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Multi-Chain Collaboration-Based Information Management and Control for the Rice Supply Chain

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Abstract: The issue of food quality and safety is a major concern. Rice is considered one of the three staple foods. Rice quality and safety problems have occurred frequently, which seriously affect human health. The rice supply chain is characterized by complex links, discrete data, and numerous types of hazardous substances. Strengthening the information management and control capabilities of the rice supply chain is an important means to ensure the quality and safety of rice. Based on multi-chain collaboration, we have conducted research on information management and control of the rice supply chain. First, a multi-chain collaborative model of "blockchain + sub-chain" is designed. Based on this model, the following four mechanisms are designed: a trusted chain mechanism, a multi-level sub-chain encryption mechanism, a trusted supervision mechanism, and a hierarchical consensus mechanism. These mechanisms jointly serve the multi-chain collaborative management and control of the rice supply chain information. Secondly, smart contracts and operating procedures are designed, and a comparative analysis of them is executed. Finally, the design and implementation of the prototype system is carried out, and an example is verified and analyzed in a grain enterprise. Results show that this model serves the information supervision of the rice supply chain by studying the multi-chain collaboration. The study solves the real-time data interaction problem between each link of the rice supply chain. The credible management of information and control of the rice supply chain is accomplished. This study applies new information technology to the coordination and resource sharing of the food supply chain and provides ideas for the digital transformation of the food industry.

Keywords: rice supply chain security; supply chain information management and control; blockchain; multi-chain collaboration; smart contracts; food safety

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1. Introduction

Grains and oils are the collective name for crops such as cereals, potatoes, and beans and their processed finished and semi-finished products, which are the necessities of life on which human beings depend. As one of the world's three staple foods, rice is grown in 122 countries around the world. According to Statista, the global rice supply is expected to be 705.4 million tons in 2021/22, compared to 700.4 million tons in 2020/21. Global rice production, trade, and supply are all higher compared to 2020/21. On top of the increase in all rice indicators, rice hazards such as heavy metal contamination, pesticide residues, mold contamination, and fumigant residues are seriously affecting the quality and safety of rice globally [1,2].

To reduce the inflow of problematic rice into the market and safeguard people's health, some scholars have focused on three aspects, namely, the formulation of relevant laws, risk management mechanisms within enterprises, and information traceability, as reflected in the following. The first aspect is meant to accelerate the construction of rice-related standards, laws, and regulations worldwide to control rice quality and safety issues in terms of production and processing behaviors of rice producers [3]. The second aspect aims to improve the risk management mechanisms within companies to reduce the generation of problematic rice in the production and processing process [4]. The third aspect explores the use of traceability identification codes, electronic tags radio frequency identification, two-dimensional code technology, Internet of Things, near-field communication technology, and electronic product codes to enhance the control of information in the rice supply chain. The use of rapid inspection techniques, such as spectral inspection for rice products to enhance the control of rice information, was investigated [5]. Although the above studies have reduced the occurrence of rice quality and safety problems to a certain extent, the rice supply chain is characterized by a long life-cycle, complex links, a large amount of data, many people involved in production, etc. The problems in the flow of information in its own supply chain cannot be fully solved from the above aspects alone.

Blockchain is a new application model of computer technologies such as distributed data storage, point-to-point transmission, consensus mechanism, and encryption algorithm. A smart contract is a computer program with status and conditional response running on a distributed ledger. The contract completes the encapsulation, verification, and execution of the complex behaviors of distributed nodes through preset rules, and it achieves the functions of information exchange, value transfer, and asset management. The joint application mode of blockchain theory and smart contract technology has the characteristics of immutability, decentralization, openness, autonomy, and anonymity. It is a new means to address the issue of data security in the food supply chain [6]. The community technology of blockchain smart contract can address the drawbacks of the traditional food supply chain centralized management model, such as low data transparency, poor security, low credibility of traceability data, proneness to a single point of failure, etc. [7].

In recent years, researchers have begun to explore the application of blockchain smart contract technology to agricultural products and foodstuffs, mainly in the following aspects. First, by studying the decentralized nature of the blockchain and combining it with the data flow characteristics of the agricultural and food supply chain, the feasibility of applying the blockchain to agricultural and food products is studied from a theoretical perspective [8–17]. Secondly, by combining the characteristics of blockchain smart contract technology such as its traceability, automatic execution, and the fact that it is tamper-proof, we will study the application of blockchain to the credible management of data and credible traceability of agricultural products and foodstuffs [18–38]. Thirdly, the integration of blockchain technology with cutting-edge technologies in other fields will be explored to serve the collection, analysis, and prediction of data in the agricultural and food industries [39–42]. As a type of agricultural product, the supply chain of rice is highly similar to other agricultural and food supply chains. Therefore, applying blockchain to the rice supply chain can enhance its centralization and better serve the sustainability of rice.

There are some studies that focus on improving the decentralization and enhancing the supervisory capability of the rice supply chain. However, there is a huge body of data collected in the global rice supply chain, and the number of rice-related workers is large and widely distributed, resulting in the collection of rice information with spatial and temporal intervals. Most of the existing blockchain technology applications are single-chain architectures such as “production blockchain” and “processing blockchain”, and there are barriers to information interaction among the single chains, making it difficult to interoperate effectively [43,44]. The distribution of grains and oils food supply chain data varies greatly in space and time, and the existing blockchain research cannot realize the credible management of all the information from data collection to storage on the blockchain. Moreover, the types of information underlying the supply chain are complex, and the existing studies face difficulty in controlling all the data [45,46]. The whole-life circulation process of the rice supply chain is complex and requires synergy between each link to advance the flow of rice. The existing blockchain research applications have a low level of cooperativeness of the whole link, and there is an urgent need to realize the data interaction of the whole supply chain. To address the low availability of the traditional blockchain, this paper replaces the traditional blockchain with a multi-chain architecture based on the idea of multi-chain collaboration. It also combines digital signature technology, identification analysis technology, hash locking mechanism, and smart contract technology to build an information control model applicable to the characteristics of the rice supply chain.

The rest of this paper is organized as follows. Section 2 explains the contribution of this paper. Section 3 describes the preliminary work of this study. Section 4 designs the rice supply chain information management and control model, including framework design, trusted chaining mechanism design, multi-level sub-chain encryption mechanism design, trusted supervision mechanism design, and hierarchical consensus mechanism design. Section 5 implements the model and analyzes the results. Section 6 provides the conclusion and discusses the outlook for future research.

2. Contributions of this Article

2.1. The research Questions Involved in this Study

(1) The data collection, analysis and use of the rice supply chain has a spatial and temporal interval.
(2) It is difficult to effectively interconnect the various segments of the rice supply chain.
(3) The whole link of information trustworthy management of data from collection to storage on the blockchain and the ability to control all the data in real time are poor.
(4) The degree of cooperativeness level of enterprises in the whole rice supply chain is low.
(5) There are scalability issues related to the blockchain in large-scale data storage and management.

2.2. Problem-Solving Challenges

(1) Applying the blockchain to the rice supply chain is a complex process because of the complex distribution links in the rice supply chain.
(2) There is no guarantee of the trustworthiness of the data before it is stored on the blockchain.
(3) The security of data interactions across all links is vulnerable to threats.
(4) Consensus among the various users involved in the rice supply chain is difficult to reach quickly.

2.3. Contribution of this Study

(1) Based on the idea of multi-chain collaboration, a new architecture model of "blockchain + sub-chain" is proposed. It is used for the decentralization, interconnection, and collaborative management of all links and members of the rice supply chain.
(2) Digital signature technology is cited in the model. To achieve timely and effective accountability with a peer supervision mechanism within the blockchain and responsibility linkage mechanism between the blockchain to ensure the trustworthiness of rice data before it is stored in the blockchain.
(3) The model introduces hash locking technology, identification analysis technology, and smart contract technology. The model is designed to facilitate better data interaction between participating companies in the rice supply chain, better data query by consumers, and better management and control of real-time information of rice by regulators to achieve food quality and safety of rice from the information level.

3. Related Prior Works

The research on information management and control of the rice supply chain based on multi-chain collaboration has higher requirements for data privacy, security, collaboration, and efficiency of the rice supply chain. In this section, we introduce some of the recent trends of the blockchain in the field of agricultural and food products and some blockchain-related cutting-edge research, which is shown in Table 1.

Table 1. Research review table.

Category	Research Content	References
Blockchain-based agricultural products and food management framework or model theoretical research aspects.	Exploring the impact of blockchain on agricultural products and food through theoretical research	[8–17]
Blockchain-based Research on Trusted Control of Agricultural Products and Food Information	Focus on enhancing information control of agricultural and food products through blockchain decentralization, tamper-proof and irreversibility	[18–29]
Blockchain-based Research on Trusted Traceability of Agricultural Products and Food Information	Blockchain-based agricultural and food traceability solutions to achieve credible information collection and traceability	[30–38]
Blockchain-based joint application of agricultural products and food with IoT, deep learning algorithms, etc.	Optimize the application of blockchain by integrating research with cutting-edge technologies in other fields	[39–42]
Blockchain-based Grains Information Management	Blockchain smart contract as a technical means to build a grains information management model	[43–47]
Preliminary study on blockchain for agricultural products or food based on multi-chain idea	Extending blockchain application scenarios by changing blockchain architecture, etc.	[48–51]

Our study of the blockchain-based agricultural products and food management framework or model theoretical research aspects has been divided into three main levels: rationale, benefits, and barriers. At the rationale level, Dutta and Choi (2020) pointed out that agricultural supply chains are complex, involving a large number of stakeholders, and therefore need to be digitized and improved through blockchain [12]. At the benefits level, Lezoche et al. (2020) and Kramer et al. (2021) point out that blockchain solves the problems of decentralization, anonymity, and security in the agricultural supply chain [9,10]. Kamble et al. (2021) and Lee et al. (2022) pointed out that blockchain technology will help empower smallholder farmers to organize themselves [13,14]. Liu et al. (2020) pointed out that the information service business based on big data and blockchain in the field of green agricultural products brings more value to the members of the supply chain [15]. Kamble et al. (2020) pointed out that blockchain is one of the most important technical resources to promote data analysis capabilities, which provides technical infrastructure such as digitization, automation, and tracking for agri-food supply chains [16]. Nurgazina et al. (2021) pointed out that blockchain can enhance the sustainability of various agricultural products in three dimensions (i.e., economic, social, and environmental) [17]. At the barriers level, Vu et al. (2021) pointed out that major barriers to using blockchain in the agricultural supply chain include privacy and transparency dilemmas, high implementation costs, and the scalability of blockchain technology [8]. Lin et al. (2020) pointed out key challenges in using blockchain-related technologies in agricultural applications: scalability, integration with existing legacy systems, and security and privacy [11]. The above research points to some theoretical analysis of using the decentralized characteristics of blockchain to apply it to the field of agricultural products and food. However, the security of data before it is stored on the blockchain is not discussed.

