IS6200 – Blockchain Technology and Business Application

Research Project

A Food Supply Chain Traceability System Based on Blockchain Technology

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Note: I have used a large language model to aid in the drafting of my work. All content influenced by AI assistance has been thoroughly reviewed and edited to ensure it adheres to the academic standards and originality required by IS6200 as well as reflect my own understanding of the course materials.

Abstract

In the context of a highly complex global food supply chain, this study explores how a traceability system that incorporates blockchain technology and IoT devices can be implemented to improve food safety, transparency, and efficiency. This paper outlines the three main stages of a comprehensive traceability system: production, logistics, and sales. The production stage mainly uses a voting process to assess the trustworthiness of suppliers, while the logistics and sales stages are intelligently connected with IoT devices to achieve data automation and verification through non-fungible tokens (NFTs).

The main findings show that the system significantly improves product traceability by efficiently providing a tamper-proof record of each product from origin to consumer. The use of IoT devices for data collection and the combination of a dynamic voting mechanism for supplier credibility assessment further enhance accountability and trust among stakeholders. In summary, this study contributes to transparent food supply chain management, enhanced consumer confidence, and real-time compliance with food industry regulations.

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1 Introduction

1.1 Research Background

In recent years, the global food supply chain has gained further complexity due to factors such as changes in customer demand, diversification of products, and volatility of supplier performance. These factors, along with the bifurcated structure, multi-layered nature, dispersed network, and diverse regulatory environment, result in making modern supply chains face increasing pressure.

The bifurcated structure splits the supply chain into distinct but interconnected branches, complicating coordination. The multi-layered nature means multiple tiers of suppliers, manufacturers, and distributors, adding complexity to managing the flow of goods and information. The dispersed network involves entities spread across different regions or countries, making communication and control more challenging. Lastly, the diverse regulatory environment, with varying rules and standards by country or industry, adds another layer of complexity to compliance and operations. This is particularly challenging for the food and pharmaceuticals industries which operate under stringent safety and quality standards because product traceability becomes significantly more complex than it needs to be. These industries eco-systems and stakeholders need further transparency, efficiency, and credibility.

This is precisely why establishing a robust and effective traceability system is essential. Demanding greater transparency and traceability in supply chains often leads to inefficiencies in traditional models, which in turn erodes consumer confidence. Moreover, traditional traceability systems, even simple ones such as single-step forward (the tracking process from raw materials to final products) and single-step backward (the process of tracing from the final product to the raw materials) tracing, often encounter issues with data integrity or rely excessively on third-party systems for data management. For example, many enterprises use traditional databases to store and manage supply chain data, but these systems are vulnerable to attacks, prone to single points of failure, and make data tampering difficult to trace. Some companies also depend on centralized security certification systems, such as digital certificates issued by CA (Certificate Authority) institutions for identity verification and data encryption, but this approach has the problem of centralized trust. Additionally, some companies may use third-party cloud service platforms to store and process data, but these platforms may face risks of data loss, errors, or tampering. These single-step tracing methods, which focus only on direct upstream and downstream links, fail to provide a comprehensive view of the supply chain, leading to potential data gaps or inaccuracies that can undermine the comprehensive assessment of product quality, safety, and compliance. Furthermore, if third-party systems encounter problems, it could negatively impact the traceability capabilities of the entire supply chain.

Blockchain is a new approach that uses a decentralized distributed ledger at its core, allowing for unique enhancement capabilities for traceability and offering totally new solutions for observing and managing supply chains.

As a key feature of blockchain technology, smart contracts enable automated and highly secure transactions. By providing transparent, verifiable, and tamper-proof records of product flows, smart contracts have the potential to further improve the efficiency and reliability of the traceability system under the blockchain. They reduce the need for intermediaries, thereby enhancing trust through increased transparency and security.

