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Performance optimization of agricultural traceability blockchain based on sharding technology

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RESEARCH ARTICLE

Abstract

With the increasing global concerns over food safety, ensuring the transparency and traceability of agricultural products throughout their entire production-to-consumption process has become a key issue of societal interest. Blockchain technology, due to its decentralized, immutable, and transparent nature, offers a novel solution for the traceability of agricultural products. However, traditional blockchain systems encounter performance bottlenecks when handling large-scale agricultural data, particularly under conditions of high data volume and frequent transactions, where issues such as processing delays and insufficient throughput commonly arise. Sharding technology, a critical approach for improving blockchain performance, has the potential to significantly enhance system throughput and response time by partitioning the blockchain network into multiple independent shards for parallel processing. However, the application of sharding technology in agricultural traceability systems faces several challenges, including shard load imbalance, communication delays between shards, and inefficiencies in consensus algorithms. To address these challenges, two innovative approaches were proposed in this study: firstly, to address the issue of uneven load distribution in sharding, a jump hash sharding algorithm was designed to optimize shard allocation strategies, thereby improving resource utilization and processing efficiency; secondly, to tackle the performance bottleneck of consensus algorithms, an enhanced consensus algorithm was introduced to improve consensus efficiency while maintaining security. Experimental results demonstrated that the proposed method significantly outperformed traditional blockchain-based traceability systems in terms of performance and scalability, providing a more efficient and reliable technological solution for the application of blockchain technology in the agricultural sector. This research not only offers a more efficient technological solution for agricultural product traceability but also paves the way for new applications of blockchain technology within the agricultural domain.

Keywords: agricultural product traceability; blockchain; consensus algorithm; hump hash sharding algorithm; performance optimization, sharding technology

Introduction

As the global issue of food safety continues to emerge, ensuring the transparency and traceability of agricultural products from production to consumption has become a focal point of societal concern (Ahamed *et al.*, 2024; Manoj *et al.*, 2023; Nguyen *et al.*, 2024; Puška and Stojanović, 2022; Rajput *et al.*, 2023; Reffatti *et al.*, 2022; Zhai *et al.*, 2024). Agricultural supply chain traceability systems worldwide face challenges related to information transparency, data immutability, and rapid response. Blockchain technology, with its decentralized structure and high security, has become a key solution in this field. With its decentralized nature, immutability, and transparency, blockchain technology has provided a new solution for the traceability of agricultural products (Agarwal *et al.*, 2023; Bistarelli *et al.*, 2023; Mishra *et al.*, 2024; Salimibeni *et al.*, 2022; Trinh and Nguyen, 2023). However, given the vast data and complex traceability demands of agricultural products, traditional blockchain systems encounter significant performance challenges, necessitating technological innovations to enhance their scalability and efficiency.

Traditional blockchain traceability systems, as illustrated in Figure 1, consist of three main components: the front-end functional module, the back-end functional module, and the contract functional module. The front-end module primarily provides the interaction interface between the system and users. The back-end module serves to provide interfaces for the front-end pages. The contract functional module facilitates the querying and tracing of on-chain data using standard hash algorithms. However, the limited shelf life and vast variety of agricultural products result in large data volumes and complex traceability requirements. Traditional sharding algorithms often struggle to achieve load balancing across multiple nodes, leading to low utilization of computing resources. Moreover, consensus algorithms like PBFT experience a sharp decline in efficiency as the number of nodes increases, limiting the system's scalability and real-time performance. In this context, research on blockchain traceability systems for agricultural products based on sharding technology is of significant importance (Girish Kumar *et al.*, 2022). Sharding technology, by dividing the blockchain network into multiple independent shards, enables systems to process more transactions in parallel, thereby substantially increasing the blockchain's processing capabilities and throughput (Bhatnagar and Thankachan, 2023; El-Kosairy *et al.*, 2024; Kumarswamy and Sampigerayappa, 2024; Liu *et al.*, 2024; Shreya and Nagamani, 2023; Rajo-Iglesias *et al.*, 2014; Xiao *et al.*, 2023). This not only enhances the performance of agricultural product traceability systems but also promotes the widespread application and adoption of blockchain technology in agriculture, further safeguarding food safety and consumer rights.

In recent years, research on the application of blockchain technology in the agricultural sector has gained increasing attention, particularly in areas such as food traceability, supply chain management, and quality monitoring. Much of the research has focused on how blockchain can address issues related to data tampering, information transparency, and cross-departmental collaboration. However, despite

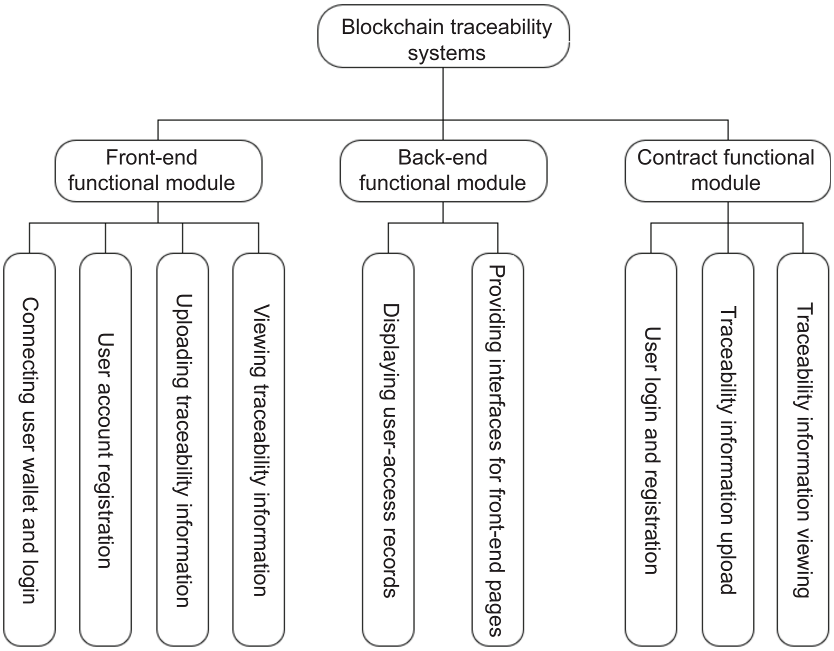

Figure 1. Traditional blockchain traceability systems.

certain progress in small-scale agricultural traceability systems, blockchain systems for large-scale agricultural production and distribution still face numerous challenges (Bikoro, 2022; Nandhini *et al.*, 2024). A key issue that remains unresolved is how to handle the diversity and seasonal fluctuations of agricultural products, along with the associated demand for large-scale data processing.

The scalability problem of blockchain is a significant barrier to its application within the agricultural sector. Traditional blockchain systems process all transactions through a single-chain structure, but as transaction volumes increase, system performance and response speed rapidly decline (Honari *et al.*, 2022; Lanjewar *et al.*, 2022; Liang *et al.*, 2021; Zhang *et al.*, 2022). In recent years, sharding technology has been proposed and gradually applied in various fields as an effective means of enhancing blockchain performance and scalability (Dhulavvagol *et al.*, 2023; Joni *et al.*, 2023; Liu *et al.*, 2023; Ramburn *et al.*, 2023). In agricultural product blockchain traceability systems, a primary research focus has been on optimizing sharding strategies to accommodate large-scale agricultural data while ensuring high throughput and low latency. However, existing sharding technologies are not yet fully matured in the agricultural sector and continue to face issues such as shard load imbalance, transaction latencies, and inter-shard communication problems.

The perishable nature of agricultural products and seasonal fluctuations make the distribution process of such products highly complex. The journey of agricultural products from field to table typically involves multiple stages and participants, including planting, processing, transportation, and sales. Traditional traceability methods face challenges such as information silos and data opacity. Blockchain technology, with its immutability and transparency, offers significant advantages in ensuring the authenticity and integrity of data (Lu *et al.*, 2024; Salah *et al.*, 2019; Zheng *et al.*, 2023). However, these unique challenges in the agricultural sector present numerous difficulties in the practical application of blockchain. For example, in cases of significant seasonal fluctuation, the rapid changes in agricultural product production and demand require blockchain systems to have high throughput and fast response capabilities to handle frequent transactions and data updates. Furthermore, the perishable nature of agricultural products necessitates traceability systems that can monitor and record the status of each stage in real time, ensuring the timely transmission and updating of information. Consequently, the design of an efficient, low-latency, and scalable blockchain traceability system has become central to resolving traceability issues in the agricultural sector. An optimized solution based on sharding technology is proposed in this study to improve the adaptability of blockchain systems in agricultural applications.

This study primarily investigates two aspects: first, the introduction of a jump hash sharding algorithm tailored for agricultural product blockchain traceability systems, aimed at addressing the issue of shard imbalance and enhancing system processing capabilities; and second, the design of a new consensus algorithm specifically for sharded blockchain in agricultural product traceability systems, intended to improve the system's consensus efficiency without compromising security. The first part of this paper provides an overview of the current status and challenges of sharding algorithms. The second part presents a jump hash sharding algorithm to achieve better load balancing. The third part designs a new consensus algorithm to enhance both efficiency and security. Finally, the fourth part validates the effectiveness of the aforementioned algorithms through experiments. This study seeks to provide more efficient and reliable technological solutions for agricultural product blockchain traceability systems, fostering a deeper application of blockchain technology in the field of agriculture.