Our study of the blockchain-based trustworthy control of agricultural and food information aspects was divided into three main levels: technical, application, and analysis. At the rationale level, Hao et al. (2021) proposed a consumer sentiment prediction method combining blockchain and deep learning models to formulate regulatory measures in the food market [19]. Shahid et al. (2020) proposed an end-to-end solution for blockchain-based agricultural and food supply chains, enabling traceability, accountability, and security [26]. Alkahtani et al. (2021) developed a cooperative (Co-op) sustainable e-agriculture supply chain management model by considering web design indices and variable demand to determine agricultural product shipments, selling prices, cycle times, and advertising costs [28]. At the application level, Ali et al. (2021) took halal food as an example and pointed out that blockchain can increase the transparency of the food supply chain of halal food SMEs [21]. Yadav et al. (2020) analyzed the Indian agricultural supply chain, stating that “lack of government regulation and lack of trust among agricultural stakeholders in the use of blockchain” are significant barriers to blockchain adoption in India’s agricultural supply chain [25]. Wang et al. (2022) applied blockchain technology at a grain and oil company in Changde, Hunan Province, China, to optimize the information-based regulatory process of the rice supply chain regulator, providing a viable solution for grain and oil quality and safety regulation [29]. At the analysis level, Hassoun et al. (2022) pointed out that some hurdles related to regulation, privacy leakage, limited storage capacity, and latency issues in the application of blockchain in the food industry need to be addressed [18]. Donaghy et al. (2021) pointed out that blockchain can enhance real-time management and traceability of food supply chains, but there are still some challenges in terms of data ownership, interoperability, and accessibility [20]. Iftekhar et al. (2021) pointed out that blockchain technology establishes a new industry trust mechanism, improves corporate responsibility, and eliminates tampering throughout the supply chain [22]. Tsolakis et al. (2021) pointed out that the blockchain system can solve the problem of agricultural product fraud [23]. Benyam et al. (2021) pointed out that blockchain can be used to track information and identify potential sources of pollution in agricultural supply chains in agricultural digitalization technologies [24]. Katsikouli et al. (2021) showed that using a blockchain-based system to manage agricultural supply chains offers significant benefits, such as faster and more reliable traceability [27]. The above research demonstrates that the application of blockchain in the field of agricultural products and food can enhance the transparency of the supply chain and improve the credibility of data, thereby improving the food quality supervision capabilities of agricultural products and food. However, how to deal with the huge amount of data and complex links in the agricultural products and food supply chain has not been discussed.

Our study of the blockchain-based research on trusted traceability of agricultural products and food information aspects was divided into three main levels: technical, application, and analysis. At the rationale level, Dey et al. (2021) propose FoodSQRBlock (Food Safety Quick Response Module) to digitize food production information and make it easy for consumers and producers to access, trace, and verify through QR codes [30]. Chen et al. (2020) propose a “blockchain-based electronic agriculture” framework to solve the problems of agricultural information asymmetry, unreliable third-party agencies, and poor traceability of organic food [32]. Bhutta et al. (2021) propose a blockchain-based supply chain management architecture, focusing on the use of IoT and blockchain for secure identification, traceability, and real-time tracking of agri-food supplies during transportation [35]. Cao et al. (2021) develop a human–machine coordination mechanism that traces the responsibilities of all supply chain stakeholders [36]. Mangla et al. (2021) implement a system theory combining blockchain technology with system dynamics modeling to map the milk supply chain to explore the traceability of information flow [38]. At the application level, Liu et al. (2020) point out that smart contracts (or distributed ledger technology) and network security are two key applications of blockchain in agriculture, and the digital transformation of agri-food supply chains is expected to achieve traceability and transparency through blockchain-based smart contract technology, a trusted and intelligent ecosystem [34]. At the analysis level, Khler et al. (2020) state that blockchain-based technologies are widely used in food supply chains because their immutability and decentralization of information improve transparency, traceability, and trust [31]. Niknejad et al. (2021) state that traceability, transaction, Internet of Things (IoT), safety, and food supply chain are the most frequently used terms for blockchain in the food and agriculture industry [33]. Garrard and Fielke (2020) state that the use of blockchain enables product traceability through the supply chain without the need to worry about the origin of the item being fraudulent or tampered with [37]. The aforementioned study points out that blockchain can enhance the quality and safety of agricultural products and food products, transparency, etc., which is important for agricultural products and food traceability. Again, how to ensure the security of data before it is stored in the blockchain is not discussed.

Our study of the blockchain-based joint application of agricultural products and food with IoT, deep learning algorithms, etc., was divided into two main levels: application and analysis. At the application level, Khan et al. (2020) point out that an optimized supply chain provenance system is proposed for Industry 4.0 in the food industry using state-of-the-art technologies such as IoT, blockchain, and advanced deep learning [41]. At the analysis level, Amentae and Gebresenbet (2021) state that the use of digital technologies such as blockchain, Internet of Things, big data analytics, artificial intelligence, and ICT (Information Communication Technology) can facilitate sustainable transformation of food systems [39]. Rejeb et al. (2021) point out that in the current digital age, emerging disruptive technologies such as the Internet of Things, blockchain, and artificial intelligence are gradually affecting the way the food industry operates, giving rise to data-driven, sustainable, and circular food supply chains [40]. Torky and Hassanein (2020) investigate the importance of the IoT and blockchain technology in developing intelligent systems and precision agriculture applications, noting that blockchain can provide new insights into the long-term security and performance challenges existing in IoT-based precision agriculture systems [42]. The above research explores the integration of blockchain with cutting-edge technologies in other fields such as the Internet of Things and deep learning algorithms for applications that increase the scalability of blockchain.

Our study of the blockchain-based grains information management was divided into two levels: technical and analysis. At the technical level, Deng and Feng (2021) propose an RFID-based grain supply chain traceability model and combined it with the GTIN coding standard in the GS1 system to encode each batch of grain to improve traceability [46]. At the analysis level, Zhang et al. (2020) point out that the use of blockchain in the food supply chain is beneficial for reducing management costs and improving management efficiency [43]. Iftekhar et al. (2021) explore the potential managerial role of blockchain in grain reserve strategies [44]. Lakkakula et al. (2022) point out that the grain and oil industry can reduce transaction costs and improve market efficiency through blockchain [45]. Yadav et al. (2021) state that incorporating blockchain-based systems into agricultural supply chains can contribute to sustainable food security [47]. The aforementioned studies apply blockchain to the field of food information management, which can enhance the information management capability of food. However, the food supply chain links are complex, the data volume is redundant, and there are time and space intervals, so how to ensure the information management all the data has not been explored.

Our preliminary research into blockchain for agricultural products or food based on multi-chain idea was divided into two levels: theory and technical. At the theory level, He et al. (2021) propose a multi-chain charging model for shared charging piles, which stores different types of information on different blockchains to improve the storage and query efficiency of the blockchain [49]. Lin et al. (2020) introduce a novel permissioned blockchain architecture that seeks to strike a balance between anonymity and regulation, while achieving transparency and confidentiality [50]. Li et al. (2021) propose a multi-chain storage structure based on node division to reduce the time and space of data synchronization and improve the scalability of the system [51]. At the technical level, Alkhateeb et al. (2022) conducted a systematic literature review, pointing out that Artificial Intelligence (AI)-enabled Hybrid Blockchains, Energy-Efficient Hybrid Blockchains, Interoperable Hybrid Blockchains, and Privacy-preserving Hybrid Blockchains are future research directions [48]. The above research extends the storage capacity of blockchain, reduces the high latency of data, and provides ideas for blockchain to serve big data interactions.

The above research summarizes some explorations, studies, and analyses of blockchain applications by scholars in the field of agricultural products and food in recent years from six broad levels. Blockchain is a distributed ledger technology that stores agricultural products and food supply chain data on the blockchain to achieve information backup of all nodes, thus ensuring the traceability of data. Whenever there is a change in the data, consensus of a certain percentage of the nodes, such as the upstream enterprises and regulators, is required, thus strengthening the security of the data and also providing information control capability for regulators. The use of blockchain can strengthen the credibility of data and realize the development of precision agriculture as well as sustainable agriculture from the information level.

In China, rice cultivation covers more than 30% of the total grain area and there are more than 70,000 varieties of rice. With the exception of Qinghai Province, rice is grown in every province, autonomous region, and municipality directly under the central government. In China alone, there are 270,600 rice cultivation-related enterprises. The rice supply chain is extremely complex in terms of the people involved and the flow of the chain. In this paper, we propose a new architecture based on "main chain + sub-chain" that is founded on the idea of multi-chain collaboration. We combine digital signature technology, hash lock technology, smart contract technology, and identification analysis technology to build a rice supply chain information management and control model to improve the controllability of rice supply chain information and ensure the quality and safety of rice.

4. Rice Supply Chain Information Management and Control Model

4.1. Rice Supply Chain Analysis

We analyzed the rice supply chain by referring to the supply chain design method [52–55]. Figure 1 shows the basic structure of the rice supply chain, which contains six main links and nine sub-links, and the participants include various types of enterprises, consumers, and regulators, and the generated data contain information on the contaminants, basic information, and personnel information of each link.