1.2 Significance of Study

This study aims to address the pitfalls of traditional food supply chain management by implementing blockchain systems integrated with smart contracts. The relevance is outlined below:

First, the systems can fundamentally enhance food safety dramatically by improving regulatory compliance processes through accurate tracking and quick response to product issues. This not only enables effective recalls and improves organizational efficiency but also fosters a trustworthy environment for consumers to make informed decisions.

Secondly, the system aims to solve existing gaps and limitations of traceability methods. Compared to traditional models, the use of blockchain technology improves data integrity, lesser reliance on the unstable system developed by third party, and better trust among supply chain members.

Overall, this study makes a contribution not only in the development of the theory of blockchain enabled supply chain traceability, but also in the practical approach in the food industry which helps in developing efficient and transparent systems of tracing food products which helps in the overall digitization of supply chain management.

2 Literature Review

2.1 Innovation and Practice in Real Business Cases

Kshetri (2018) mentioned that Walmart used IBM blockchain solution based on the Hyperledger Fabric framework, which builds a decentralised food safety traceability system. For example, the unique identification code on each pork package, which offers consumers the full chain of information from origin to shipping history. At present, Walmart possesses the ability to quickly trace a batch of food sources within 10 seconds, which takes several days or even weeks compared with a manual search.

In addition, a typical multi-party collaboration case is JD.com, Inc. enhancing its cooperation with Kerchin Cattle Industry Co., Ltd. by developing blockchain applications. As a food supplier, Horqin Cattle is responsible for recording information about the food itself. JD.com, as a logistics provider, is responsible for recording information about the logistics of the food. This collaboration is a typical example of multi-party collaboration in the supply chain, showing how producers and e-commerce platforms can optimise the food traceability system through blockchain technology.

In conclusion, blockchain is feasible and effective in real-world business environments. It could be applied to multi-party cooperation across the entire supply chain, and provide critical support for the digital transformation of the food industry.

2.2 Challenges

Wang Puqing et al. (2019). pointed out that in the food supply chain, due to information asymmetry, suppliers may engage in behaviors such as expelling good products with inferior ones and using inferior products downstream, which affects the efficiency of the supply chain and even food safety. Blockchain technology can solve this problem. For blockchain supply chains, the challenge we face is how to ensure the authenticity and reliability of the data provided by suppliers and avoid information tampering and concealment.

Babich and Hilary (2020) argues that enterprises have to consider the high cost of deployment and maintenance of blockchain. The high cost of public chains stems mainly from the consensus mechanism and decentralised redundant design. Although private chain reduces part of the cost, the upfront deployment and ecological synergy investment still constitute the threshold. This is a big hurdle, and key research direction, how to lower operating expenses at improve operational efficiency at the same time keep the nature-favoring of blockchain.

The complexity of the food chain itself has also been raised as an important dimension. As Kshetri (2021) notes in his analysis of agri-food blockchain projects, over 60% of implementations face integration barriers with legacy IoT and ERP systems due to data format incompatibilities and process misalignment. And most studies are at the level of traceability system feasibility, and few of them take into account practical and complex issues to integrate new technologies with existing technologies (like IoT, ERP) or interoperability challenges between different blockchain networks.

In summary, the application of blockchain technology in the food supply chain has broad prospects, but the current challenges also need to be addressed. Future research should attend removing costs and augmenting efficiency in addition to encouraging technology integration, as well ensuring data authentication.

3 Traceability System Description

In the food supply chain, the real-time and accuracy of data are crucial to ensure food safety, improve efficiency and enhance transparency. Traditional data recording methods rely on manual recording and manual entry, resulting in untimely data updates, low accuracy, and delays in data synchronization between different systems.

To solve the problems of traditional data recording, this paper proposes a traceability system for the food supply chain, which combines blockchain and IoT technologies to intelligently manage the logistics system, thereby improving transportation efficiency and transparency.

The system architecture is divided into three main stages, which are described in detail below: production phase, logistics stage and sales stage.