Jump Hash Sharding Algorithm for Agricultural Product Blockchain Traceability Systems

Algorithm principle

This study focuses on enhancing the performance and efficiency of blockchain in agricultural product traceability systems. The investigation revolves around two core components: the optimization of the jump hash sharding algorithm and the consensus algorithm. The application of the jump hash sharding algorithm in agricultural product blockchain traceability systems primarily aims to address issues related to data storage and access efficiency. In traditional blockchain systems, each node is required to store and process the entire blockchain's data, which not only consumes substantial storage space but also increases the time required for data processing. By introducing the jump hash sharding algorithm, the blockchain network's data is sharded and stored across different nodes, with each node only needing to handle and store the data relevant to itself. This approach significantly reduces the storage burden on individual nodes and greatly enhances the efficiency of data access and processing. Figure 2 illustrates the blockchain sharding model for agricultural product blockchain traceability systems. Nodes are randomly assigned to various shards based on the jump hash rule and automatically adjust their allocation according to the load. When a shard becomes ineffective, the algorithm automatically rebalances the load.

Agricultural product blockchain traceability systems need to handle a large volume of data, including detailed information about production, transportation, and sales.

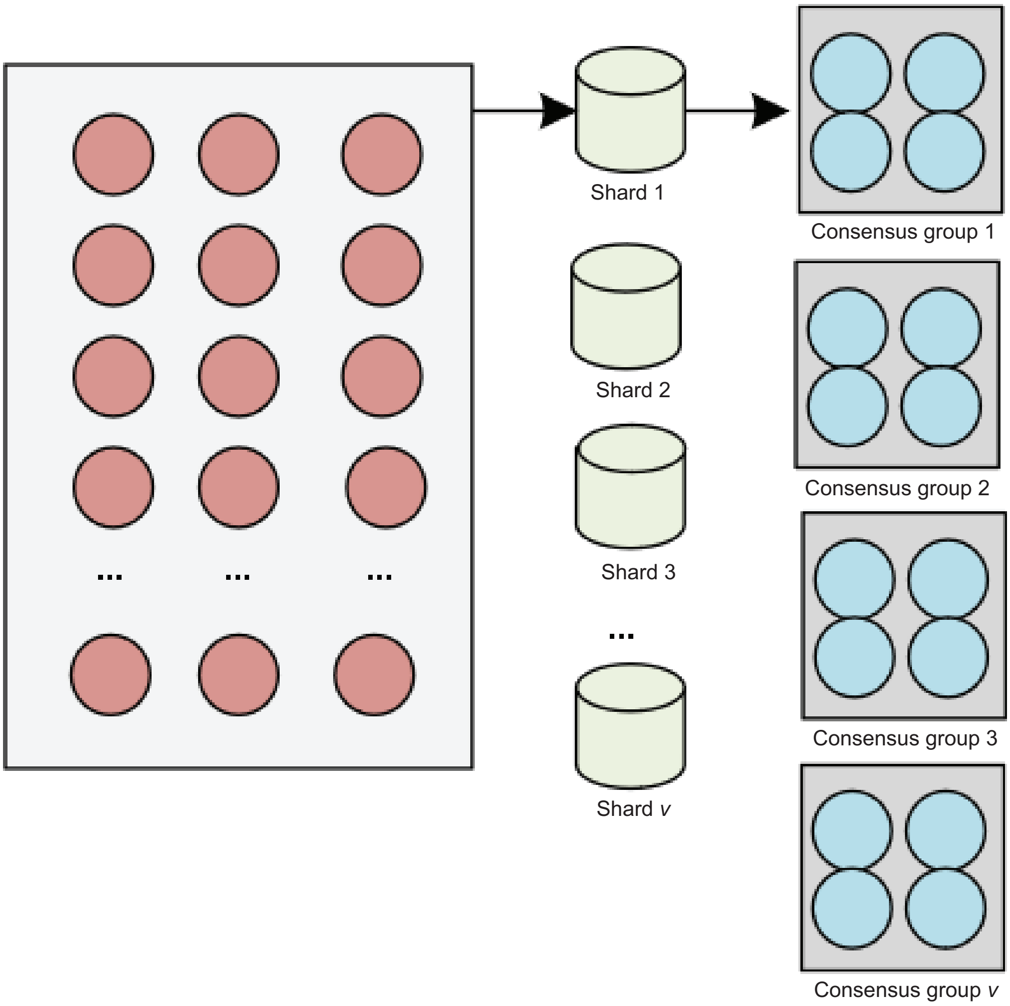

Figure 2. Blockchain sharding model for agricultural product blockchain traceability systems.

This imposes high demands on the systems' storage and processing capabilities. The traditional consistent hash algorithm fails to effectively address the issues caused by node performance variability, leading to excessive load on some nodes while others remain underutilized, thereby affecting the overall efficiency of the systems. Additionally, as the systems scale and nodes dynamically change, the traditional sharding algorithm may result in extensive data migration, increasing network communication costs and further reducing system efficiency. To overcome these challenges, a jump hash sharding algorithm based on dynamic weights is proposed in this study. This algorithm employs a two-dimensional weight matrix M, dynamically mapping the performance indices of nodes to the weight dynamics of shards, thereby achieving rational allocation and dynamic adjustment of shards.

Specifically, the algorithm enhances system performance through two core mechanisms: dynamic weight allocation and two-dimensional weight matrix mapping. Shard weights are dynamically adjusted based on the actual performance of each node, ensuring that the load each node bears matches its processing capabilities. This adjustment prevents overloading or underutilization of nodes, thereby enhancing overall resource utilization and processing efficiency. By constructing a two-dimensional weight matrix, nodes and shards are efficiently mapped. This matrix not only accounts for performance differences among nodes but also allows for rapid adjustment of shard distribution when nodes are dynamically added or removed, minimizing unnecessary data migrations and communication overhead, and thereby enhancing the system's adaptability and stability.

In the context of agricultural product blockchain traceability systems, the three steps of the jump hash sharding algorithm can be elaborated as follows:

Step 1: Measuring shard weights

The adaptability and processing efficiency of blockchain systems are particularly crucial for managing data across all stages of agricultural product production, transportation, and sales. By accurately measuring node load, shard credit, and transaction rate, the systems ensure the timeliness and accuracy of traceability information, enhancing the transparency and reliability of the supply chain. The metrics of node load, shard credit, and transaction rate respectively reflect the workload of the node, the credibility of the shard within the system, and the frequency of transaction processing. The weight values for each metric are determined through multiple experiments to ensure they accurately reflect the actual operational status of the systems. Specifically, the total number of nodes is denoted by v, and the number of shards by l (where $l << v$). The u-th shard is represented by t_u, where $u = 0,1,...,l\text{-}1$. The weight q_u of each shard is measured based on node load, shard credit, and transaction rate.

Step 2: Standardization of metrics

The numerical processing of shard credit and transaction rate can be standardized to convert them to the same scale. The numerical processing of node load must also be standardized to ensure that the loads across different nodes can be fairly compared and measured. After standardization, the values of each metric can directly participate in the weight calculation, thereby accurately reflecting the actual state of each shard. Assuming the original value is denoted by r'_{uk}, and the processed value by r_{uk}, with the minimum and maximum values denoted by MIN and MAX, respectively, the equation for processing the values of shard credit and transaction rate is given by:

$$r_{uk} = \left[\frac{r'_{uk} + 1 - MN}{MAX + 1 - MIN} \times \frac{v}{l} \right] \tag{1}$$

The equation for processing the value of the node load is given by:

$$r_{uk} = \left[\frac{1}{\log\left(r'_{uk} + 1\right) + 1} \times \frac{v}{l} \right] \tag{2}$$

Step 3: Calculation of shard weights

In the agricultural product blockchain traceability systems, the weight calculation formula for the u-th shard is: $q_u = \sum_{k=1}^{3} q_{uk} r_{uk}$, where q_{uk} represents the weight of the u-th shard on the k-th metric, and r_{uk} represents the standardized value of the i-th shard on the j-th metric. Using this equation, the composite weight of each shard is calculated. Ideally, if all metric values for each shard are zero, then the weight q_u equals v/l, indicating that each node corresponds to one virtual shard, achieving a perfectly uniform state. However, this is nearly impossible in practice. The shard weight q_u determines the number of virtual shards for each shard, aiming to achieve load balancing and efficient data processing.