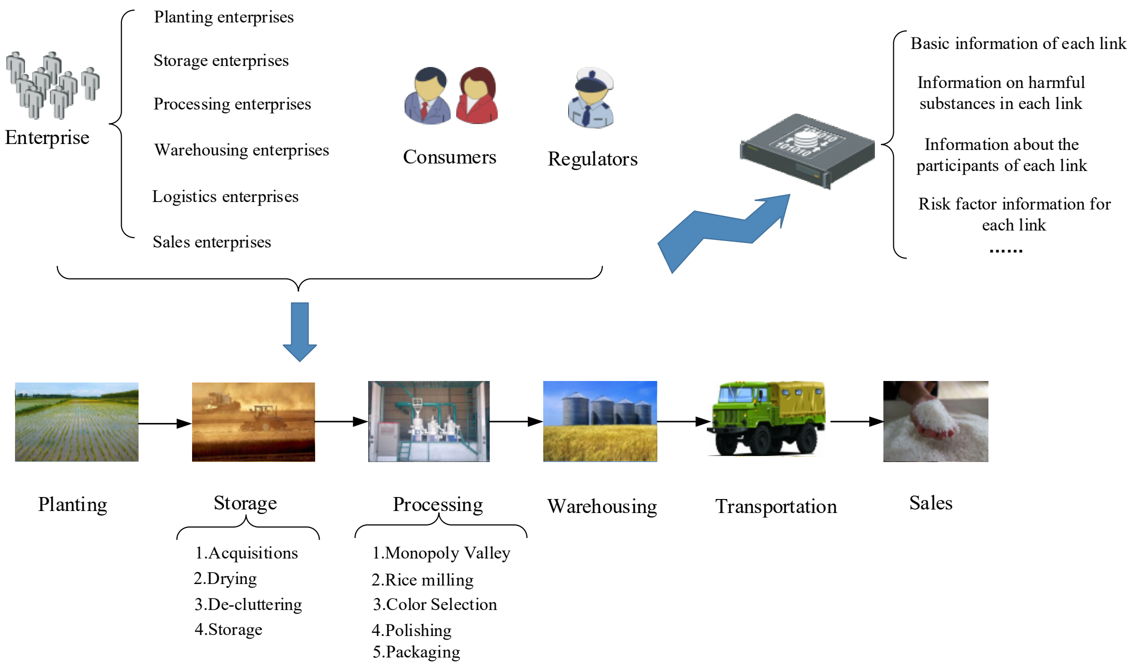

Figure 1. Basic structure of the rice supply chain.

4.2. Framework

The rice supply chain is complex, with a wide variety of information and a huge amount of data. Strengthening the management and control of rice supply chain information forms a strong guarantee for the quality and safety of rice. A rice supply chain information management and control model based on the idea of multi-chain integration is constructed. Figure 2 shows the model of rice supply chain.

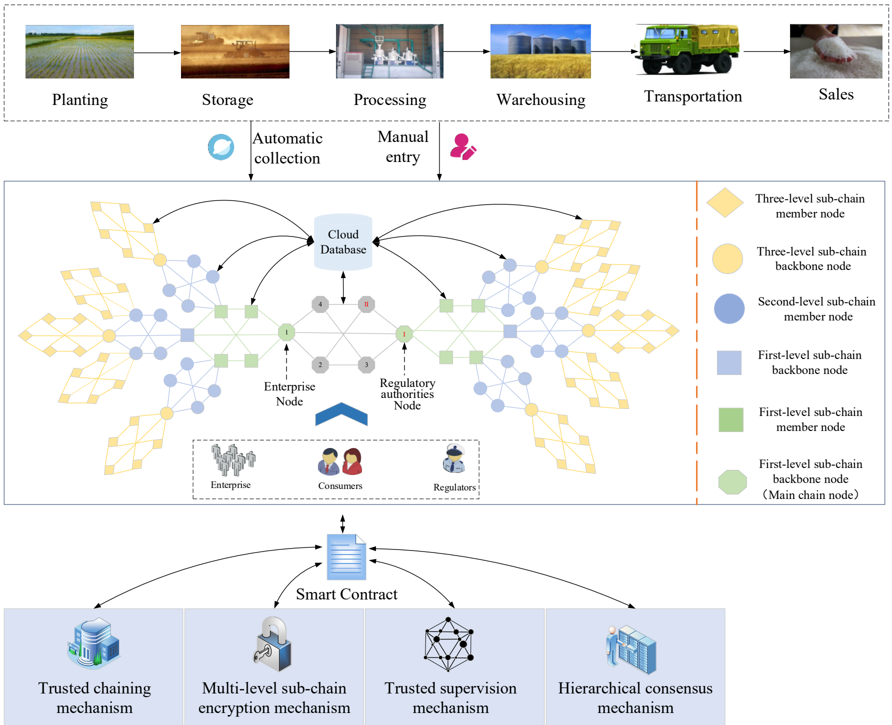

Figure 2. Information management and control model of rice supply chain.

The model is divided into a multi-chain collaboration part and a technical mechanism module. The multi-chain collaboration module includes two parts: blockchain and cloud database. The storage mechanism used in this model is the "blockchain + cloud database" dual-mode storage mechanism. Using digital signature technology, data abstracts are stored in the blockchain, and basic data are stored in cloud databases, realizing data diversion. This storage method not only relieves the pressure of blockchain storage but also ensures the security of data. The technical mechanism module is divided into four trusted mechanisms.

The rice supply chain information control model mainly collects data through two ways: automatic collection by IOT (Internet of Things) devices and manual entry. The IOT devices include computers, RFID (Radio Frequency Identification), thermometers, etc. The model obtains the uploaded data from the devices or employees after authenticating them, performs the data cleaning as well as standardization process, and then uses the four mechanisms designed to process the data.

The blockchain part consists of the main chain and three sub-chains. Each node of the main chain corresponds to enterprise personnel, supervisors, and consumers in the rice supply chain. Enterprises correspond to the types of production, storage, processing, warehousing, transportation, and sales. Nodes are divided into six categories, namely, the third-level sub-chain member (backbone) node, the second-level sub-chain member (backbone) node, and the first-level sub-chain member (backbone) node. The backbone node of the first-level sub-chain is the main chain node. Each main chain node extends a progressive first-level sub-chain. The first-level sub-chain corresponds to the subordinate department (second-level unit) under the enterprise (regulatory department) corresponding to the main chain node. Each first-level sub-chain node extends a progressive second-level sub-chain. The second-level sub-chain corresponds to the subordinate group of the department (unit) node. Each second-level sub-chain node extends a progressive three-level sub-chain. The three-level sub-chain corresponds to the subordinate staff node of the group node.

The technical mechanism module serves the operation of the multi-chain collaborative module. This module includes a trusted chaining mechanism, a multi-level sub-chain encryption mechanism, a trusted supervision mechanism, and a hierarchical consensus mechanism. Each mechanism serves the data interaction between the main chain and sub-chains through custom-designed smart contracts. The trusted chaining mechanism verifies the data before the data is stored in the blockchain by using the "joint and several responsibility systems". This mechanism can dynamically manage and control data through progressive review. The multi-level sub-chain encryption mechanism uses hash locks to encrypt data according to different levels of sub-chains. The credible supervision mechanism realizes the credible supervision of information through identification analysis technology. The hierarchical consensus mechanism implements different consensus categories. For different consensus requests, the model adopts different consensus methods to ensure efficient consensus among multi-chain nodes.

This model combines the idea of multi-chain collaboration, identification analysis technology, hash locking technology, smart contract technology, digital signature technology, etc., to realize the credible management and control of the whole process of the rice supply chain data from collection to sales.

4.3. Mechanism

4.3.1. Trusted Chaining Mechanism

The application of blockchain technology ensures that the data stored on the blockchain cannot be tampered with, thereby maintaining the security and credibility of the data. To achieve the credibility of the whole chain data of the rice supply chain, it is necessary to ensure the security and credibility of the data before the chain. Figure 3 shows the trusted chaining mechanism, which is designed to solve the credibility problem of the collected data. The trusted chaining mechanism is divided into two sub-mechanisms: supervision sub-mechanism and reward and punishment sub-mechanism. For the supervision sub-mechanism, the physical space and work content between the nodes in the same sub-chain is similar, and the same-level supervision mechanism in the chain is implemented. The position level of each node between different levels of sub-chains is different, and the inter-chain progressive supervision mechanism is implemented. For the reward and punishment sub-mechanism, a joint responsibility mechanism is adopted to ensure the credibility of the data. Each node is responsible for each datum through a digital signature.

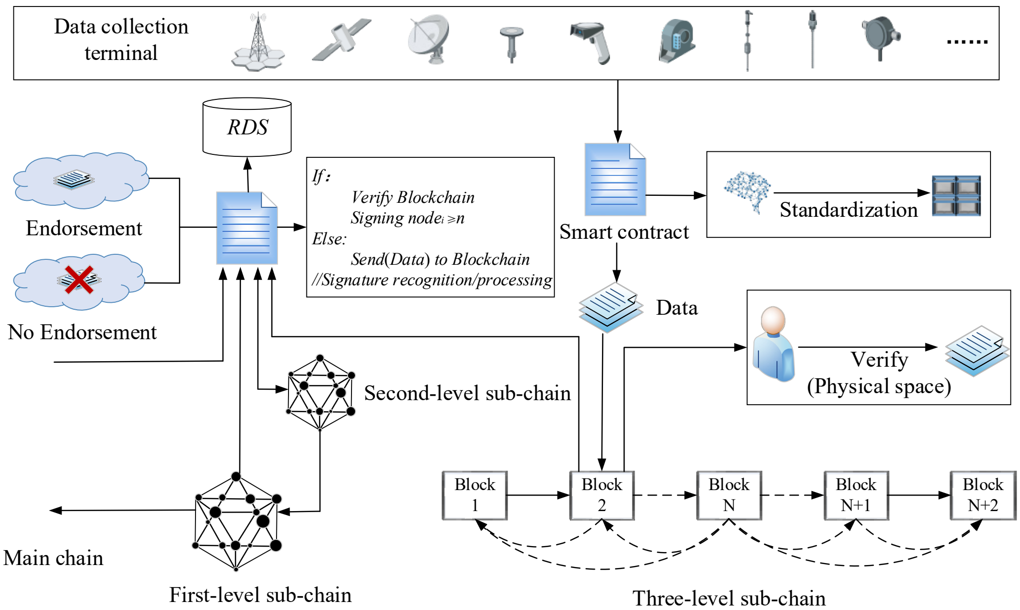

Figure 3. Schematic diagram of trusted chaining mechanism.