3.1 Production Phase

In this phase, basic food information is first submitted by the producers, which are the suppliers for the dominant company in the entire supply chain. And the authenticity and reliability of the suppliers need to be ensured through a voting mechanism when introducing them. After the producer onboarding, the smart contract verifies the basic food information submitted by the producer and records it on the blockchain. The NFT ledger is then automatically updated through IoT sensors (including RFID tags, GPS trackers, and status sensors) pre-deployed in packaging or pallets to record the location and handler ID. All data collected in the above process is transmitted to the blockchain node through a secure API. There, the smart contract verifies and attaches it to the NFT.

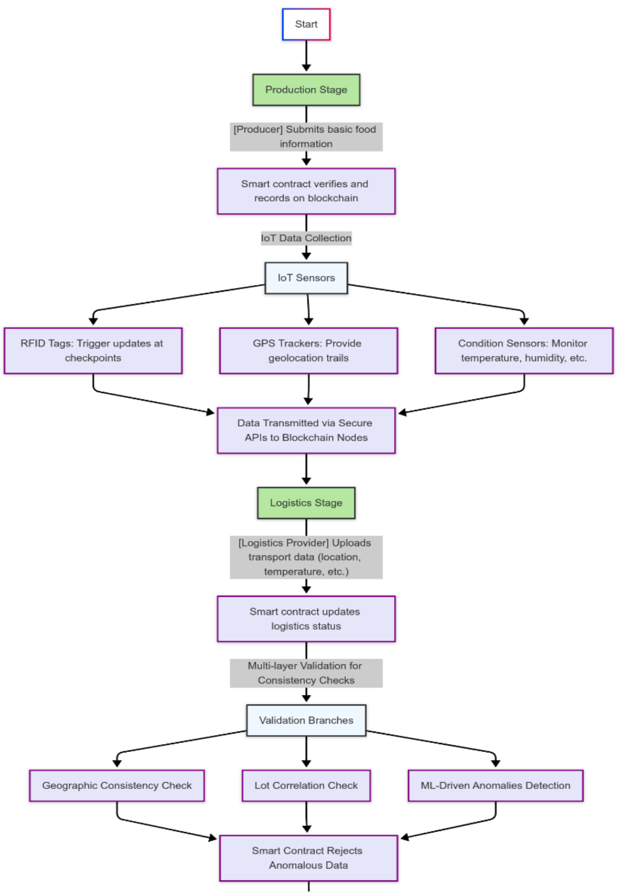
3.2 Logistics Stage

In the logistics stage, logistics providers upload transportation data (such as location, temperature, etc.) to blockchain nodes. After receiving the data, the smart contract updates the logistics status and performs multiple layers of verification to ensure data consistency *(See Section 3.4.2 for details)*. If abnormal data is detected, the smart contract will reject the data and trigger an automatic response mechanism. At the same time, the NFT metadata related to the goods will be updated based on real-time data during transportation.

3.3 Sales Stage

The inspection agency will first upload the quality inspection results and mark the food status through smart contracts.If the quality is guaranteed, the retailer can automatically complete the payment through smart contracts after confirming the arrival of the goods and confirming the quality of the food.

After entering the sales stage, when consumers buy food, they only need to scan the QR code to obtain the complete food traceability information associated with the NFT. The system will display the complete food processing information in the QR code, including detailed data on production, transportation and inspection, etc., to meet consumers' right to know about the food processing process and improve consumers' trust in food safety.