The algorithm pseudocode is as follows:

```
def jump_hash_sharding(data, num_shards):
    # Initialize hash function and number of shards
    hash_function = hashlib.sha256
    num_shards = num_shards
    # Compute the hash value of the data
    hash_value = hash_function(data.encode(‘utf-8’)).hexdigest()
    # Calculate the shard path using jump hash method
    hash_int = int(hash_value, 16)
    shard_index = hash_int % num_shards
    # Return the target shard for the data
    return shard_index
```

Algorithm analysis

In the agricultural product blockchain traceability systems, various nodes are required to process batches of agricultural product data, which include critical information such as production dates, places of origin, quality inspection details, and transportation routes. To ensure effective data access and management, the sharding algorithm must guarantee a balanced distribution of data across all nodes. Specifically, in the context of agricultural product blockchain traceability systems, the probability of any virtual shard being allocated to a particular node is $1/\sum_{u=0}^{l-1} q_u$ for the jump search algorithm. Consequently, the average number of nodes contained in each shard is $v/\sum_{u=0}^{l-1} q_u$. For a given shard t, the number of nodes it includes is calculated as $v \times q_t / \sum_{u=0}^{l-1} q_u$. This indicates that the jump search algorithm can dynamically adjust the allocation quantity based on the weight of the shard while allocating the nodes, thereby meeting the requirements for balance. In the algorithm, the row and column numbers of the target shard in the two-dimensional weight matrix are also determined through the jump search algorithm. When searching for a target row, the probability of selecting row u is $\sum_{k=0}^{w-1} L_{uk} / \sum_{u=0}^{o-1} \sum_{k=0}^{w-1} \sum L_{uk}$. Within the target row u, the probability of locating the target column k is $L_{uk} / \sum_{u=0}^{o-1} L_{uk}$. Thus, the probability of a node being mapped to a corresponding shard in the two-dimensional weight matrix is $O(u,k) = \sum_{k=0}^{w-1} L_{uk} / \sum_{u=0}^{o-1} \sum_{k=0}^{w-1} L_{uk} \times L_{uk} / \sum_{k=0}^{w-1} L_{uk} = L_{uk} / \sum_{u=0}^{o-1} \sum_{k=0}^{w-1} L_{uk}$, which is proportional to the shard's weight, indicating that the jump hash sharding algorithm based on dynamic weights satisfies the requirements for shard balance.

Efficient data processing is also a key requirement within agricultural product blockchain traceability systems. During peak periods of agricultural product circulation, key data such as quality inspection information and transportation routes might be frequently updated and accessed. The proposed sharding algorithm can utilize a dynamic weight mechanism to adjust the weights of these data in real time, ensuring they are distributed across nodes with lighter loads to avoid performance bottlenecks caused by overloaded nodes. Moreover, the time complexity of the algorithm ensures that the efficiency of node mapping remains within an acceptable range, even when the number of shards is large. Specifically, the time complexity for constructing the two-dimensional weight matrix L is linearly related to the number l of shards, denoted as $P(l)$. When calculating the corresponding shard for a node, which involves locating the target shard's row and column, the associated time complexity is $P(log\ O)$, primarily due to the efficient search techniques, such as binary search, employed by the jump search algorithm. Therefore, considering the time complexities for building the two-dimensional weight matrix and computing node shard assignments, the total time complexity is $P(l)+P(log\ O)$. However, since changes in shard weights do not occur frequently, L is recalculated only once every epoch in actual systems, allowing the time costs of matrix construction to be distributed across multiple node mapping processes and considered negligible. Thus, in practical scenarios of agricultural product blockchain traceability systems, the time complexity of the jump hash sharding algorithm based on dynamic weights can be considered $P(log\ O)$.

In agricultural product blockchain traceability systems, node migration caused by shard failure is orderly and controlled. The proposed sharding algorithm organizes shards using a two-dimensional matrix, ensuring that the failure of a row's shard only leads to the migration of nodes within that row, without affecting other rows' shard nodes. For any shard originally weighted as q_j, only $\nu \times q_j / \sum_{u=0}^{l-1} q_u$ nodes need to be migrated. This design ensures the locality and efficiency of the migration process, avoiding a global load imbalance. As system load increases, especially during the agricultural harvest season or peak sales periods, nodes may face higher data processing pressures. To mitigate this high load state, system performance can be enhanced by increasing the number of shards. Assuming the weight of a new shard is q_j, based on the balance after shard addition, the new shard can eventually acquire $\nu \times q_j / \sum_{u=0}^{l-1} q_u$ nodes. This process involves migrating some nodes from existing shards to the new shard, thereby balancing the load across shards. This dynamic adjustment ensures that new shards effectively share some data processing tasks, reducing the pressure on individual shards and enhancing the overall response speed and processing efficiency of the systems. Conversely, when the number of nodes in certain system shards falls below a safety threshold, possibly due to seasonal variations in the agricultural market or temporary delisting of certain categories, it may be necessary to cancel that shard and migrate its nodes to other shards. According to the design of the jump search algorithm, after a shard fails, its nodes will migrate to the next shard. For instance, if the j-th shard with a weight q_j fails, then $\nu \times (q_t / \sum_{u=0}^{l-1} q_u - q_j) - q_t / \sum_{u=0}^{l-1} q_u$ nodes from that shard need to migrate to the j+1-th shard. This process will continue sequentially until the nodes from the l-2-th shard migrate to the l-1-th shard, with a total migration volume of $WO = \sum_{u=t+1}^{l-1} (\nu \times \sum_{u=0}^{l-1} q_u) + \nu \times \Delta q / \sum_{u=0}^{l-1} q_u$.

Consensus Algorithm for Agricultural Product Blockchain Traceability Sharding Systems

In agricultural product blockchain traceability systems, traceability information encompasses data from the entire process, from field cultivation and harvesting to processing, transportation, and sale. This data must be shared and verified efficiently across multiple nodes to ensure that consumers and regulatory bodies can access reliable traceability information in real-time. Based on these requirements, a consensus mechanism derived from the Reputation-based Practical Byzantine Fault Tolerance (R-PBFT) algorithm, termed the Agricultural Product Blockchain Traceability Sharding System Consensus Algorithm (Agri-PBFT), is proposed in this study. The Agri-PBFT algorithm filters high-reputation nodes through a trust mechanism to enter the consensus node group, which is responsible for processing critical traceability data, thereby ensuring the authenticity and timeliness of the data. Additionally, by randomly selecting the primary node, the system prevents the failure of a single node or attacks by malicious nodes, enhancing the system's security and stability. Figure 3 illustrates the architecture of the consensus algorithm for the agricultural product blockchain traceability sharding system. During the consensus process, each node participates based on its trust value, with nodes that have lower trust values being dynamically adjusted in their participation frequency.

Trust mechanism

To effectively enhance consensus efficiency and ensure data reliability and security, an improved trust mechanism was employed. This trust mechanism, based on the Reputation-based Trust Model (RTM), evaluates nodes' historical behaviors to compute direct trust values and recommendation trust values. These values are then weighted to derive a comprehensive score for each node. The design of this trust mechanism not only meets the needs of agricultural product blockchain traceability systems but also addresses the issue of high communication complexity in the traditional Practical Byzantine Fault Tolerance (PBFT) algorithm, where all nodes participate in the consensus. Figure 4 illustrates the role of the trust mechanism within the algorithm.

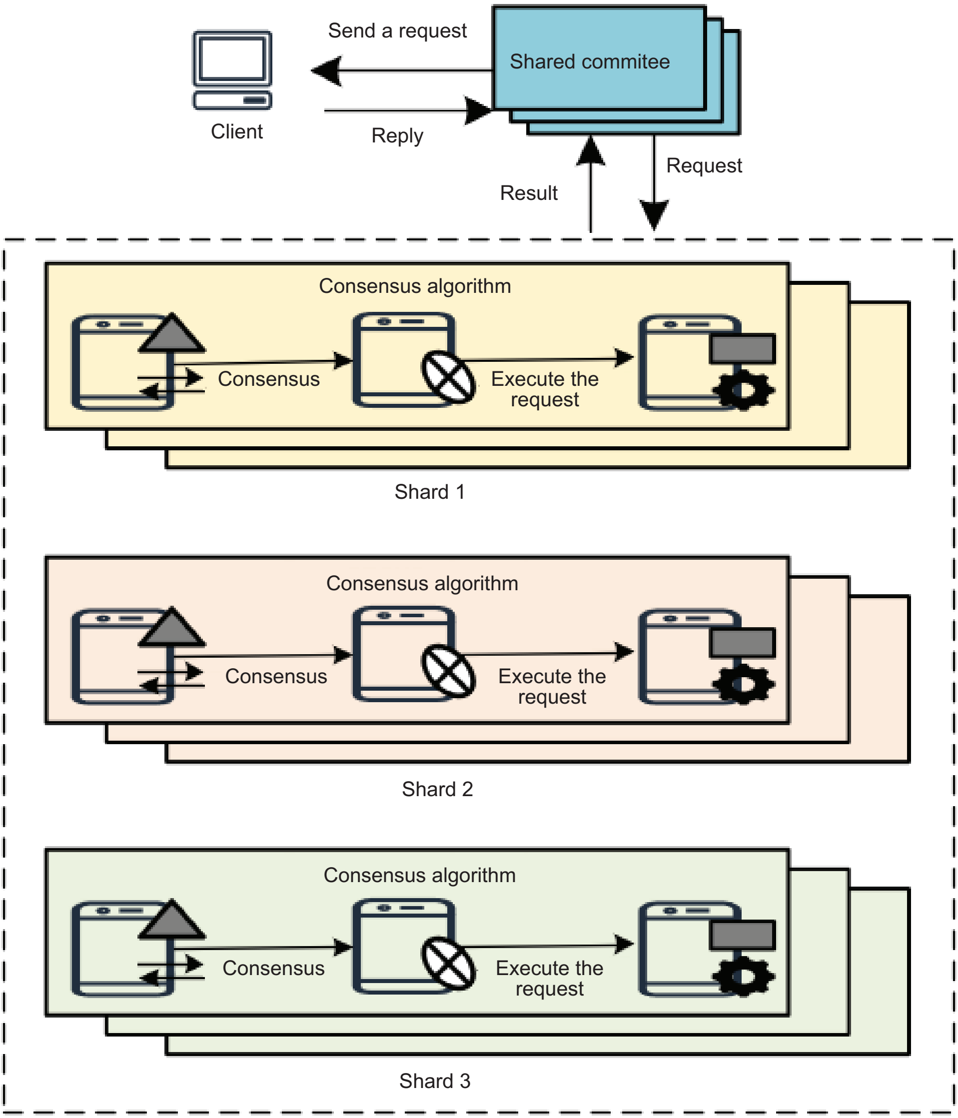

Figure 3. Architecture of the consensus algorithm for the agricultural product blockchain traceability sharding systems.