Take the three-level sub-chain as an example: after the data collection terminal collects the data, the user uploads the batch of data in the client terminal. The smart contract standardizes the data to form the data package *Data*, as shown in Equation (1). The contract performs the relevant hash operation on the *Data* to obtain the relevant data digest *Ds*. After that, the contract uploads *Ds* to the third-level sub-chain, as shown in Equation (2). *Ds* is broadcast in the third-level sub-chain in the form of point-to-point broadcast.

$$Send(Data) = \sum_{k=1}^{m} \mathrm{type}_k \sum_{i.j=1}^{n} \{key_i, value_j\} \quad (1)$$

In Equation (1), type is the data category, *m* is the maximum number of categories, *key* is the key, *value* is the value, and *n* is the maximum number of key-value pairs.

$$Send(Ds) = \sum_{i=1}^{n} Hash(Data_i) \quad (2)$$

In Equation (2), each data type is hashed and then spliced to form a data digest.

Each node of the third-level sub-chain is verified by the data in the physical space to determine whether the data are authentic (the same-level supervision mechanism in the chain). In this way, the model performs dynamic management of data. If the data are trustworthy, the node authenticates the signature of the data digest according to Equation (3). After the smart contract makes a judgment (the judgment method is shown in Figure 2), the data are encrypted and uploaded to the cloud database.

$$Sig(Ds) = \mathrm{Ds}_{skp} + \mathrm{C} \quad (3)$$

In Equation (3), sk_p is the user's private key, and *C* is the authentication signature.

The conditions for the contract to judge the credibility of the data and the processing measures after the judgment are set as the following three points: The first point is that the uploading data node must obtain the digital signatures of all nodes in the third-level sub-chain. The second point is that when a node has a clear objection to the data, the contract implements an inter-chain progressive supervision mechanism to feed back the data to higher-level sub-chains. Higher-level sub-chains check the data and, through consensus, determine whether the data are true. If it is an objection node problem, the contract deletes the malicious node and punishes the malicious group leader. If the higher-level sub-chain cannot reach a consensus on the data, it will give feedback to the higher-level sub-chain. If the highest-level sub-chain cannot reach a consensus, the contract will feed back the data to the supervisory authority. These data are subject to regulatory review by regulatory authorities. The third point is that when there is a problem with the data and there are digital signatures of other nodes, other nodes and the uploading data node share the "joint responsibility mechanism". By customizing the logic of the design contract, the trusted chain of data and real-time supervision of information are realized.

The trusted on-chain and dynamic management and control of data can be achieved through the trusted chaining mechanism. After the data are stored in the blockchain, a multi-level sub-chain encryption mechanism is designed to ensure the security of the data in the cross-chain process. Through this mechanism, the security and trustworthiness of the model in the process of data cross-chain transmission are realized.

4.3.2. Multi-Level Sub-Chain Encryption Mechanism

To ensure the security of cross-chain transmission data in the model, a multi-level sub-chain encryption mechanism is designed. This mechanism uses a hash lock to encrypt and transmit cross-chain data, as shown in Figure 4. There are four main types of data circulating in the rice supply chain information management and control model, namely, collection data, data summary, encrypted data, and identification code. The model involves the existence of four entities: acquisition equipment, client, national identification center, and cloud database. The multi-level sub-chain encryption mechanism realizes the secure transmission of data.

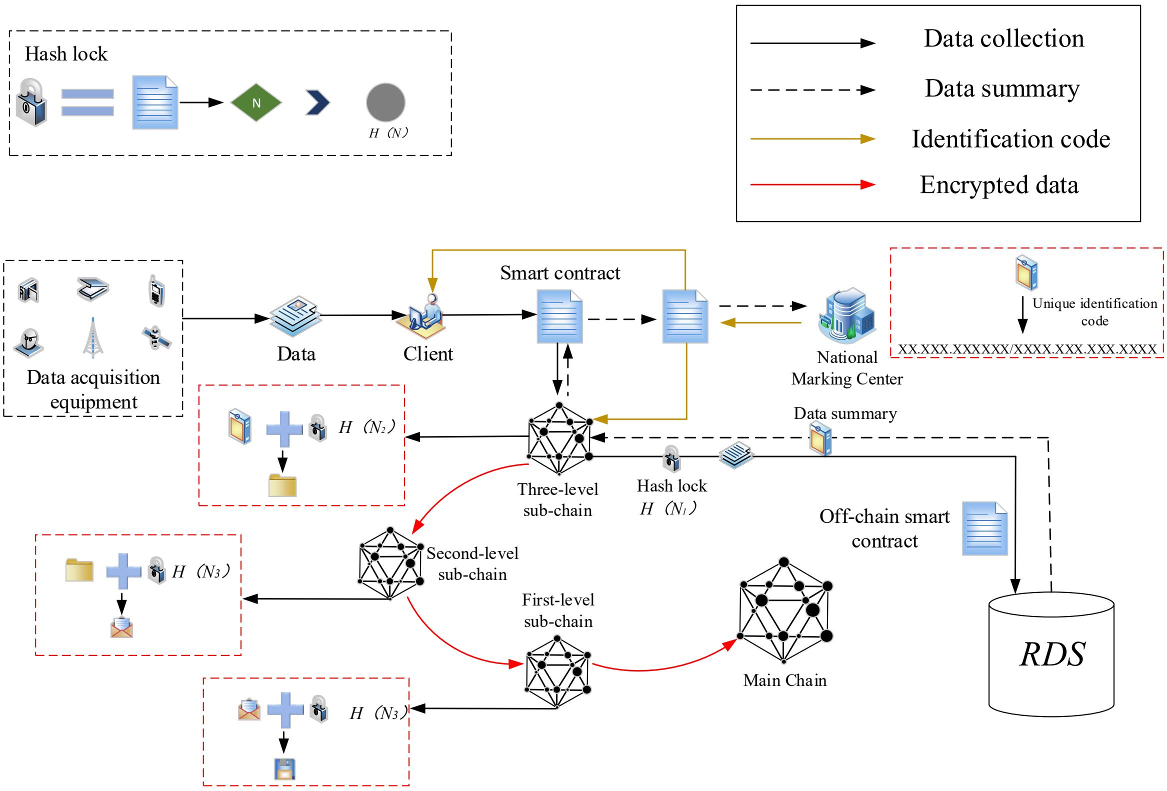

Figure 4. Schematic diagram of multi-level sub-chain encryption mechanism.

Taking the third-level sub-chain as an example, employees use the collection device to collect data and then store the data summary in the blockchain. After the smart contract judges whether the data are credible, the contract generates a random number N_1 and calculates the hash $H(N_1)$ (hash lock). Then, $H(N_1)$ is used to encrypt the basic data, data digest, and data signature and upload them to the cloud database. The upload method is shown in Equation (4). The smart contract outside the blockchain obtains the data digest by performing the same hash operation on the basic data. Through comparison, it is determined whether the data have been tampered with during transmission.

$$Send(Data, Ds, Sig(Ds))_{H(N_1)} = \{RDS\{\text{Batch}\{\text{Link}\{key, value\}\}\}\} \quad (4)$$

In Equation (4), *RDS* is the cloud database, Batch is the batch location, and Link is the link location.

The cloud database returns the data storage address. *Ds* is updated through consensus inside the third-level sub-chain, that is, the data storage address is spliced with the original *Ds*, as shown in Equation (5).

$$Send(Ds) = \sum_{i=1}^{n} Hash(Data_i) + Hash(Add) \quad (5)$$

In Equation (5), *Hash (Add)* is the address hash.

The data digest is transmitted to the National Identification Center through the contract to obtain a unique identification code. The contract returns the identification code to the client and the third-level sub-chain. The client compares the identification information stored in the blockchain with the parsed information to determine whether the identification code has been tampered with. After that, the contract randomly generates a number N_2 and takes the hash value $H(N_2)$. The contract uses $H(N_2)$ to encrypt the updated data digest and transmits the encrypted data to the second-level sub-chain through the backbone nodes in the third-level sub-chain. Similarly, the contract encrypts the encrypted data again using the hash value $H(N_3)$ of the random number N_3 in the secondary sub-chain and transmits it to the primary sub-chain by the backbone node. Finally, it is transmitted to the main chain. After the second-level sub-chain and the first-level sub-chain generate data, the same third-level sub-chain broadcasts the data across the chain and performs multi-level sub-chain encryption.

The multi-level sub-chain encryption mechanism adopts the hash locking mechanism to perform multi-level encryption on the data digest. This mechanism ensures that data information is encrypted on three levels of sub-chains at the same time. This encryption method has three main functions. First, when the supervisory department needs to call the information, it only needs the contract verification authority to issue the corresponding random numbers $N_{1,2,3}$ for decryption. Secondly, multi-level sub-chains increase the complexity of decrypting encrypted data and ensures the security of data between sub-chains of different levels. Malicious attacks need to attack all nodes contained in the three sub-chains at the same time to tamper with information. The sub-chains are resistant to common attacks such as witch attacks. Thirdly, the broadcast backup of the entire network data is realized, and the data are more secure.

4.3.3. Credible Supervision Mechanism

To strengthen the efficiency of the rice supply chain information management and control, a credible supervision mechanism based on identification analysis technology is designed. The National Identification Center assigns a unique identification code to the data of each link. Through identification analysis, regulatory agencies can quickly obtain relevant information about rice. The accuracy of the identification information is compared by the client and the information obtained by scanning the identification with the information in the blockchain to determine whether the identification has been tampered with. The rice supply chain coding rules based on handle codes are designed to ensure the uniqueness of each identification code. The design rules are shown in Figure 5.