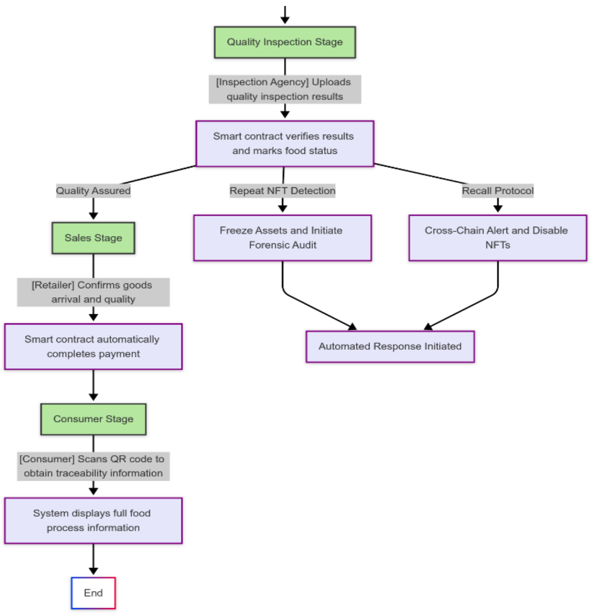


Figure 1. Flowchart： Food Supply Chain Traceability System

3.4 Assurance Measures

In order to ensure the authenticity and immutability of supply chain data, the system takes a series of assurance measures.

3.4.1 Data Source Authenticity

(1) Supplier Due Diligence

Due Diligence Process: Apply the architecture and logic of decentralized autonomous organizations (DAOs) to enhance the transparency of the bidding process and ensure that the qualifications of the selected suppliers are authentic and valid.

Data Entry: Ensure the transparency of potential supplier information through on-chain governance, and all due diligence and bidding materials are stored on the blockchain. Design smart contracts to verify the validity of data and improve work efficiency.

Voting Mechanism: Use a combination of weighted voting and quadratic voting to ensure that the voting weights of various stakeholders are reasonably distributed. *(See Section 4.1.1 for details)*

Incentive Alignment and Accountability: Set reasonable internal incentive rules through smart contracts to ensure that the interests of participants are consistent with the company's requirements. Design an accountability mechanism to ensure that suppliers who do not meet the company's expectations are held accountable. *(See Section 4.1.2 for details)*

(2) Check Supplier Products

Smart Contract Input Product Information: Trigger smart contracts during the supply process to record product details and verify their integrity.

Supplier Private Key Signature: Use private keys to hash and encrypt data, generate digital signatures, and ensure the authenticity of original data.

Cargo Inspection: After the product arrives at the company, use the public key to decrypt the digital signature and verify the authenticity of the information. Realize seamless integration of blockchain and traditional systems to improve work efficiency.

3.4.2 Data Source Consistency

Ensure complete consistency of data sources, and build a consistency assurance chain of "collection-verification-execution" by improving the logical design of the blockchain system.

(1) Logical design of the data collection layer

Deploy IoT sensors to realize real-time collection and automatic upload of product information, adopt a unified data format and preset field verification rules, and intercept non-standard data.

(2) Logical design of the data verification layer

Geographic consistency check: Use smart contracts to compare GPS tracks with transportation time to prevent data falsification.

Batch association check: Ensure that batch numbers correspond one-to-one in upstream and downstream links.

Machine learning-driven anomaly detection: Identify abnormal patterns and issue real-time alerts.

(3) Logical design of the abnormal response layer

Data verification and automatic freezing: Automatically trigger asset freezing and forensic auditing when duplicate NFTs are detected.

Rule solidification and early warning: Automatically execute early warning notifications when triggering conditions to ensure consistency and timeliness.

Cross-chain recall protocol: When product quality does not meet standards, automatically send alerts to all cooperative blockchains to prevent problematic products from flowing into the next link.

4 Technical Support

4.1 Vote: Blockchain Technology in Production

4.1.1 Voting Mechanism

In the production process, the main aim is ensuring the credibility of suppliers. Because trustworthy suppliers can provide convincing data sources and goods, which can ensure the authenticity of data sources.

(1) Determine the tokens and voters

In the process of introducing suppliers, it mainly involves submitting relevant materials and voting to select suppliers.

- Token for material submission:

The token for material submission is designed by the company that needs to introduce suppliers, which is the dominant player in the entire supply chain .

The token is specifically used for submitting all materials and it does not have voting rights. It can be allocated to suppliers and employees who is responsible for uploading bidding materials and due diligence materials.