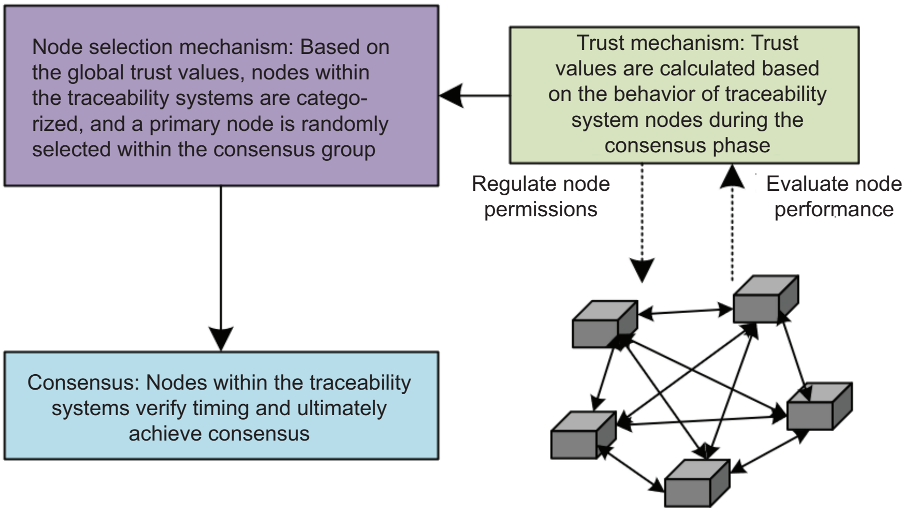

Figure 4. Schematic diagram of the trust mechanism in the algorithm.

In agricultural product blockchain traceability systems, the calculation method for direct trust values ensures the transparency and reliability of nodes' behavior when processing traceability data for agricultural products. Throughout the stages of cultivation, harvesting, processing, transportation, and sale, nodes representing farms, processing plants, transportation companies, and retailers continually transmit and verify traceability data. By assessing the historical behavior of nodes, the systems identify those that have demonstrated stability and reliability in data transmission and validation, thus prioritizing these nodes for participation in the consensus process. Specifically, if a node at a processing plant consistently transmits processing information accurately and on time, aligning with the majority of node records, it can attain a high direct trust value. Conversely, if a node at a transportation company frequently fails to update transport information on time or provides data records inconsistent with other nodes, its direct trust value is reduced. Nodes with high direct trust values are more likely to be selected in future consensus processes, thereby enhancing the overall efficiency and data reliability of the systems. The transaction influence factor, when the l-th message from node k is rated as $T(k,l)$, is denoted by IF(k,l). The equation for calculating direct trust values is:

$$F(u,k) = \frac{\sum_{l=1}^{v} T(k,l) U_d(k,l)}{\sum_{l=1}^{v} U_d(k,l)} \tag{3}$$

In agricultural product blockchain traceability systems, nodes involved in various stages continuously transmit and validate traceability information. To ensure system transparency and data reliability, nodes must rely not only on direct trust values but also on recommendation trust values to assess the credibility of other nodes. When a node i at an agricultural processing plant needs to evaluate the credibility of a transportation company node k, it considers not only its direct interaction history with node k but also assessments from other related nodes about node k. If these recommending nodes l have historically demonstrated stability and a strong ability to make recommendations, their trust evaluations of node k can provide significant reference value for node u. Specifically, if a recommending node l has consistently provided accurate and reliable data in previous traceability records and is widely trusted by other nodes in the system, node u will place considerable importance on the trust evaluation of node k made by node l. By synthesizing evaluations from multiple high-reputation recommending nodes, node u can more accurately assess the credibility of node k, thus deciding whether to continue collaborating with it or select a more reliable transportation company. Suppose the number of times node u has been satisfied with node l in their transaction history is denoted by $T(u,l)$, and the number of times node u has been dissatisfied with node l is represented by $D(u,l)$. The recommendation capability of the recommender can be characterized by the following equation:

$$G(u,l) = \frac{T(u,l)}{T(u,l) + D(u,l)} \tag{4}$$

The recommendation trust value can be calculated using the following equation:

$$E(u,k) = \frac{\sum_{l \in V} F(l,k) G(u,l)}{\sum_{l \in V} F(l,k)} \tag{5}$$

In agricultural product blockchain traceability systems, global trust values are used to comprehensively assess the credibility of each node. This evaluation mechanism is essential for ensuring the transparency of the entire traceability system and the accuracy of its data. For instance, in a typical agricultural product supply chain, when a retailer node u needs to assess the credibility of a processing plant node j, retailer node u considers both its direct interaction history with processing plant node k and the recommendation trust values from other related nodes regarding node k. If both direct and recommendation trust values are high, the global trust value of processing plant node k will also be high, indicating that the node is trustworthy within the system. This approach enables the system to effectively identify and isolate untrustworthy nodes. For example, if a node consistently provides inaccurate information, both its direct and recommendation trust values will decrease, resulting in a reduction in its global trust value. As a result, other nodes can use the global trust value to decide whether to continue interacting with that node, ensuring that data is transmitted and validated by nodes with high credibility at each stage of the supply chain. Assume the initial reputation value of a node is $S_k^n = 0.5$, with the current view number denoted as n and the node number as k.

$$S_k^n = \beta \frac{\sum_{l=1}^{v} T(k,l) U_d(k,l)}{\sum_{l=1}^{v} U_d(k,l)} + (1-\beta) \frac{\sum_{l \in V} F(l,k) G(u,l)}{\sum_{l \in V} F(l,k)} \tag{6}$$

In agricultural product blockchain traceability sharding systems, updating global trust values is a crucial process that ensures the dynamic adjustment of node reputations within the system, directly impacting their reliability and transparency. Along with the trust mechanism in the R-PBFT algorithm, the method for updating global trust values can be divided into four steps.

Step 1: Reputation update request

In the agricultural product supply chain, retailers may wish to update the reputations of participating nodes within the system at the end of a transaction round. To initiate the reputation update process, retailers send their reputation update requests to the primary node in the current view. The format of the request message is $<<RQ_S,n,f>,\delta_{nz}>$, where n, RQ_S, and δ_{nz} represent the current view number, reputation value update request message, and the signature of the request message, respectively, and f is the message digest of RQ_S.

Step 2: Primary node response and preparation message

Upon confirming the retailer's reputation update request, the primary node sends a preparation message to the other consensus nodes, notifying them of the impending reputation update process. The format of the reputation update preparation message is $<<PR_S,f>, \delta_{no}>$.

Step 3: Consensus node verification and response

Upon receiving the preparation message issued by the logistics company, the farm and processing plant nodes verify the authenticity of the message. Subsequently, each node sends lists of both direct and recommendation trust values for other nodes to the retailer. These lists include their interaction records and recommendation trust evaluations within the supply chain. The response information, $<<RE_S,ME,ME\ E,ID,f1,f2,\delta_n>>$, includes lists of direct trust values represented by $ME\ F$ and recommendation trust values represented by $ME\ E$. ID denotes the identity proof of the node, while $f1$ and $f2$ represent the hash digests of both direct and recommendation trust value lists, respectively, and δ is the node's signature on the response message.

Step 4: Client verification and result message

The retailer verifies the response information from the farms, processing plants, and logistics companies, ensuring the authenticity of their direct and recommendation trust value lists. Upon successful verification, the retailer calculates the global trust values for each node and sends the result message to all nodes to update the overall reputation status of the system. The result message $<<RE_S, ME\ S, f,\delta_n>>$ is sent to all nodes, with the result message and its message digest represented by $ME\ S$ and f, respectively, and the client's signature on the result message denoted by δ_{nz}.

Through these four steps, the agricultural product blockchain traceability sharding systems dynamically update the global trust values of each node. This trust value update process not only ensures the accurate adjustment of each node's reputation but also improves the system's transparency and security.

Node selection mechanism

In the actual agricultural product supply chain, various types of nodes, such as farms, processing plants, logistics companies, and retailers, participate in the operation of the system. Small farms and individual transporters, due to their lower activity volume or recent addition to the system, are typically designated as ordinary nodes. Their primary tasks include transmitting transaction information and synchronizing block data. In contrast, large farms, reputable processing plants, and logistics companies, characterized by their long-term stable transaction records and higher trust evaluations, are designated as consensus nodes. These nodes participate in the consensus process, validating the authenticity of transactions and ensuring that data at every stage, from farm to consumer, is genuine and trustworthy.