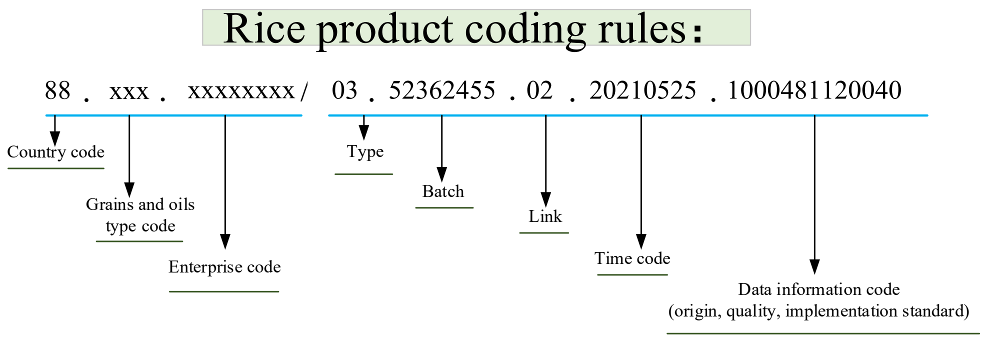

Figure 5. Schematic diagram of identification coding rules.

The identification code consists of two parts. The prefix consists of the country code, grains and oils type code, and enterprise code, respectively. The suffix is composed of the type, batch, link, time code, and material information code (origin, quality, implementation standard). In the prefix, the country code, grains and oils type code, and enterprise code are given by the National Identification Center. In the suffix, the type consists of two digits, corresponding to indicia rice, japonica rice, and glutinous rice, respectively; the batch consists of eight random digits, and the maximum number of supported identifications is hundreds of millions. The link consists of two digits and corresponds to the link where the rice is now. The time code consists of eight digits. The first four digits are the year, the middle two digits are the month, and the last two digits are the specific date. The material information code consists of 13 digits. The first six digits are the regional zip code, and the middle two digits are the quality code. We set 11 to be excellent, 10 to be good, 01 to be middle, 00 to be poor, and the last five digits to perform standard coding for rice.

The rice supply chain includes six main links: plant, purchase and storage, processing, transport, storage, and sale. The purchase and storage link is divided into four parts: acquisition, dry, edulcorating, and warehousing. The processing link is divided into five parts: ridge valley, rice milling, color selection, polishing, and packing. Starting from the plant process, the identification codes related to the same batch of rice are updated as the process progresses. Each enterprise receives the raw materials of the previous link after verifying the correctness of the identification code. Through the contract, the rice information in this link is added, and then the identification code is updated. Upon reaching the sales link, the final identification code is formed. The regulatory authorities can quickly and credibly supervise the rice in different links through the identification code. This in turn enhances the regulatory agency's ability to manage and control rice supply chain data.

4.3.4. Hierarchical Consensus Mechanism

To ensure efficient consensus speed between sub-chains at all levels and the main chain, a hierarchical consensus mechanism is designed. First, the different types of consensus requests are classified (Table 2). Consensus requests are divided into two categories: inter-chain consensus and intra-chain consensus, including new node access, node shutdown, identity update, and new consensus additions. This consensus request is stored on the blockchain, which ensures fast matching of consensus. This research customizes the design of smart contracts, verifies the consensus request, and determines the consensus type. For different types of consensus, the corresponding consensus is carried out, respectively. The consensus process is shown in Figure 6.

Table 2. Consensus request classification table.

Consensus Request	**Category**	
	Inter-Blockchain Consensus	**Intra-Blockchain Consensus**
Access new node	√	
Close node	√	
Add new consensus	√	
Identification code update		√
Data stored in blockchain validation		√
Data traceability	√	
Data query on blockchain		√
. . . . . . (More requests)	. . . . . . ("√" or None)	. . . . . . ("√" or None)

The model first determines the consensus type of the request made by the client through the smart contract. If the request is an intra-blockchain consensus, the consensus process is as follows: Assume that the client request comes from the third-level sub-chain. The request is subject to the consensus of each node within the three-level sub-chain. After the consensus is completed, the backbone nodes broadcast the consensus results to all nodes of the model to realize full multi-chain consensus storage. The fault tolerance rate of the consensus is the fault tolerance rate of the PBFT mechanism, that is, the fault tolerance rate of one-third of the faulty nodes. The calculation formula is shown in Equation (6) [43].

$$f + f + f + 1 = n \rightarrow f = (n-1)/3 \tag{6}$$

In Equation (6), f is the number of error nodes, and n is the number of summary points.

If it is an inter-blockchain consensus, the consensus process is as follows: In the figure, it is assumed that the chain where the client is located is a first-level sub-chain. The request is broadcast on the whole chain (first-level sub-chain), and the backbone node transmits the request to the adjacent chain and broadcasts it, and so on, until the request is broadcast to all nodes. Each blockchain performs intra-blockchain consensus based on the PBFT consensus mechanism. The consensus result is returned to the smart contract, and the contract judges whether the consensus has been reached according to the number of consensus response nodes. Inter-blockchain consensus has a fault tolerance rate of one-third. The calculation formula is shown in Equation (7).

$$\frac{\frac{1}{3}x_1 + \frac{1}{3}x_2 + \frac{1}{3}x_3 + \frac{1}{3}x_4}{x_1 + x_2 + x_3 + x_4} = \frac{1}{3} \tag{7}$$

In Equation (7), x_1 is the total number of first-level sub-chain nodes, x_2 is the total number of second-level sub-chain nodes, x_3 is the total number of third-level sub-chain nodes, and x_4 is the total number of main chain nodes.

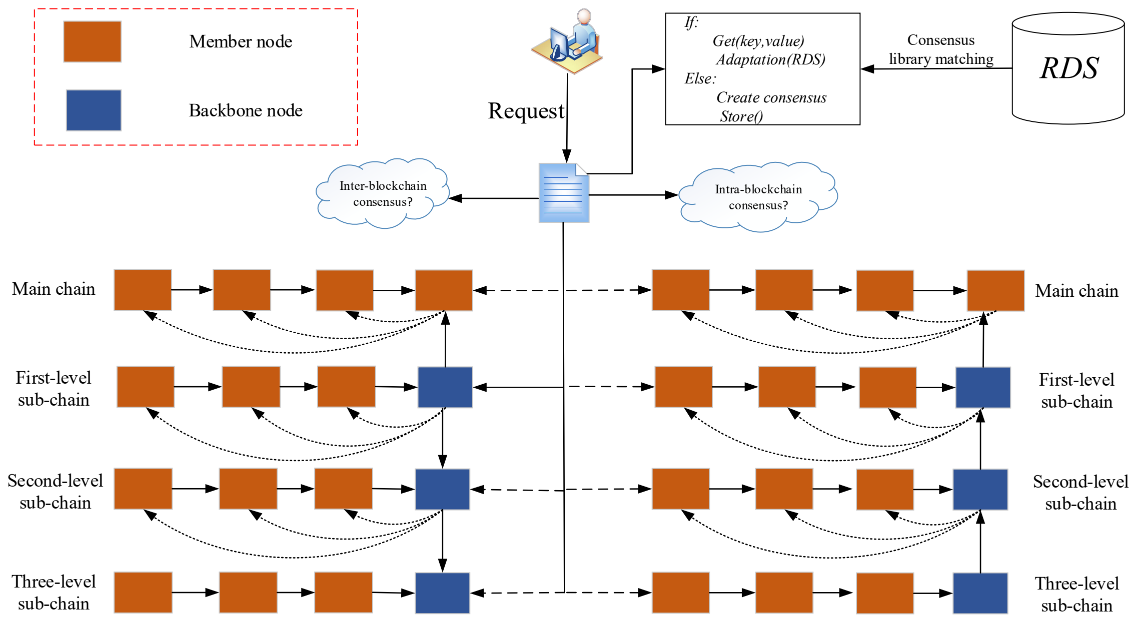

Figure 6. Schematic diagram of hierarchical consensus mechanism.

5. Results and Analysis

5.1. Composition Description

Based on the trusted chaining mechanism, multi-level sub-chain encryption mechanism, credible supervision mechanism, and hierarchical consensus mechanism, the actual modeling, comparative analysis, and example verification of the rice supply chain information management and control model are carried out. The actual modeling part mainly customizes the smart contract design and analyzes the model operation process. In the comparative analysis part, a qualitative comparative analysis is made between this model and existing research. In the example verification part, the prototype system is established according to the model, and the example verification is carried out, relying on the prototype system.

5.2. Results

5.2.1. Smart Contracts

A smart contract is a computer program with status and conditional response running on a distributed ledger. The contract completes the encapsulation, verification, and execution of complex behaviors of distributed nodes through preset rules, and realizes the functions of information exchange, value transfer, and asset management. To ensure the intercommunication of all links in the rice supply chain and the realization of various functions, we designed five smart contracts to encapsulate the operation logic of the rice supply chain information management and control model. The five smart contracts are

Data Standardization Smart Contract (DSSC), Data Verification Smart Contract (DVSC), Data Encryption Smart Contract (DESC), Identity Resolution Smart Contract (IRSC), and Consensus Discrimination Smart Contract (CDSC). We have designed the specific functions and pseudo codes of each contract. To distinguish the different mechanisms of the role of each contract, three Boolean variables are designed to distinguish the contracts.

DSSC: The contract acts on the standardization process of data collected by data collection equipment. Its functions include key-value pair matching for data, data category sorting, data de-noising, and other operations. This contract serves the standardized storage of data to the blockchain and lays the data foundation for subsequent model operations. The DSSC pseudo code is shown in Algorithm 1.

Algorithm 1: DSSC

```
Input: {true, true, true}; Data; User; DVSC
Package Chain-network-integration-A
Func Chain-network-integration-A(){
Call contract(DVSC)// Call DVSC to authenticate user identity
Retrieve data(Data)// Get the data uploaded by the user
Category comparison(Data)// Match data categories
Data de-drying(Data) {// Clean the data
Remove duplicate data
Incomplete data deletion
Delete data with the wrong data type
}
Return User
Key-value matching (Data)// Data key-value pair matching
Return Child chain I~III// Data storage to the blockchain
H(Data)→Ds
Return Child chain I~III
}
```

DVSC: The contract acts on the authentication of user rights, the verification of data, and the interaction of node information. DVSC serves the real-time management and control of data, including real-time resolution of problem data and dynamic management of fraudulent nodes. In this way, the trusted storage of data to the blockchain is realized. The DVSC pseudo code is shown in Algorithm 2.