- Voter:

The voters are the member of the company that needs to introduce suppliers, including: the founder, senior executives, and all managers and general employees in relevant departments. The relevant departments include the direct downstream business departments of in the supply chain that directly interfaces with the potential supplier, as well as all functional departments responsible for reviewing supplier materials, such as the finance and legal departments.

(2) Voting methods

We first use a quadratic voting method by using Snapshot, which is an off-chain governance, and the voting results are calculated by smart contract code for guiding succeeding on-chain governance.

The voting credits allocated to voters are specifically used for the voting process. And credit ratio is 30:20:15:10 for founder: senior executives: managers: general employees, ensuring that higher vocational level people have relatively greater voting rights.

When calculating the voting results, in order to prevent the results from being influenced by the majority due to the imbalance of department size, it is necessary to normalize the final voting results.

In addition, the minimum requirements and voting security measures for voting are as follows: the minimum number of votes shall not be less than 90% of the total votes; A tie vote is not allowed when everyone votes; If there is a tie in the final result, a new vote is needed to break the tie.

(3) Full process execution

- Material Token Stage:

a) Initial Token Allocation and Collection: created and allocated by the company that introduces suppliers. The smart contract automatically assigns 1 token to each supplier after registering an account in the blockchain platform, which is used to submit bidding proposals.

b) Preliminary proposal inspects: After the supplier submits the proposal, the review team designated by the company will conduct the inspect process, and the members of the team are authorized to view the content of the proposal.

c) Token Allocation for due diligence materials: If the proposal is approved, the review team will click the "approve" button, triggering the smart contract and assigning 1 token from the contract account to the employee account responsible for uploading due diligence materials.

d) Submission of due diligence materials: The company employee responsible for due diligence submits the due diligence materials, and deducts 1 token from their account at the same time.

e) Due diligence inspects: After the due diligence materials are submitted, they will be reviewed by the due diligence team of the company. If the due diligence is passed, a transaction will be automatically triggered, allowing the supplier to receive 1 token.

f) Submission of formal bidding materials: After receiving the token, the supplier can submit formal bidding materials, and 1 token will be automatically deducted when submitting.

- Waiting period (30 days):

During the waiting period, relevant parties who will participated in voting can further verify the submitted materials from the suppliers and prepare for voting.

- Voting phase (5 working days):

Voters use the allocated credits to vote for suppliers and using the voting mechanism described earlier, and the voting results will determine whether the supplier is selected.

- Time lock (3 working days):

After the voting ends, enter the time lock phase and wait for confirmation of the voting results.

- Result execution:

Succeed: If the supplier passes the vote, they will be granted permissions of entering cargo data, and become an official supplier.

Failure: If the supplier fails to pass the vote, this application will be failed.

During this process, every transaction is recorded on the chain, and smart contracts ensure that only authorized personnel can trigger specific contract functions. In addition, if sensitive data is involved in the process, it will be encrypted to ensure the integrity and immutability of the data.

4.1.2 Incentive Alignment and Accountability

In order to ensure consistency of interests between voters and the company, we will set a mechanism to incentivize and penalize voters based on the vote mechanism. Clearly distinguishing incentive and accountability is a good way to promote a fair and effective decision-making process.

(1) Credit adjustment mechanism and decision support

The voting behavior of each voter is recorded by creating a voting transaction. When voters press the "confirm vote" button, a transaction signature is triggered from the blockchain wallet to confirm the voting behavior. The transaction records include voting time, voter information, and voting details. And all the records are displayed on the blockchain platform, voters can use encryption technology and zero knowledge proof to encrypt their personal information. After the blockchain node verifies the validity of the transaction, the transaction is packaged into a block and permanently recorded on the chain, ensuring the transparency and immutability of the voting results.

