimization Technical Countermeasure – Intelligent Sharding Strategy

The intelligent sharding strategy system constructed in this study establishes a decision-making model based on the ontological characteristics of agricultural products and data behavior patterns. This system realizes classification decision-making through a multi-dimensional feature matrix encompassing physical attributes, circulation characteristics, and supervision levels. For perishability-dominated agricultural products, a high-frequency sharding strategy is adopted, and the sliding time window algorithm is used to dynamically control the data encapsulation interval within the range of 5-10 minutes, which meets the strict requirements of industry standards for the real-time performance of traceability. For cold chain-dependent products, a multi-replica sharding architecture is designed, with a triple redundancy storage mechanism deployed at cold chain nodes. Combined with blockchain Merkle tree verification technology, it strengthens the guarantee of data integrity. For products under strong supervision, an encrypted sharding mode is implemented, and a data encryption system is built using the national cryptographic SM4 algorithm.

The sharding strategy generator automatically configures parameters according to product classification codes. The storage interval is dynamically calculated based on the corruption rate index, with the time threshold controlled within 10 minutes and following an exponential function relationship. The number of replicas is determined based on cold chain coverage in accordance with linear constraint rules, while the encryption strength forms a composite encryption mechanism with a positive correlation to the supervision level. The dynamic adjustment module integrates an LSTM neural network to construct a time series prediction model. By analyzing 12-dimensional feature parameters such as regional transaction volume fluctuations and cold chain equipment status, it outputs a sharding granularity adjustment coefficient β to achieve adaptive optimization. When the β value exceeds 1.5, it triggers a sharding fission mechanism based on geographic grids; when it is lower than 0.8, it initiates a data aggregation process driven by locality-sensitive hashing. Empirical verification shows that, on the premise of ensuring traceability timeliness, this system increases the utilization rate of distributed storage resources to over 92%, achieving a balance between efficiency and stability.

4. Implementation of the Multi-Chain Collaborative Blockchain System Architecture

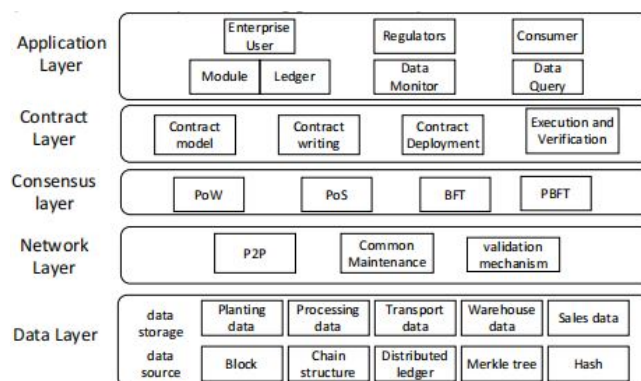


Figure 1. Multi-chain collaborative blockchain architecture

This study constructs an optimized architecture for the agricultural product quality and safety traceability system based on multi-chain collaborative blockchain technology, adopting a five-layer design, which is mainly divided into the data layer, network layer, consensus layer, contract layer, and application layer, as shown in Figure 1. Data Layer: Stores full-process data including planting, processing, logistics, warehousing, and sales. Blockchain technology is used to ensure data immutability and traceability. Network Layer: Composed of planting, processing, logistics, warehousing, sales, and regulatory nodes, enabling distributed storage and sharing of data. Consensus Layer: Adopts the DPoS (Delegated Proof of Stake) mechanism to verify the authenticity of data in each link, preventing tampering and forgery. Contract Layer: Automatically executes business rules through smart contracts, such as freezing inventory for excessive pesticide residues, recalling products for cold chain disruptions, and recalling expired products, reducing human intervention. Application Layer: Provides services such as terminal query, full-link dashboards, and risk early warning for consumers, enterprises, and regulatory authorities, achieving transparent management of the entire process. By integrating blockchain technology with smart contracts, the system establishes a multi-party participatory, efficient, and trustworthy agricultural product traceability system, effectively improving food safety supervision and consumer trust.

During the field research at a vegetable cooperative in Zhengzhou, this study constructed a quality and safety management system for the vegetable supply chain based on the multi-chain collaborative blockchain model. With an annual output of over 50,000 tons, the cooperative covers the entire processes of seedling cultivation, planting, harvesting, sorting and packaging, cold chain logistics, and terminal sales. The research revealed that due to the cooperative's adoption of the "company + farmer" business model, there are pain points in the production process, such as non-standard agricultural operation records, opaque information on the use of agricultural inputs, and difficulties in defining quality responsibilities across different links.

After the application of this model, the L2 production chain records in real-time the temperature and humidity sensor data from the seedling base and the electronic agricultural operation logs of growers. By adopting lightweight sharded storage, the daily 4.6 TB of IoT data is compressed to 1.2 TB. The L1 supervision chain automatically synchronizes the

sampling inspection reports from quality inspection departments. When excessive pesticide residues are detected in a certain batch of products, the smart contract freezes the inventory of the relevant batch within 17 seconds. Empirical data shows that after the implementation of the system, the integrity rate of the cooperative's agricultural operation data has increased to 94%.

5. Conclusion

This study systematically constructs a blockchain technology system for the full-chain traceability of agricultural products. Through the combination of theoretical innovation and practical verification, it solves the performance challenges of blockchain in agricultural scenarios. The three-dimensional decision model constructed based on the ontological characteristics of agricultural products realizes the collaborative optimization of high-frequency sharding, redundant storage, and secure encryption through the fusion of multi-dimensional features such as physical attributes, circulation characteristics, and regulatory levels. The gradual evolution path from single chain to chain network constructs a distributed ledger system covering the entire process of production, circulation, and supervision.

Follow-up research will focus on exploring a cross-chain privacy computing framework based on federated learning to break the trust barrier in multi-subject data collaboration, improving the mechanism of agricultural digital asset securitization, and constructing an on-chain credit evaluation and risk early-warning model.

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