Algorithm 2: DVSC

```
Input: {true, true, false}; H(user); Ds; CDSC
Package Chain-network-integration-B
Func Chain-network-integration-B(){
Authority authentication(H(user))// Verify User Unique Hash
{ Request permission match()//Request verification
}
Contract status certification(true, false, true ... )// Verify the calling contract
Trusted chain(){
Data distribution(Ds)// Dataset distribution
Signed endorsement()//Signature endorsement
Verification of the number of signatures()//Credibility verification
if true
Return Credible
Exit
Else
Return Higher level sub-chain
}
Call contract(CDSC)// Real-time control of data and nodes, broadcast through consensus, and
deal with problems
}
```

DESC: The contract serves the multi-level sub-chain encryption mechanism. DESC performs multi-level sub-chain encryption by using hash locks on data. The main steps of encryption include generating random numbers, hashing random numbers, and encrypting data by hashing. After DESC calls the DVSC smart contract to authenticate user rights, it decrypts the encrypted data. The DESC pseudo code is shown in Algorithm 3.

Algorithm 3: DESC

```
Input: {true, false, true}; DVSC; Ds; User
Package Chain-network-integration-C
Func Chain-network-integration-C(){
Call contract(DVSC)
Data upload(Ds)// Upload to National Identification Center
Get identification code// get identification code
Distribution identification code(User, blockchain)
Hash lock(Data, Ds)// Hash lock on data
Decrypt data(Data, Ds)// Decrypt data
}
```

IRSC: The contract is mainly used for the transmission of data digests. IRSC connects the blockchain and the National Identification Center to realize data interaction between the two. At the same time, it serves and updates the identification codes of the same batch of rice in different links between various enterprises in the main chain. The IRSC pseudo code is shown in Algorithm 4.

Algorithm 4: IRSC

```
Input: {false, true, true}; DVSC; DESC; H(Add); code_i; Ds
Package Chain-network-integration-D
Func Chain-network-integration-D(){
Call contract(DVSC)
Logo resolution()//Parse the content of the identification code
Data comparison()//Compare and verify with the content on the blockchain
Verification code(code_i)// Verify the accuracy of the enterprise identification code in the previous link
Call contract(DESC)
Data Update(H(Add))// Ds added and updated
Call contract(DESC)
}
```

CDSC: The contract is mainly used to determine the type of consensus. CDSC compares the consensus with the consensus repository, determines the type of consensus, and then implements an inter-blockchain consensus or an intra-blockchain consensus. The CDSC pseudo code is shown in Algorithm 5.

Algorithm 5: CDSC

```
Input: { false, false, false }; DVSC; C; Data_c
Package Chain-network-integration-E
Func Chain-network-integration-E(){
Call contract(DVSC)
Gain consensus(C)
Consensus type matching(Data_c)// Comparing consensus storage databases
Consensus classification(C)
}
```

For DSSC, the contract invokes DVSC to authenticate its identity and perform the initial matching of data. After determining the key information such as the data type, the data are cleaned to remove noise data. Then, key-value pair matching on the data is performed. Finally, the data are stored in the blockchain. For DVSC, the contract verifies the user hash and matches the identity authority. Afterwards, the data set is distributed, and the reliability of the data is judged through the digital signature feedback of the nodes. Finally, the whole chain nodes are broadcasted. For DESC, the contract realizes the data interaction between the blockchain and the national identification center, the multi-level encryption, and decryption of the data. For IRSC, each node of the main chain verifies the correctness of the identification code through this contract. IRSC updates the identification code for the same batch of rice. For CDSC, the contract serves all nodes in the model. CDSC is responsible for distinguishing the consensus categories and then specifying the corresponding consensus methods. The rice supply chain information management and control model relies on customized smart contracts to operate. By quantitatively designing the execution conditions of the contract, we provide a feasible solution for information management and control in the entire life cycle of the rice supply chain. DSSC, DVSC, DESC, IRSC, and CDSC call and supervise each other. To ensure the credibility of the smart contract code, we set the trigger conditions through customization so that it can help the rice supply chain information management and control model to achieve the expected functions. Taking advantage of the fact that smart contracts cannot be tampered with, the model can realize trusted storage of data to the blockchain, encryption of multi-level sub-chains, trusted supervision, and consensus grading. Based on the customized smart contract design, we have constructed a rice supply chain information management and control model.

5.2.2. Running Process

Based on the idea of multi-chain collaboration, a rice supply chain information management and control model is constructed, and the sequence diagram of its operation process is shown in Figure 7. The operation process is divided into three parts: the trusted storage of data to the blockchain, the real-time management and control of the rice supply chain information, and the rapid achievement of consensus requests.

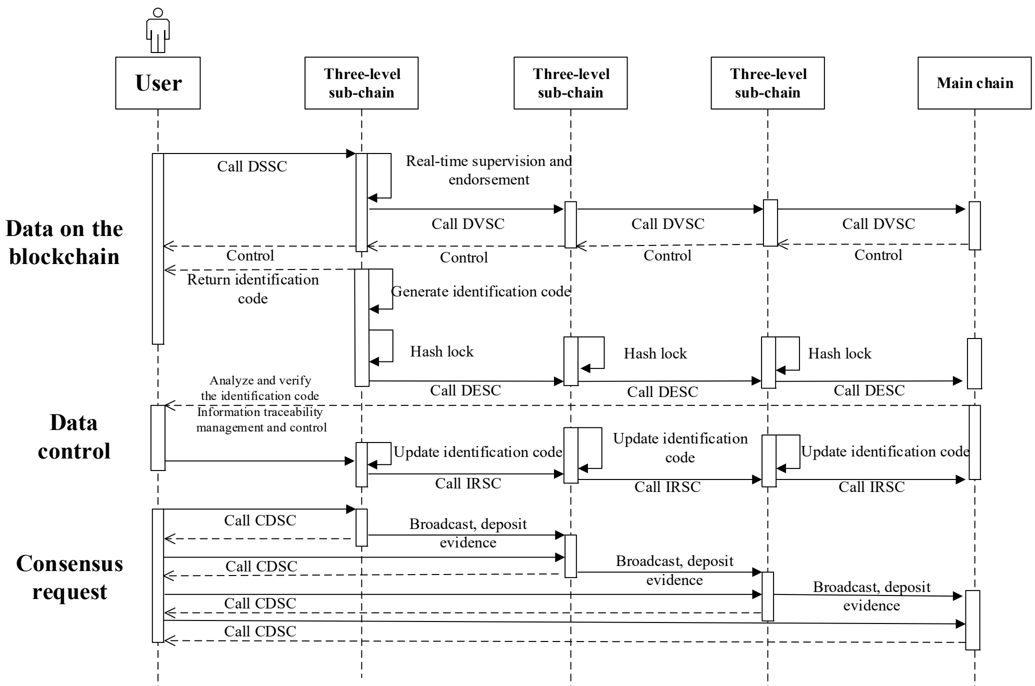

Figure 7. Model running process sequence diagram.

The trusted uploading of data begins with the client submitting data. Taking the third-level sub-chain as an example, the model calls DSSC to standardize the data, and then each node of the third-level sub-chain conducts real-time supervision and digital signatures.

DVSC verifies the signature. If the verification fails, DVSC will carry out progressive control: it will review according to the sub-chain level from low to high until it is handed over to the regulatory department for processing. The trusted on-chain process adopts a joint responsibility mechanism. The digital signature of each node is responsible for the data. Through the progressive management and control method, the data can be managed and controlled in real time on the chain. The control part mainly refers to the verification and updating of the identification code. To ensure the accuracy of the regulatory information, the regulatory authorities can control the rice supply chain information. The main process is the following: after the user parses the identification code of the data in the previous link, it is compared with the data in the blockchain for verification. After the enterprise confirms that it is correct, it will supplement the new information in this link and deliver it to the National Identification Center to generate a new identification code. The identification code will be repeatedly verified and updated with the circulation of rice until the final sale. The management and control part is aimed at the data trust verification process between enterprises corresponding to each link in the main chain. The consensus request part mainly refers to the classification of consensus within the blockchain. Through the judgment of the CDSC contract, different types of consensuses can be used for intra-blockchain consensus or inter-blockchain consensus. After the consensus is completed, all nodes are broadcast in the form of P2P, and the certificate is stored on the blockchain.

The rice supply chain information management and control model based on multi-chain collaboration can realize the trusted storage of all data in the rice supply chain to the blockchain, the trusted supervision of data, and the real-time management and control of information. Based on a hierarchical consensus mechanism, the model can quickly process consensus requests. This greatly reduces the occurrence of model concurrency problems.

5.3. Discussions

Blockchain technology has the characteristics of decentralization and transparency, and it is tamper-proof. Scholars have conducted considerable research on the application of blockchain technology to food safety supervision. Tao et al. (2019) designed a food safety supervision system based on a hierarchical multi-domain blockchain network [4]. The system includes a Hierarchical Multi-Domain Blockchain (HMDBC) network structure and a secondary verification mechanism, which supports timely correction and replacement of malicious supervisory nodes [4]. Compared with the traditional blockchain system, the system has lower broadcast complexity and supports management node replacement. Mondal et al. (2019) proposed a blockchain-inspired IoT architecture for creating trusted food supply chains [6]. The architecture uses an object proof-based authentication protocol and is implemented via RFID and blockchain. RFID provides a unique identification of a product and sensor data that facilitates real-time quality monitoring. The blockchain architecture helps create a tamper-proof digital database of food packaging in each instance. We compared and analyzed the rice supply chain information management and control model based on multi-chain collaboration designed in this study (Table 3).

Table 3. Comparative analysis table.