We can dynamically adjust the credits that voters will receive in the next round of voting based on the voting results and the performance of the selected suppliers. According to the credit settings mentioned earlier, if the supplier supported by the voter does not meet the performance standards, the voter's weight will be reduced by 1 credits, with a minimum reduction of 5 credits; If the performance is excellent, the weight will increase by 1 credits, with a maximum increase of 5 credits. The results of the weight adjustment will also be pushed to the blockchain platform after the supplier assessment is completed (eg. quarterly assessment), and voters can query the records and reasons for the weight adjustment. The evaluation results of the onboard supplier will be written into the blockchain, and the smart contract will adjust the voting weight accordingly.

Furthermore, in order to align voters' interests with the company's requirements while enhancing everyone's sense of participation in governance, we can also link the increase or decrease in credit to employee bonuses, then providing incentives for well performing voters. Also, the performance evaluation of suppliers can also provide reference for the company to renew contracts. All relevant information will be transparently recorded on the blockchain, and automated credit adjustment and decision support will be achieved through smart contracts to ensure the transparency and immutability of the process.

4.2 NFT: Blockchain Technology in Logistics and Sales

4.2.1 Definition and Technical Architecture of NFTs

The Non-Fungible Token (NFT) framework is designed as the backbone of the food supply chain traceability system, directly addressing the challenges of fragmented data and manual record-keeping outlined in the original document. Each NFT acts as a dynamic digital twin for a product batch, encapsulating its lifecycle data through IoT automation, cryptographic verification, and smart contract logic.

(1) Technical Implementation

- Token Standard:

The system uses a hybrid ERC-1155 standard on the Hyperledger Fabric, enabling traceability at the batch level (fungible) and unit level (non-fungible). For example, a batch of 500 boxes of fruit is represented by a master NFT and 500 sub-tokens.

- Metadata storage:

Key data, such as origin, temperature logs, certifications, etc., are stored in JSON format on IPFS and linked to the NFTs via content hashes. This ensures decentralization while maintaining compatibility with legacy systems such as ERP through a REST API.

- Cryptographic Signature:

During each transmission, which in this context means throughout the process from the producer to the logistics stage and then to the retailer, the current owner signs the NFT metadata with a private key. For example, a logistics provider adding GPS data must sign and verify the update against their on-chain public key.

(2) Minting Mechanism

- Minting Trigger:

NFTs are automatically minted when completed production batches are detected by IoT devices such as RFID tags, GPS trackers, etc. A practical example would be an RFID tag embedded in a food box automatically triggering a smart contract when it is detected that it has reached the package completion checkpoint.

- Geo-fencing validation:

The smart contract cross-references the mint location with predefined GPS coordinates, such as orchard registration boundaries. If the mint location is outside the allowed area, the NFT will automatically mark it invalid.

4.2.2 Basic Logic of NFT Workflow

(1) The basic logic of the NFT workflow

In the production stage, when the product batch is completed and detected by IoT devices (such as RFID tags, GPS trackers, etc.), the smart contract automatically triggers NFT minting. Each NFT is given a unique identifier that correlates with the initial information of the product batch, such as the origin of raw materials, production time, etc. In the logistics stage, as the goods are transported, the IoT device collects data such as location, temperature, and humidity, and the logistics party needs to sign the updated metadata with a private key and transmit it to the blockchain node through a secure API. The smart contract updates the NFT metadata after multi-layer verification of the data such as geographic consistency and batch correlation; If the data is abnormal (such as a deviation from the transportation route or a temperature exceedance), the smart contract will freeze the NFT and notify the relevant parties. During the sales phase, the inspection agency uploads the quality inspection results, and the NFT status is updated after the smart contract is verified. If the quality is acceptable, the ownership of the NFT is transferred from the logistics party to the retailer. Consumers can scan the QR code to obtain the complete traceability information (production, transportation, inspection data) associated with the NFT, ensuring the authenticity and source of the product.