In agricultural product blockchain traceability systems, the definition and role differentiation of node sets are crucial for ensuring the system's efficient operation. Consensus nodes, through their historical transaction records and activity within the system, acquire higher global trust values and are selected for the consensus node set. Ordinary nodes, with lower global trust values, are selected for the ordinary node set. By distinguishing between consensus and ordinary nodes, the system effectively leverages the computational and verification capabilities of high-reputation nodes, while ensuring that transaction information is propagated and backed up across the entire network. Ordinary nodes, by receiving and forwarding transaction information, help ensure widespread dissemination and accessibility of data. On the other hand, consensus nodes, by participating in the consensus process, ensure the authenticity of transactions and the security of the blockchain.

Specifically, let the set of nodes in the network be denoted by V, the set of consensus nodes by V_n, and the set of ordinary nodes by V_v. It is established that:

$$V = V_u \cup V_v \quad \text{and} \quad V_n \cap V_v = \varnothing \tag{7}$$

For a single node u in set V, denoted as V_u, the following equation holds:

$$\forall V_u, V_u \in V \tag{8}$$

At the same time, the equation satisfies the following conditions:

$$\begin{cases} V_u \in V_n, u \in [0,n) \\ V_u \in V_v, u \in [n,l) \end{cases} \tag{9}$$

Due to the complexity and diversity of the agricultural product supply chain, the reputation and stability of nodes may change over time. By reassessing the global trust values of nodes after each consensus round, the system can dynamically adjust the role allocation between consensus and ordinary nodes. This approach not only enhances the efficiency and accuracy of the consensus process but also motivates nodes to improve their reputations and actively engage in the operation of the system. For example, a newly joined farm may initially participate in the system as an ordinary node. However, as its transaction records accumulate and its service quality improves, its global trust value may gradually increase, eventually surpassing the threshold Z and qualifying it as a consensus node. Conversely, if a consensus node performs poorly in a given round, its global trust value could decrease, leading to its demotion to an ordinary node.

Primary node selection

In agricultural product blockchain traceability systems, the primary node is responsible for coordinating and managing the consensus process. If this node is controlled by malicious actors, the security of the entire system and the credibility of the data could be severely compromised. By randomly selecting the primary node from within the group of consensus nodes, the risk of a single node being repeatedly targeted by attacks is significantly reduced, thus enhancing the overall security and stability of the system. Specifically, at the end of each consensus round, a group of consensus nodes is selected based on their performance and reputation values. The primary node is then chosen from these consensus nodes using a random algorithm. This ensures that even if a node has the highest reputation, it is not selected as the primary node consecutively multiple times, reducing the risk of malicious attacks. Suppose the identifier of the selected primary node is denoted by O, the current view number by N, and the total number of nodes in the network by E, then the equation is:

$$O = N \ MOD \ E \tag{10}$$

The agricultural product supply chain involves multiple stages, from production and processing to transportation and sales, with each stage requiring accurate and tamper-proof record-keeping. If the primary node is controlled by malicious entities, the credibility of the entire system and the integrity of the data could face severe threats. By randomly selecting the primary node from the group of consensus nodes, the probability of a malicious node becoming the primary node is effectively reduced, minimizing the risk of attacks on the system. Specifically, the system selects a group of consensus nodes based on their reputation values and historical performance. Among these consensus nodes, the primary node is chosen using a random algorithm. Each node can verify the legitimacy of the primary node using a predetermined algorithm and view number, ensuring that the selection process is transparent and tamper-proof. For example, in a given view with the view number N, the systems use a random algorithm to select the primary node O from the group of consensus nodes. Other nodes validate the legitimacy of O using the same algorithm; if inconsistencies are discovered, they reject that node's request.

In organic fruit supply chain management, quality traceability and supply chain transparency are crucial for ensuring the freshness of fruit and maintaining consumer trust. However, due to factors such as the distribution of fruit-growing regions, variability during the distribution process, and seasonal fluctuations, the nodes in the supply chain exhibit high dynamism, especially during peak production seasons. During this time, many farmers, wholesalers, and distribution centers may temporarily join or leave the system, making it challenging for traditional sharding algorithms to accommodate the frequent changes in nodes. This dynamic environment often leads to uneven data sharding, which can cause system processing delays. The jump hash sharding algorithm and the new consensus algorithm proposed in this paper are designed to address the practical issues in such high-dynamism scenarios. Our approach is adaptable to various stages of the supply chain: during the planting period, the jump hash sharding algorithm allocates farmer nodes appropriately to ensure load balancing across shards. For example, when a farmer pauses supply due to adverse weather, the algorithm can automatically redistribute the load to other nodes, preventing system imbalance. During the harvesting and transportation period, the algorithm dynamically allocates resources to maintain system stability as it handles a large number of newly added nodes. The consensus algorithm efficiently updates traceability records to ensure that key information, such as origin, harvest time, and transportation status, is synchronized in real time. In the distribution and sales phase, to cope with frequent inquiries from distribution centers and retailers, the system reassigns nodes through the jump hash algorithm. The new consensus algorithm ensures that high-frequency query nodes participate in consensus as a priority, meeting consumer demand for product information inquiries.

Although traditional sharding algorithms are effective in general environments, their performance often falls short in agricultural contexts. Firstly, traditional sharding algorithms struggle to efficiently handle large-scale datasets, particularly in agricultural supply chains, where agricultural product information and transaction data are frequently updated. These algorithms often lead to shard imbalances, causing heavy loads on certain shards, which negatively impacts the system's response time. Secondly, traditional algorithms typically exhibit poor throughput when faced with high concurrency and frequent data updates, making them unsuitable for real-time traceability requirements. For example, fixed-hash-based sharding algorithms tend to create hotspots, where computational resources are overly concentrated on specific shards, reducing overall efficiency. In contrast, the jump hash sharding algorithm introduces a dynamic sharding strategy that intelligently adjusts shards based on data load, resulting in more uniform data distribution and improved system throughput and latency. Furthermore, jump hash sharding reduces inter-shard data exchanges, alleviating bandwidth pressure and making it more suitable for the complex network environments typical of agricultural supply chains.

Taking the traceability system of an actual agricultural product supply chain as an example, the jump hash sharding algorithm demonstrates its ability to maintain good data processing efficiency in large-scale transaction environments. For instance, during the agricultural production phase, farmers use sensors and smart devices to record real-time growth and environmental data of agricultural products. This data is then uploaded to the blockchain for storage and traceability. When traditional sharding algorithms are employed, the system experiences latencies and load imbalances under high concurrency, resulting in extended data processing times that hinder real-time traceability. By introducing the jump hash sharding algorithm, the system can dynamically adjust data sharding based on real-time load, effectively preventing load concentration and bottlenecks, while significantly improving bandwidth utilization. For instance, after the introduction of this algorithm, system processing times were reduced by approximately 30%, and data transmission latency remained within acceptable limits even with 1,000 nodes. Additionally, by optimizing the consensus algorithm, the consensus time was significantly reduced, ensuring both data timeliness and security. In this way, real-time, transparent, and secure traceability is achieved throughout the entire process of agricultural product production, processing, and sales.

Experimental Results and Analysis

In this study, to ensure the repeatability and stability of the experimental results, the experimental environment was carefully designed, and detailed experimental setups were provided. The experimental environment operated on a high-performance server with the following hardware configuration: an Intel Xeon E5-2620 v4 processor (8 cores, 16 threads, 2.1 GHz base clock), 64 GB DDR4 RAM, and a 1 TB SSD to support large-scale blockchain data storage and rapid data retrieval. All experiments were deployed under the Ubuntu 20.04 LTS operating system, with distributed node management facilitated by Docker containers. Each blockchain node operated within an isolated Docker container, and inter-container management was handled by Docker Compose to ensure environment consistency and controllability. Regarding network configuration, the experimental network bandwidth was set to a 100 Mbps local area network (LAN), with network latency strictly controlled to under 1 millisecond, minimizing any potential interference from the network environment on the experimental results. Additionally, to ensure efficient blockchain data access, MongoDB 4.4 was selected as the distributed database, capable of supporting large-scale data storage and high-concurrency query operations. These hardware and software configurations were meticulously chosen to provide stable performance and efficient resource management in large-scale experiments, ensuring the reliability and consistency of the experimental data.

In this study, detailed information on three types of agricultural products was collected and analyzed for the performance optimization of blockchain traceability systems based on sharding technology. Specifically, the data covers detailed aspects of packaging, production, and quality inspection for each product, and it has been systematically organized and labeled. The three types of products involved in the study and their specifications are as follows:

The first product, Sample A, consists of corn strips from a brand substituting cocoa butter in puffed chocolate products. Its main characteristics include a strawberry flavor, a net content of 40 grams, and the absence of trans fats, dairy, soy, and wheat components. The manufacturer is Liwayway (China) Co., Ltd. The product's standard number is GB17401, with the production date being December 1, 2023, and the production line number SC11231011800261.