Performance	Index	Tao et al., (2019) [4]	Mondal et al., (2019) [6]	Our Study
Security	Fault tolerance	33%	51%	33%
	Attack diversity	middle	high	high
	Security recovery	high	middle	high
	Attack cost	high	middle	high
Model efficiency	Throughout capacity	high	middle	middle
	Delay	middle	high	low
Scalability	Resource consumption	high	middle	high
	Application scalability	middle	middle	high

In terms of security, the rice supply chain supervision model adopts a trusted chaining mechanism to ensure the credibility of the data in the whole process of rice from raw grains to finished products. The model adopts a hash locking mechanism to design a multi-level sub-chain encryption mechanism, which increases the security of data cross-chain transmission. On this basis, through the identification analysis technology, the trusted supervision of data is realized. Compared with the Tao et al. (2019) and Mondal et al. (2019), this study is based on the PBFT consensus mechanism, and its node fault tolerance rate is 33% [4,6]. The communication complexity is the same as in Tao et al. (2019), which is $O(m^2 + x^2)$ [4]. The model is resistant to attacks such as Sybil attacks, communication network monitoring, and data network denial of service attacks. For the safety and recovery of data, this study implements "sub-chain + main chain" full node information backup. Compared with the single-chain architecture, the data security recovery in this study is higher, and the attack cost is higher.

The efficiency of the rice supply chain information management and control model is reflected in its consensus mechanism. The model can quickly complete node consensus on client requests. The model classifies the types of consensus requests in advance and stores the classification results on the chain. Smart contracts quickly match requests to determine the type of consensus, and then perform corresponding intra-blockchain consensus or inter-blockchain consensus. Compared with the traditional consensus method, the consensus efficiency of the hierarchical consensus mechanism is faster. Through the rapid classification of consensus requests by smart contracts, the synchronous consensus of different types of consensus requests is realized. The hierarchical consensus mechanism joins the intra-blockchain consensus. This consensus category serves the consensus of the internal nodes of the enterprise and does not require all nodes in the model to participate in the consensus. Therefore, the consensus speed can be greatly enhanced. In addition, the consensus results can be broadcast through the backbone nodes of each sub-chain to realize the full model node storage. The immutability of the consensus result is guaranteed. Second, consensus concurrency is reduced. The number of rice supply chain consensus requests is enormous. This model can effectively reduce the probability of consensus problems through a multi-level consensus mechanism. We custom designed CDSC, which can quickly match consensus requests and realize multi-chain consensus requests synchronously.

In terms of scalability, due to the large number of nodes, although the hierarchical consensus mechanism is implemented, the consumption of the computing and storage resources of the model is generally larger than that of Mondal et al. (2019) [6]. However, in terms of application scalability, this study is more scalable than those of Tao et al. (2019) and Mondal et al. (2019) [4,6]. This research is not only limited to the rice supply chain, but also provides new ideas for food quality and safety in the field of grains and oils, and even the digital transformation of information in the supply chain of all categories.

In general, the model of rice supply chain information control constructed in this paper has certain advantages in terms of security, efficiency, and scalability compared with the existing research on blockchain in the field of agricultural products and foodstuffs. Moreover, it can solve a series of problems such as collaborative management of all types of data and personnel, credible uploading of data, and efficient consensus of nodes faced by blockchain applications in agricultural and food fields. However, this paper adopts a multi-chain architecture, so the model designed in this paper has more nodes than single-link blockchains such as "production chain" and "processing chain". Although this paper designs a hierarchical consensus mechanism, the overall resource consumption is still higher than that of a single-layer blockchain architecture.

5.4. Prototype System Implementation

Based on the rice supply chain information management and control model, a prototype system of the rice supply chain information management and control is built. The development environment is as follows: the Linux (Linus Benedict Torvalds, America) version is 16.0.0, and the Ubuntu (Mark Shuttleworth, Britain) version is 20.04.1. Fabric 2.1 is used for building, the Docker (Solomon Hykes, America) version is 20.10.7, the docker-compose version is 1.25.0, the Go language (Ken Thompson, Rob Pike, Robert Griesemer, America) version is 1.17.2, and the storage medium is RDS. For the front end of the prototype system, we adopt the Angular framework for design. To test the practicability of the prototype system, the model has designed eight main chain nodes, which correspond to the six links of the rice supply chain: production, storage, processing, transportation, warehousing and sales, representing enterprises, as well as regulatory authorities and consumers. For sub-chains, we have built seven first-level sub-chains, seven second-level sub-chains, and seven third-level sub-chains, which help enterprises and internal personnel in regulatory departments to upload to the chain.

By investigating a batch of the rice supply chain in Northeast China, the data of this batch of rice were recorded in detail and kept intact. In one company, we analyzed and validated the rice supply chain information control system using the batch of rice data and tested this system by example. Then, with the help of a supervisory unit, the practicability of the system is tested. The test interface diagram of the system is shown in Figure 8.

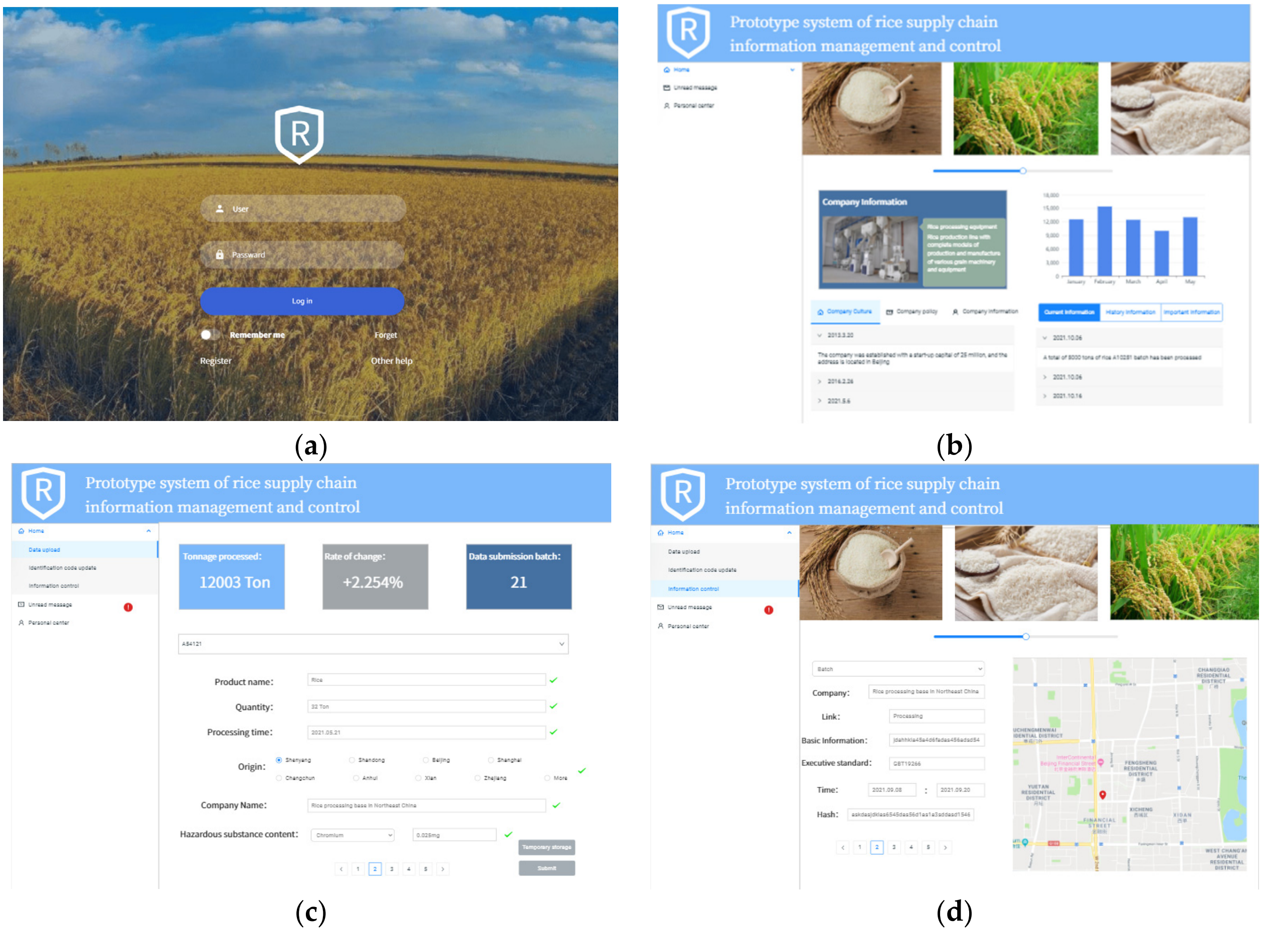

Figure 8. Schematic diagram of the prototype system interface: (**a**) Schematic diagram of the login screen; (**b**) Schematic diagram of the main page; (**c**) Schematic diagram of the data upload interface; (**d**) Schematic diagram of the trusted supervision interface.

Figure 8a shows the login interface of the prototype system. The user matches the corresponding function by entering the account password. Take an enterprise account as an example to log in. Figure 8b shows the main page of the prototype system. The left side of the interface shows where you are. Above is a carousel of rice pictures. In the middle are the basic introduction of the enterprise and the visual display of the amount of rice processed in half a year. At the bottom of the interface is the information display module, which contains the company culture, introduction of other companies, and the latest news notification. Figure 8c shows the data upload interface. The upper part of the interface shows the amount of rice processed this month, the rate of change compared to the previous month, and the total number of batches. Below is the data submission section. Users submit data as required. The submitted data can be temporarily saved to the system or directly submitted to the blockchain. Figure 8d shows the trusted supervision interface. The client scans the QR code, and the system then parses the identification. On the left is the data information, and on the right is a map display of rice-related locations. Users can compare the data in the blockchain with the parsed data of the identification here. If they are consistent, the identification code has not been tampered with.