(2) Transaction Transfer Details

Each ownership transfer is executed by a smart contract and recorded on the blockchain and cannot be tampered with. For example, after the logistics party completes the transportation and passes the verification, the smart contract transfers the ownership of the NFT to the retailer, and the retailer officially changes the ownership after confirming the receipt; When consumers make a purchase, the transaction information is also recorded in the NFT transaction history, ensuring that the process is transparent and traceable.

4.2.3 Application in the Food Supply Chain

In this system, NFT plays an important role mainly in the logistics and sales stages, effectively improving the transparency and traceability of the supply chain and improving the efficiency and security of records. The following section will explain in detail the application of NFT in these two stages:

(1) Logistics Stage: Recording and Monitoring of Cargo Information

When goods enter the logistics stage from the production stage, NFT is created or updated. Each batch or lot of goods is represented by a unique NFT. NFTs contain metadata such as batch number, cargo source, transportation route, estimated delivery time, and any specific processing requirements. During transportation, data such as cargo location, temperature, humidity, etc. collected by IoT devices are updated in real time to the metadata of NFTs. These data are transmitted to blockchain nodes through secure APIs and written to NFTs after verification by smart contracts, so as to achieve real-time updates on the blockchain. To ensure the integrity and authenticity of the data, logistics providers also sign the updated metadata with their private keys. This allows all stakeholders to obtain the latest and most accurate information about the batch of goods.

At the same time, smart contracts perform multi-layer verification of the data in NFTs according to preset rules to ensure data consistency. Verification includes geographic consistency checks, batch correlation checks, and machine learning-driven anomaly detection *(Refer to Section 5.2 for more information)*. If any abnormal data is detected (such as cargo deviating from the scheduled route or temperature exceeding the safe range), the smart contract will automatically trigger an alarm and take appropriate measures, such as freezing the relevant NFT and notifying relevant parties to investigate.

For example, if a batch of perishable goods experiences a temperature surge during transportation, the status sensor will detect this anomaly and update the NFT metadata to reflect the potential risk of corruption. The smart contract can then trigger an alarm to notify relevant parties (such as retailers or quality control departments) to take appropriate measures, enabling better management of risks and decision-making throughout the supply chain.

(2) Sales Stages: NFT Ownership Transfer and Consumer Access

After the goods arrive at the retailer, the inspection agency will upload the quality inspection results to the blockchain, and the smart contract will verify these results and update them to the NFT's metadata. If the goods meet the quality standards, the NFT will be marked as "approved" and ready for sale. NFT ownership is transferred from the logistics provider to the retailer.

When consumers purchase products, they can scan the QR code linked to the NFT to obtain complete traceability information, including detailed data on production, transportation, and inspection. This transparency enhances consumers' trust in product quality and safety and satisfies consumers' right to know about the food processing process. At the same time, as a digital certificate, NFT can verify the authenticity and source of the product, prevent counterfeit and shoddy products from entering the market, increase consumers' trust in the source of the product, and improve transaction efficiency.

For instance, a batch of organic apples is transported from a farm to a retailer. When the apples arrive at the retailer's warehouse, the inspection agency conducts a rigorous quality inspection on the batch of apples, including indicators such as appearance, freshness, and pesticide residues. After the inspection results meet all quality standards, the inspection agency uploads these results to the blockchain, and the smart contract automatically verifies and confirms the accuracy of these data. Subsequently, the smart contract updates the status of the NFT to "approved" and officially transfers the ownership of the NFT from the logistics provider to the retailer, marking that the batch of apples is ready to enter the sales link.

When consumers purchase these organic apples in retail stores, they can easily access the NFT associated with the batch of apples by scanning the QR code on the product packaging. This QR code links to a user-friendly interface where consumers can see the complete traceability information of the apples, such as the origin of the apples, the planting method, the picking date, the environmental records during transportation, and the specific results of the quality inspection, confirming that these apples have passed all necessary tests before arriving at the retail store.

4.3 IoT Devices：Data Collection

IoT devices play a significant role in the traceability system by providing real-time data collection and transmission throughout the food supply chain. These devices include RFID tags, GPS trackers, and various sensors that monitor environmental conditions. Each type of device serves a specific purpose in ensuring the integrity and transparency of the supply chain.