The second product, Sample B, consists of potato chips from a brand, characterized as fried puffed food with a Beijing sauce roast duck flavor and a net content of 60 grams. It contains 5.1 grams of trans fat and includes soy, wheat, and dairy components. The manufacturer is Baishi Food (China) Co., Ltd. The product's standard number is QB/T2686, with the production date being December 2, 2023, and the production line number SC11231011700309.

The third product, Sample C, consists of large crab crisps from a brand, classified as oil-containing puffed food with a mixed fragrant crab flavor and a net content of 60 grams. It contains gluten cereals, fish, and soy components. The manufacturer is Tianjin Quanwei Food Co., Ltd. The product's standard number is GB17401, with the production date being December 3, 2023, and the production line number SC11251018200547.

Each product's packaging box contains 20 bags, each carefully labeled with the manufacturer, production date, production line number, batch number, and quality inspector. These data enable precise traceability of each product within the packaging box, ensuring food safety and quality control. Additionally, key data such as the nutritional content, ingredients, and allergens of the three products were recorded on the blockchain, further enhancing the transparency and reliability of the traceability systems.

According to the data presented in Figure 5, the traditional hash sharding algorithm shows a significant imbalance across various shard numbers. When the number of shards is set to 10, the imbalance index for the traditional hash sharding algorithm is recorded at 240. Although this index decreases to 60 when the number of shards increases to 100, the reduction in imbalance is minimal. This indicates that while increasing the number of shards alleviates some imbalance with the traditional hash sharding algorithm, the improvement is not substantial. In contrast, the jump hash sharding algorithm proposed in this study demonstrates excellent balance under the same conditions. With 10 shards, its imbalance index is only 55. As the number of shards increases, this index steadily decreases to 28. This clearly shows that the proposed algorithm excels in managing shard balance, enabling more efficient allocation of system resources. Figure 5 illustrates a comparison of the processing efficiency between the jump hash sharding algorithm and traditional sharding algorithms under different load conditions. The experimental results indicate that, as the number of nodes increases, the processing time of the jump hash sharding algorithm rises more gradually, while the traditional sharding algorithm shows a clear performance bottleneck, especially when the number of nodes exceeds 1,000, where the processing time increases rapidly. The jump hash sharding algorithm demonstrates higher processing efficiency compared to the traditional algorithm, particularly under high-load conditions, where it effectively reduces data processing time. These findings suggest that the jump hash sharding algorithm holds greater potential for application in high-concurrency agricultural product blockchain traceability scenarios.

When selecting performance evaluation metrics, particular attention was given to two indicators: reduction in computation time and bandwidth optimization. Computation time directly impacts system response speed and throughput. Specifically, in large-scale data storage and query operations, reducing computation time can significantly enhance system processing efficiency. In distributed systems, communication overhead between nodes is typically high, especially in scenarios involving large volumes of data transfer. By optimizing bandwidth and reducing data transmission time, the overall system performance can be greatly improved. Bandwidth optimization not only reduces network load but also decreases latency, ensuring that the system can efficiently synchronize and validate data. Therefore, these two metrics are essential for evaluating the performance of agricultural product blockchain traceability systems. In the experiments, improvements in the algorithm were assessed by comparing computation time and bandwidth consumption before and after optimization.

Data from Figure 6 illustrates the node migration volumes following the failure of 25 shards using both the traditional hash sharding algorithm and the jump hash sharding algorithm proposed in this study. Before the failure of the first 25 shards, the node migration volume in the traditional hash sharding algorithm remained stable at 200 per shard. However, after the 25th shard failed,

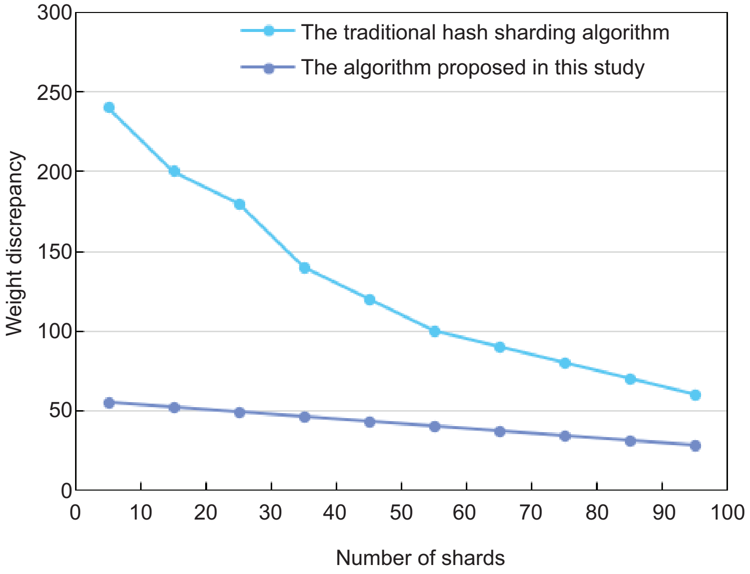

Figure 5. Comparison of balance among different hash sharding algorithms.

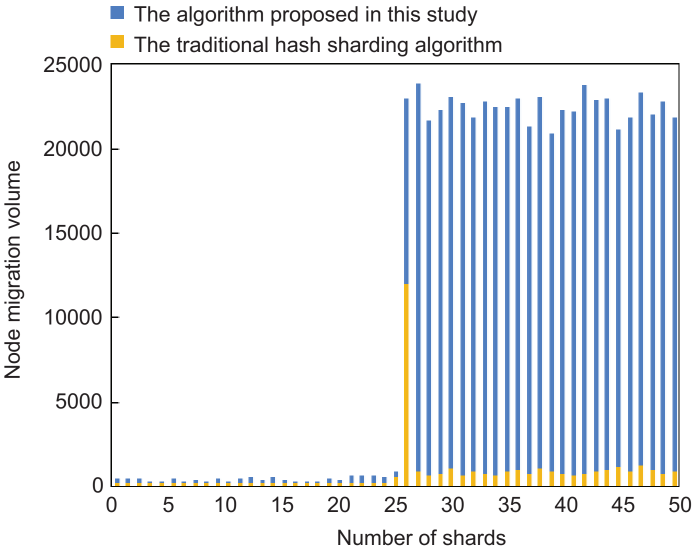

Figure 6. Node migration volumes after the failure of 25 shards in different hash sharding algorithms.

the node migration volume dramatically increased, peaking at 12,000, with subsequent shards continuing to experience high volumes, such as 900 for the 26th shard and 700 for the 27th shard. This indicates that the traditional hash sharding algorithm causes substantial node migrations when shards fail, significantly increasing the system's burden. In contrast, the proposed jump hash sharding algorithm demonstrates more stable performance after shard failures. While fluctuations in node migration volume can be observed in the early stages, such as 100 for the 4th shard and 300 for the 5th shard, the migration volumes tend to stabilize overall, especially after shard failures. Even when peaks occur, such as 11,000 for the 26th shard, subsequent node migration volumes gradually stabilize and maintain high consistency, with most ranging between 21,000 and 22,000 for shards 30 to 50. Figure 6 also compares the differences in bandwidth utilization between the jump hash sharding algorithm and other traditional algorithms. The jump hash algorithm effectively reduces bandwidth consumption by minimizing data exchange between shards. By significantly decreasing the transmission requirements between data blocks, the jump hash sharding algorithm demonstrates higher bandwidth utilization in environments with limited bandwidth. This is crucial for the real-time performance of agricultural product blockchain traceability systems.

Data from Figure 7 illustrates the time required to construct shards using various hash sharding algorithms. The proposed jump hash sharding algorithm demonstrates relatively stable construction time as the number of shard nodes ranges from 100 to 640, with a gradual increase from 5.2 seconds to 5.6 seconds, showing minimal fluctuation. In contrast, the construction time for the consistent hash sharding algorithm exhibits a clear linear growth trend as the number of nodes increases, rising from 6 seconds to 7.3 seconds. The construction time for the traditional hash sharding algorithm increases more significantly, from an initial 6.6 seconds to 8.2 seconds, indicating a substantial increase in time expenditure when handling larger scales of nodes. A comparison reveals that the proposed algorithm experiences a smaller increase in construction time as the number of shard nodes increases, demonstrating higher efficiency. Figure 7 also illustrates the throughput performance of various consensus algorithms in the agricultural product blockchain traceability system. The traditional Proof of Work (PoW) consensus, Proof of Stake (PoS) consensus, and the hybrid consensus algorithm proposed in this study were tested. In terms of throughput, the hybrid consensus algorithm outperformed both the PoW and PoS algorithms, significantly enhancing data processing capacity while ensuring system security.