We conducted an example analysis of the prototype system and tested it for a batch of data that was being circulated within the enterprise. Compared with other agricultural supply chains, the rice supply chain can be divided into 13 links, and multiple batches of rice exist in the same link, but a certain batch of rice can only be in a certain link at the same time. The information generated in the rice supply chain is heterogeneous from multiple sources, where the information on hazards is mainly on heavy metal hazards such as chromium, lead, arsenic, and other hazards such as aflatoxin (AFBI) and molds. The basic information is mainly comprised of seed sources, fertilizer sources, logistics information, etc. Personnel information is mainly the information of each participating company, regulatory agencies, and consumers. Data verification is performed on the 20 groups of data on the chain, and one group of data on the chain is shown in Figure 9.

Serial number	Category	Bstch	Link	Yield	Endorsed hash	Chromium content	Lead content	Cadmium content	AFBI
1	Rice	A12565	4	25	daasd454564asad4	0.0215	0.2556	0.0025	0.0254
2	Rice	A12566	5	24	ff545sffs45adda4sd	0.0255	0.0256	0.0024	0.2451
3	Rice	A12567	6	23	fafsa4fa65a1f321ds	0.0215	0.2487	0.0036	0.2451
4	Rice	A12568	3	22	hyh4y1u5h156y1nny	0.0254	0.0268	0.0058	0.0254
5	Rice	A12569	2	23	m11b51gh566g5j41	0.0526	0.0654	0.2145	0.0065
6	Rice	A12570	4	25	rs1f566qqs56f65s1f	0.0545	0.0257	0.0214	0.0024
7	Rice	A12571	3	30	afq4z1z23c132z1dd	0.0654	0.0784	0.0268	0.0025
8	Rice	A12572	2	32	df4a64f656q651f32	0.0154	0.0845	0.0254	0.0025
9	Rice	A12573	2	33	asdq446z5cd456zv	0.0257	0.0654	0.6547	0.0257
10	Rice	A12574	3	35	ocops546456cs161	0.2154	0.0354	0.2401	0.3684
11	Rice	A12575	4	25	wpqioqwend54d65	0.0654	0.1254	0.0256	0.0147
12	Rice	A12576	5	23	fds34f5s4f651f23sd	0.0257	0.2687	0.1452	0.3698
13	Rice	A12577	6	25	ad46qw7897c4sd1c	0.0144	0.0254	0.0265	0.4578
14	Rice	A12578	1	24	ad2656fd465gb6hN	0.1254	0.0697	0.4582	0.3695
15	Rice	A12579	4	24	dq8989opooqdjkml	0.0547	0.2547	0.2478	0.4785
16	Rice	A12580	1	25	iicuiihxasijxhd45465	0.0587	0.2654	0.3694	0.5687
17	Rice	A12581	3	25	dw1c1d1555c1d1a2	0.0365	0.0258	0.2547	0.4751
18	Rice	A12582	4	27	qwq8784z2x1c32z1	0.0247	0.0369	0.3654	0.6587
19	Rice	A12583	5	30	uk54u5k1u51y1j61n	0.0254	0.0475	0.0258	0.0025
20	Rice	A12584	3	31	ku1l21gh321fh15tth	0.0254	0.0124	0.0056	0.0027

Figure 9. Schematic diagram of data testing.

The data tested were part of a batch of rice from this enterprise, including the serial number, type, batch, link, yield (ton), hash value, chromium content, lead content, cadmium content, and AFBI value of the batch. The yield and heavy metal hazards are data that can be easily manipulated and falsified in the rice supply chain, which can have a serious impact on the quality of rice products. After comparison, the data are completely consistent with the data at the collection end, and no tampering occurs. Furthermore, the data after scanning of the identification codes corresponding to the 20 sets of data are compared, and the data coincidence rate is 100%. The results show that the prototype system can guarantee the authenticity of the identification code. To sum up, the rice supply chain information management and control model based on multi-chain collaboration is a completely feasible solution for rice digitalization.

Next, it is tested for tampering attacks. A total of 1000 groups of data stored in the blockchain were tested. The blockchain is designed as a tertiary sub-chain. Ten groups of data are tampered with, three nodes in the third-level sub-chain are set as malicious nodes, and malicious digital signatures are performed. Statistics on the data are detected by the model. Then, the model can intercept the tampered data in time. According to the digital signature, malicious nodes can be accurately located. The check update made to the identification code was tested. By simulating five batches of rice data, each batch tampered with the identification code in different links to test the protection degree of the model to the identification code. The test results are shown in Figure 10.

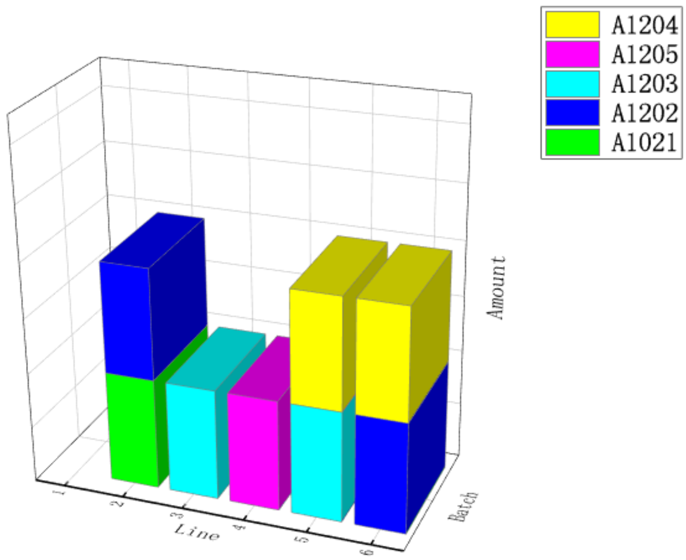

Figure 10. Identification tampering test diagram.

In the company's data tests, each of the five batches of rice tested above contained six stages of production, storage, processing, warehousing, transportation, and marketing. The X-axis in the figure corresponds to the six links in the rice supply chain. The five colors represent the five batches tested. Batch A1204 shows a yellow square, batch A1205 shows a purple square, batch A1203 shows a sky-blue square, batch A1202 shows a dark blue square, and batch A1021 shows a green square. The batches tested for tampering in the six basic sessions are displayed accordingly. The identification code of the A1201 batch of rice was detected to have been tampered with in the process of storage. The identification code of batch A1202 was detected to have been tampered with during the process of purchase, storage, and sales. The identification code of batch A1203 was detected to have been tampered with during processing and storage. The identification code of the A1204 batch of rice was detected to have been tampered with in the storage and sales links. The identification code of batch A1205 rice was detected to have been tampered with during transportation. Each enterprise relies on the model to accurately identify the fault identification code.

6. Conclusions and Future Prospects

6.1. Conclusions

To strengthen the information management and control capabilities of the rice supply chain, a rice supply chain information management and control model is designed based on the idea of multi-chain collaboration. Aiming at the complex process and huge amount of data in the rice supply chain, a trusted chaining mechanism, based on digital signature technology, hash locking mechanism, identity resolution technology, and smart contract technology, a multi-level sub-chain encryption mechanism, a trusted supervision mechanism, and a hierarchical consensus mechanism have been constructed to serve the information management and control of the rice supply chain. The model provides trusted storage of the rice supply chain information in the blockchain, accurate positioning and real-time interception of problem data, real-time monitoring of uploaded data, cross-chain communication of data between sub-chains, credible data supervision, and efficient consensus. Then, the pseudo-code design of DSSC, DVSC, DESC, IRSC, and CDSC serving the model is carried out, and the running process of the model is designed. After comparing and analyzing the models, a prototype system was built based on the rice supply chain information management and control model. The prototype system was applied to an enterprise in northeast China, and the feasibility, security, and operational efficiency of the model were analyzed and tested. The results show that it is an innovative practice to apply the idea of multi-chain collaboration to the information management and control of the rice supply chain. This study provides a feasible and pragmatic application solution for accelerating the digital transformation of the grain industry, enhancing the management and control capabilities of grain crops, and ensuring food security.

6.2. Discussion and Future Work

The rice supply chain information management and control model based on multi-chain collaboration is not only suitable for the rice supply chain supervision, but also has applicability in supply chain, medical, financial, and other fields. Specifically, the trusted chaining mechanism makes up for the problem that blockchain technology cannot guarantee the authenticity of data before being stored in the blockchain. The model ensures the credibility of the whole process from generation to use of data. The multi-level sub-chain confidentiality mechanism ensures the security of cross-chain transfer and backup of data between different sub-chains. The model can decrypt the data by verifying it with the smart contract. It not only ensures the security of data in the process of cross-chain transmission, but also realizes fast data access. The trusted supervision mechanism can control and update the identification code in real time, which can ensure the credibility of the identification code. The hierarchical consensus mechanism can handle the consensus request problem under big data and achieve efficient consensus among nodes between multiple blockchains.

In view of the unique architecture of the rice supply chain, this paper demonstrates that applying blockchain smart contracts to the rice supply chain based on the idea of multi-chain collaboration can increase the transparency of the rice supply chain and achieve complete decentralization of rice data at the information level, thus reducing users' dependence on the trustworthiness of rice quality data. This is an important contribution to the realization of Agriculture 4.0, precision agriculture, and digital transformation of agricultural products. However, rice supply chain is a huge and complex supply chain. With its diverse participants, complex links, and huge amount of data interactions, it is challenging to apply blockchain in the global rice supply chain at this stage. First, it is a complicated process to replace the traditional centralized management mode of the rice supply chain with the decentralized management mode of blockchain. Secondly, the level of trust in the blockchain system by related companies, regulators, and consumers in all aspects of the rice supply chain needs to be further improved. Next, the technical requirements to apply blockchain technology in the rice supply chain are also an important factor hindering the application of blockchain in the rice supply chain. Finally, the low storage performance and high latency of the blockchain itself is where cracking needs to be improved. In the future, we will explore the integration application methods of blockchain smart contracts with traditional rice supply chain systems and technologies for the transition of the rice supply chain from the traditional centralized information control model to a decentralized control model and increase the trust of people's blockchain smart contracts in the process, as well as the use of deep learning, machine learning, and other artificial intelligence algorithms to optimize the model's high computational volume and high latency. We will also explore the application of this model to other grain and oil crops, explore the realization of digital and credible transformation of the whole category of grain and oil food, and promote the ability of grain and oil food information control with multi-chain technology.

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