4.3.1 RFID Tags

RFID tags are affixed to packaging or pallets and are used to track the location and movement of goods. They can be read by RFID readers installed at checkpoints, such as warehouses, distribution centers, and retail stores. When an RFID tag passes through a reader, it triggers an update to the blockchain, recording the location and handler ID. This ensures that the movement of goods is tracked in real-time and provides a tamper-proof record of each handling event.

4.3.2 GPS Trackers

GPS trackers are integrated into transportation vehicles to monitor the geographic location of goods during transit. These trackers continuously send location data to the blockchain node via a secure API. The smart contract verifies the data and updates the NFT metadata with the latest location information. This helps in preventing cargo diversion and ensures that goods are transported along the planned route.

4.3.3 Environmental Sensors

Environmental sensors, such as temperature and humidity sensors, are crucial for monitoring the conditions of perishable goods. These sensors are placed inside packaging or containers and continuously monitor the environment. If the temperature or humidity exceeds predefined thresholds, the sensor triggers an alert and updates the NFT metadata to reflect the potential risk of spoilage. This ensures that any deviations from optimal conditions are immediately detected and recorded.

4.3.4 Data Transmission and Verification

The data collected by IoT devices is transmitted to the blockchain node through a secure API. The smart contract then verifies the data for accuracy and integrity. Once verified, the data is added to the NFT metadata, creating a comprehensive and immutable record of the product's journey through the supply chain.

The combination of IoT devices ensures that every aspect of the product's journey is monitored and recorded, providing a complete and tamper-proof traceability record.

5 Future Directions

5.1 Dynamic DAO Governance Based on Reputation Voting Using IoT

Current voting and incentive mechanisms lack adaptability to changing supplier performance, potentially leading to inefficiencies in long-term supplier management. Based on this scenario, data collected by the IoT, such as on-time delivery rates, compliance audits, etc., can be embedded into the reputation scores stored in the chain. Dynamically adjust a supplier's voting weight in future bids based on its compliance history recorded by IoT sensors during transportation. Stakeholders with higher scores have more influence, thus incentivizing suppliers to maintain quality.

5.2 AI-Driven Legacy System Integration Middleware

Manual ERP-to-blockchain data conversion is error-prone and delays real-time traceability. Train an NLP model to auto-map legacy ERP fields to blockchain attributes. For example, for a fruit distributor, this middleware would instantly convert harvest dates from ERP records into NFT metadata. This measurement will eliminate manual mapping errors and cut integration time.

5.3 Federated ML for Privacy-Preserving Anomaly Detection

Centralized ML models require sharing sensitive logistics data, violating the General Data Protection Regulation (GDPR). Train an anomaly detection model across encrypted IoT datasets from third-party logistics providers. For example, a model predicting route deviations would learn from GPS patterns across partners without accessing raw data. Through this method, fraud detection accuracy will be improved efficiently while preserving data confidentiality.

5.4 Automated Service Level Agreement (SLA) Penalties via Oracles

Accountability in the current framework relies on manual review, which delays penalties for SLA (Service Level Agreement) violations, such as late delivery. Connect IoT GPS data to Chainlink oracles to autonomously verify delivery times. A smart contract could auto-deduct penalties from a logistics provider's escrow if a shipment arrives over two hours late. Enforces contractual compliance without human intervention, which will significantly reduce disputes.

5.5 Cross-chain Recalls via Polkadot's Cross-Consensus Messaging (XCM)

The lack of standardization in current cross-chain alerts, especially in alerting on contaminated batches of food, complicates global recalls. Using Polkadot XCM to link hyperledger and Ethereum chains effectively solves this problem. If a contaminated food lot is detected, XCM triggers an NFT freeze on both chains simultaneously. This could reduce cross-chain recall execution time from hours to minutes.

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