Data from Figure 8 presents the standard deviation of shard weights as the number of shard nodes increases across different hash sharding algorithms. The proposed jump hash sharding algorithm shows a notable decrease in standard deviation from 56 to 37.5 as the number of nodes increases from 100 to 640. This reduction is particularly significant in the latter stages, indicating a more balanced distribution of shard weights across the shards. In contrast, the standard deviation for the consistent hash sharding algorithm decreases from 120 to 68. Although it also exhibits a downward trend, the overall standard deviation remains relatively high, suggesting that the imbalance in shard weights persists. The traditional hash sharding algorithm sees its standard deviation decrease from 96 to 56, showing some improvement;

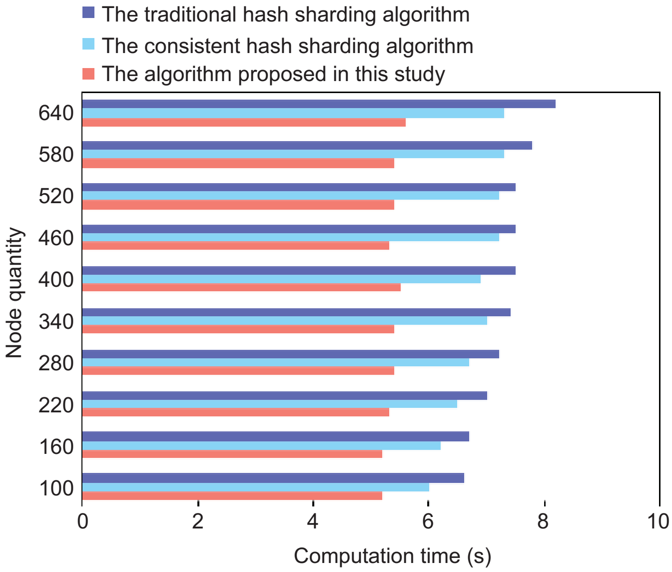

Figure 7. **Comparison of shard construction time across different hash sharding algorithms.**

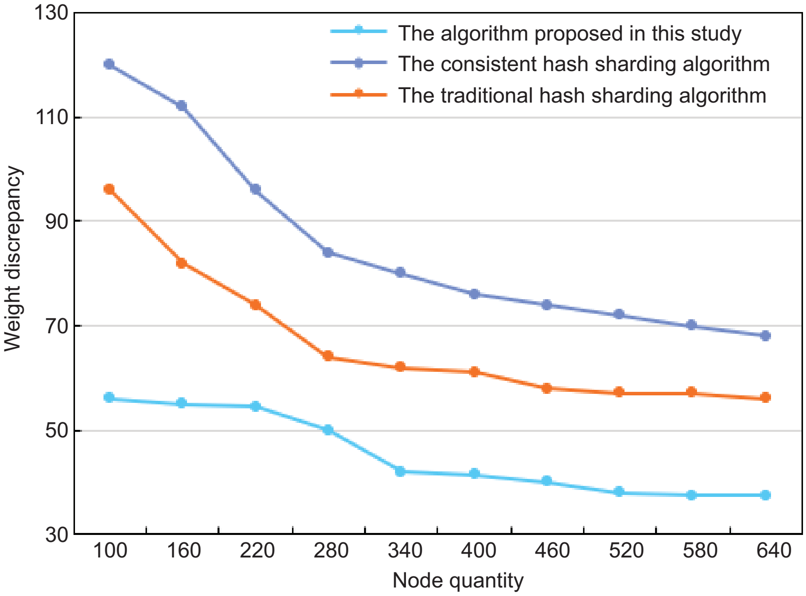

Figure 8. **Comparison of the standard deviation of shard weights among different hash sharding algorithms.**

however, the reduction is less pronounced. Furthermore, once the number of nodes reaches a certain threshold, the standard deviation tends to stabilize, indicating ongoing deficiencies in shard balance. Figure 8 also presents the performance of the jump hash sharding algorithm under varying latency conditions. The data show that the jump hash algorithm is able to maintain relatively low processing delays, even in environments with high network latency. Despite the increase in network latency, the jump hash sharding algorithm exhibited stable latency performance, demonstrating robust fault tolerance and suitability for diverse network environments that may be encountered in agricultural supply chains.

Figure 9 displays the variations in trust values for different types of nodes under the proposed consensus algorithm. For malicious nodes, as their number increases from 0 to 10, the trust value of node 1 gradually declines from 0.5 to 0.1, and the trust value of node 2 drops from 0.5 to 0.08, demonstrating the algorithm's effectiveness in identifying and reducing the trust values of malicious nodes. In contrast, the trust values of honest nodes steadily rise with each consensus round. For example, node 1's trust value increases from 0.5 to 0.91, and node 2's trust value increases from 0.5 to 0.91, indicating the algorithm's ability to continually enhance trust in honest nodes. The trust values of ordinary nodes initially rise

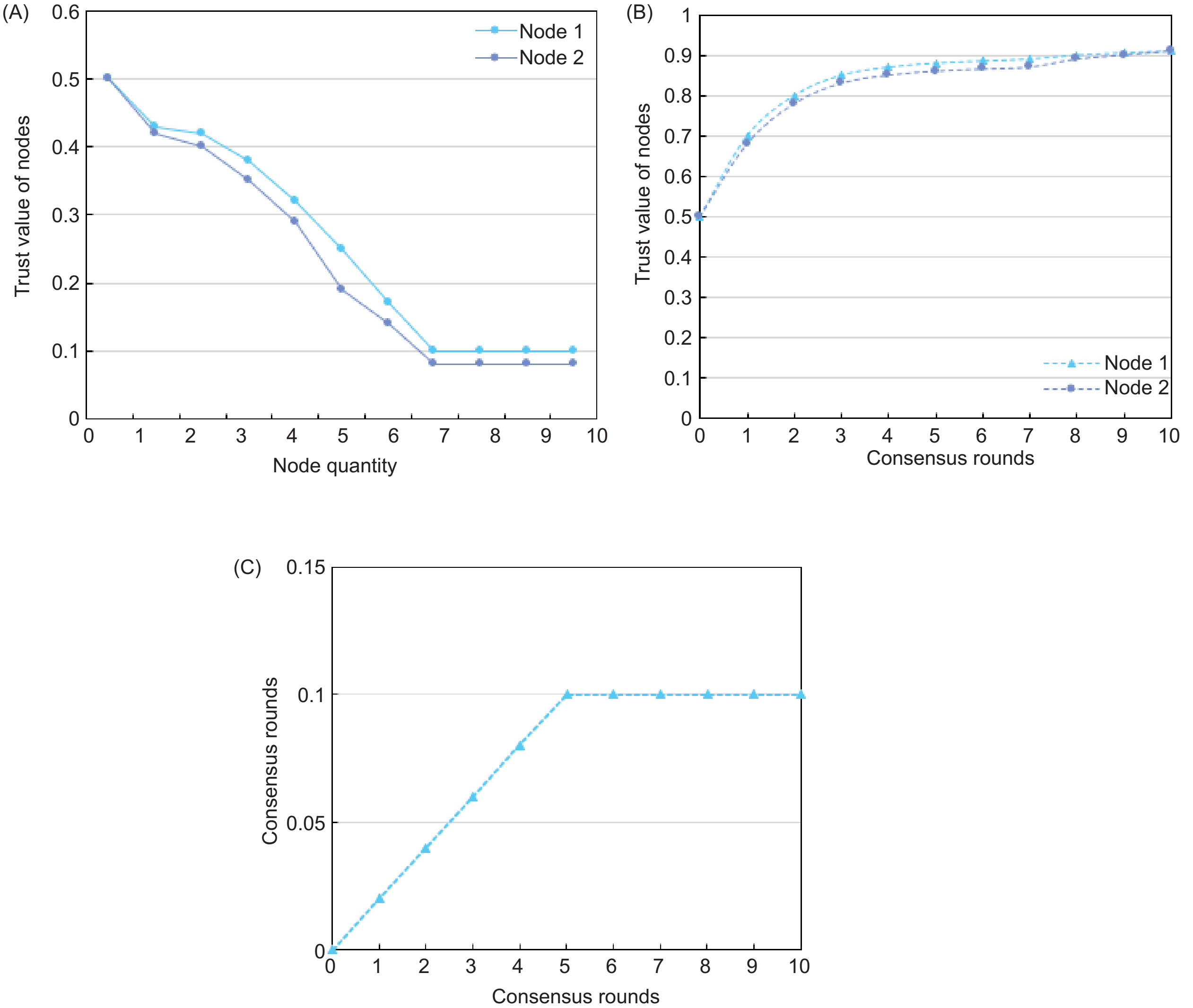

Figure 9. Trust value changes for different node types in the proposed consensus algorithm. (A) Malicious nodes; (B) Honest nodes; (C) Ordinary nodes.

from 0 to 0.1 over the first five consensus rounds and then stabilize, showing the algorithm's ability to quickly identify and elevate the trust values of ordinary nodes before reaching a stable state.

Data from Figure 10 presents the throughput variations for different consensus algorithms as the number of nodes increases. For the Agri-PBFT algorithm, throughput gradually decreases from 280 to 160 as the number of nodes increases from 5 to 30. This demonstrates that, although the system's throughput declines with an increasing number of nodes, it remains at a relatively high level. In contrast, the R-PBFT algorithm shows a more significant decrease in throughput. As the number of nodes grows from 5 to 30, throughput drops dramatically from 275 to 20. Specifically, it falls to 75 with 10 nodes, drops further to 50 with 15 nodes, and stabilizes at 20 with 20 or more nodes. This indicates a significant performance decline in the R-PBFT algorithm when handling a large number of nodes, whereas the Agri-PBFT algorithm exhibits robust resistance to pressure and maintains greater stability.

Data from Figure 11 illustrates the throughput changes for the PBFT, R-PBFT, and Agri-PBFT consensus algorithms across varying numbers of nodes. For the PBFT algorithm, throughput increases from 0 to 420 as the number of nodes rises from 0 to 16, demonstrating a linear growth trend. The throughput increase under the R-PBFT algorithm is more pronounced at the same number of nodes, rising from 0 to 760, indicating a higher processing capacity. In contrast, the Agri-PBFT algorithm exhibits a more gradual increase, rising from 0 to 200. Notably, when the number of nodes exceeds eight,

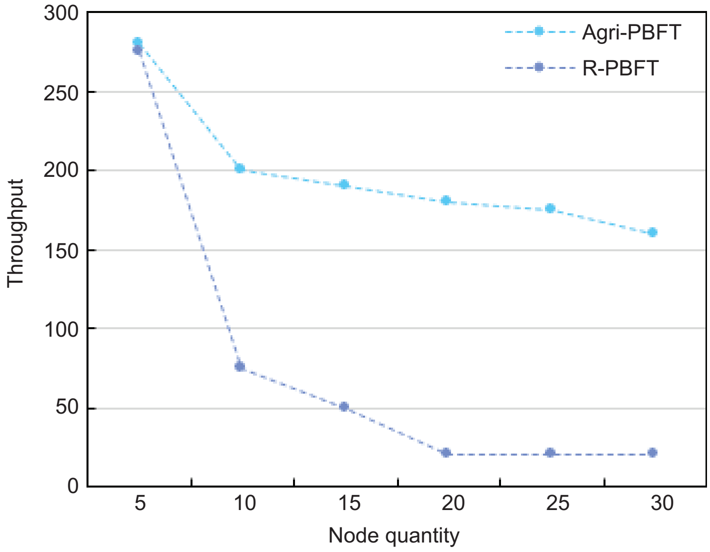

Figure 10. **Throughput analysis of different consensus algorithms.**

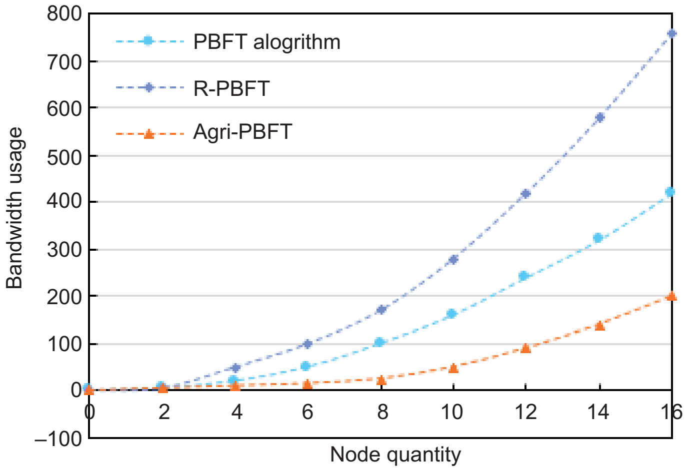

Figure 11. **Network bandwidth comparison of different consensus algorithms.**

the rate of throughput growth slows down. This suggests that while Agri-PBFT is less efficient with a smaller number of nodes, it maintains steady growth at higher node counts, though not as rapidly as R-PBFT and PBFT.

The performance of the proposed agricultural product blockchain traceability system in large-scale node environments was thoroughly evaluated through a series of scalability tests, which focused on assessing system performance across different node configurations. The tests covered configurations ranging from 10, 30, 50, 70, to 100 nodes, aiming to verify the processing capability and efficiency of the sharding algorithm and consensus mechanism in large-scale environments. By simulating varying network loads and node counts, a comprehensive understanding of the system's scalability was obtained. In each experimental round, key performance indicators were recorded, including system throughput (e.g., transactions per second (TPS)), consensus time, and latency. The results demonstrated that, as the number of nodes increased from 10 to 100, the system's throughput steadily increased, exhibiting strong linear scalability. For instance, with 10 nodes, the system achieved a throughput of 200 TPS, while with 100 nodes, throughput increased to 1500 TPS, following a linear growth trend. This indicates that the proposed sharding technology effectively enhances processing capacity in large-scale environments. Additionally, although the consensus time slightly increased with the addition of nodes, the rise was relatively stable. For 10 nodes, the consensus time per block was approximately 0.3 seconds, and with 100 nodes, it increased to about 2 seconds, suggesting that the system maintained low consensus latency even in large-scale environments. In terms of latency, the average response time of the system slightly increased as the number of nodes grew, but the increase remained within reasonable limits, with a maximum increase of 50%. This indicates that, despite the increase in node count, the system continues to ensure low transaction confirmation latencies, making it suitable for large-scale agricultural blockchain traceability applications.

Although the proposed jump hash sharding algorithm and optimized consensus algorithm have demonstrated excellent performance in the blockchain traceability system for the agricultural supply chain, certain challenges may arise during actual deployment. First, the technical complexity is relatively high. The jump hash sharding algorithm requires dynamic sharding adjustments, and the system must continuously monitor and analyze the load of each shard, which imposes high demands on the system's real-time performance and computational capacity. Secondly, cost considerations must be taken into account. While the algorithm offers significant improvements in processing efficiency and bandwidth utilization, its implementation and maintenance costs are high, particularly in large-scale applications where the required hardware and technical support may increase operational costs for enterprises. Finally, the demand for technical expertise presents a significant challenge. The design and implementation of the agricultural product blockchain traceability system require professionals with a solid background in blockchain technology. Currently, the agricultural sector has limited understanding and application of blockchain technology. Therefore, substantial technical training and promotion may be needed during the adoption process.

Conclusion

This study primarily investigates and enhances agricultural product blockchain traceability systems in two key aspects. First, a jump hash sharding algorithm was proposed to address the imbalance issues inherent in the traditional sharding algorithm, thereby improving the system's processing capabilities. Second, a new consensus algorithm specifically tailored for sharded blockchain in agricultural product traceability systems was designed to enhance consensus efficiency. These improvements were validated and analyzed through multiple experiments conducted in this study.

In terms of balance across different sharding algorithms, the jump hash sharding algorithm demonstrated superior balance compared to the traditional algorithm, reducing the migration volume of nodes across different shards, particularly after the failure of 25 shards, where it exhibited enhanced stability. In comparisons of shard construction time and the standard deviation of shard weights, the jump hash sharding algorithm also showed greater efficiency and stability, confirming its improved handling capabilities. Regarding the consensus algorithm, the proposed new algorithm performed excellently in enhancing consensus efficiency, as evidenced by the analysis of trust value changes among different types of nodes. In the throughput analysis of different consensus algorithms, although the overall throughput of the Agri-PBFT algorithm was not as high as that of R-PBFT and PBFT, it maintained stable performance growth and higher security as the number of nodes increased. Additionally, in network bandwidth comparison experiments, the new consensus algorithm also demonstrated higher bandwidth utilization efficiency.

This study provides not only a technical solution for optimizing the performance of agricultural product blockchain traceability systems but also has significant implications on broader social and economic levels. In terms of food safety, a blockchain-based traceability system ensures transparency across every stage of the agricultural product lifecycle, including sourcing, processing, and transportation. This transparency enhances food safety management, reducing the flow of counterfeit or substandard products into the market. Through the application of the jump hash sharding algorithm and optimized consensus mechanism, data processing efficiency was further improved in this study, ensuring real-time updates and transparency of food safety information. This guarantees consumers' right to be informed and make informed choices. In terms of sustainability, the blockchain traceability system improves supply chain transparency, facilitating the rational use of agricultural resources and reducing waste. For instance, the production and transportation processes of agricultural products can be managed with greater precision, helping to reduce negative environmental impacts and supporting the development of sustainable agriculture. The optimized sharding and consensus mechanisms provide more efficient data support for these processes, reducing energy consumption and resource wastage. In terms of regulatory compliance, the immutability and transparency provided by blockchain technology offer reliable evidence for governments and regulatory bodies, promoting the standardization and regularization of agricultural product quality. By incorporating the proposed optimizations, regulatory agencies can access real-time quality data, ensuring compliance, reducing fraud, and preventing quality incidents. This enhances the overall regulatory capability of the industry.

Future research could further explore the utilization of machine learning techniques to optimize the sharding algorithm and consensus mechanism. Machine learning could intelligently adjust sharding strategies by analyzing real-time load data from the blockchain network, preventing the common issue of load imbalance seen in traditional sharding algorithms and improving overall system efficiency. For example, deep learning models could be used to predict node load conditions, allowing the system to dynamically adjust data partitioning, preventing some shards from becoming too heavy and ensuring efficient network operation. Additionally, in terms of consensus mechanisms, machine learning could be applied to optimize the consensus process, reducing computational resource consumption and enhancing security. For instance, reinforcement learning algorithms could enable the system to automatically select the most suitable consensus mechanism based on historical transaction data and network conditions, optimizing consensus time and transaction throughput without compromising security. This would be an important direction for future research, contributing to the efficiency and intelligence of agricultural blockchain systems.

Authors Contribution

X.G.: Writing–original draft, Validation, Software, Investigation, Data curation; Y.Z.: Visualization, Software; J.Y: Methodology, Funding acquisition; G.T.: Writing review & editing, Supervision, Methodology, Conceptualization.

Conflicts of Interest

The authors declare no conflict of interest.

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