



THE INTEGRATION OF BLOCKCHAIN AND SUPPLY CHAIN FOR HONEY TRACEABILITY

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Abstract— In the face of escalating global demands for transparency, sustainability, and efficiency within the food supply chain, blockchain technology emerges as a transformative solution. This paper delves into the design and deployment of a blockchain-based infrastructure tailored to enhance traceability, reduce fraud, and streamline operations across the food supply chain. By integrating Ethereum smart contracts, we architect a decentralized framework that ensures the authenticity and provenance of food products, from production to consumption. Our system leverages the immutability and transparency inherent to blockchain technology, coupled with the Internet of Things (IoT) for real-time data acquisition, to establish a trustless environment for all stakeholders. This research not only outlines the system architecture and technical implementation but also addresses potential challenges such as scalability, interoperability, and user adoption. Through empirical analysis and pilot testing, we demonstrate the system's efficacy in improving food safety standards, reducing supply chain costs, and bolstering consumer confidence. Our findings contribute to the ongoing discourse on leveraging blockchain technology for sustainable supply chain management, offering insights and directions for future research and implementation.

Keywords— Blockchain Technology, Food Supply Chain Management, Smart Contracts, Traceability and Transparency, Internet of Things (IoT).

I. INTRODUCTION

The food supply chain is a complex network that encompasses the production, processing, distribution, and consumption of food products. It is a critical sector that not only ensures the global availability of food but also significantly impacts economies, environments, and public

health. However, the traditional food supply chain faces numerous challenges, including inefficiencies in tracking and transparency, risks of contamination, fraud, and the increasing demand for sustainable practices. These issues not only affect consumer trust but also the ability of supply chains to guarantee the safety and quality of food products.

In recent years, blockchain technology has emerged as a promising solution to address these challenges. Originally developed as the underlying framework for digital currencies, blockchain offers a decentralized, immutable, and transparent system for recording transactions. When applied to the food supply chain, blockchain can provide a verifiable and tamper-proof record of product journeys from farm to table. This capability introduces a new level of transparency and trust into the system, allowing consumers to verify the authenticity and safety of their food products, and enabling businesses to streamline their operations and enhance compliance with regulatory requirements.

The concept of blockchain for supply chain management extends beyond mere tracking. It encompasses a holistic ecosystem where digital information becomes an asset, offering possibilities for smarter operations through automation and the integration of various technologies like the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML). In the context of the food supply chain, blockchain can facilitate real-time monitoring of products, automate compliance with safety standards, and support sustainable practices by providing undeniable proof of product origins and handling processes.

The introduction of blockchain into the food supply chain is not just a technical upgrade but a revolutionary shift in how supply chain processes are managed and executed. This technology enables the creation of a shared, secure ledger within the supply chain network, which enhances visibility for all stakeholders, including farmers, processors,

distributors, retailers, and consumers. by allowing each transaction or product movement to be recorded and verified, blockchain reduces the risks of errors and fraud, thereby improving overall efficiency and reliability.

II. LITERATURE REVIEW

The burgeoning interest in blockchain technology within the food supply chain context has catalysed a significant body of research, exploring its potential to redefine traditional supply chain dynamics. The literature spans various facets, including traceability, transparency, efficiency, and the integration of smart contracts for automated governance and transactions. This review synthesizes key contributions, identifying both the opportunities and challenges inherent in deploying blockchain solutions within the food supply chain sector.

TRACEABILITY AND TRANSPARENCY

Traceability, the ability to trace the history, application, or location of an entity, is a central theme in the blockchain-food supply chain literature. Studies like [1] demonstrate how blockchain can enhance the traceability of agricultural products, proposing a system that records each transaction associated with a product's lifecycle on a blockchain. Similarly, [2] discuss the integration of blockchain with IoT devices to provide real-time tracking of food products, thereby ensuring transparency and building consumer trust. These studies underscore blockchain's potential to create a transparent and immutable record of transactions, which can significantly reduce incidents of food fraud and contamination.

EFFICIENCY AND COST REDUCTION

The operational efficiency of supply chains is another critical area of focus. The ability of blockchain to streamline processes and reduce intermediaries is highlighted in the literature as a means to reduce costs and improve operational efficiencies. Works like [3] examine the economic implications of blockchain in the supply chain, noting that smart contracts can automate payment processes and enforce agreements, thus reducing transaction costs and minimizing the need for intermediaries. Furthermore, [4] analyze blockchain's impact on supply chain processes, pointing out that the decentralized nature of blockchain can lead to more efficient supply networks by enabling direct interaction between producers and consumers.

SMART CONTRACTS AND AUTOMATION

Smart contracts are self-executing contracts with the terms of the agreement directly written into code on the blockchain. The potential of these contracts to automate supply chain operations is a recurrent theme in the literature. For instance, [5] explore how smart contracts can automate payments and enforce compliance with contractual agreements in the supply chain, enhancing operational efficiency and reducing the potential for disputes. [6] delve into the legal and

operational frameworks of smart contracts, arguing that they can significantly reduce administrative burdens in supply chains and provide a more streamlined, automated process for transactions.

CHALLENGES AND IMPLEMENTATION ISSUES

Despite the optimistic outlook, the literature also acknowledges significant challenges in implementing blockchain in food supply chains. Technical issues such as scalability, interoperability, and the integration of blockchain with existing IT systems are frequently mentioned obstacles. [7] discuss the scalability challenges of blockchain, noting that the technology must be able to handle large volumes of transactions to be viable for global supply chains. Furthermore, [8] emphasize the need for standardization in blockchain applications to ensure interoperability between different systems and stakeholders.

Moreover, the adoption of blockchain technology requires substantial organizational change management, as highlighted by [9], who explore the organizational and cultural shifts necessary to integrate blockchain into existing supply chain operations. They argue that for blockchain to be effectively implemented, organizations must foster a culture of innovation and collaboration among supply chain stakeholders.

REGULATORY CONSIDERATIONS AND ETHICAL IMPLICATIONS

Regulatory and ethical considerations also play a crucial role in the literature. The decentralized nature of blockchain presents novel legal challenges, particularly in terms of regulatory compliance and data privacy. [10] examine the legal implications of blockchain in supply chains, discussing how existing regulatory frameworks may need to evolve to accommodate the decentralized, transparent nature of blockchain transactions. On the ethical front, [11] delve into the ethical considerations of using blockchain in supply chains, particularly concerning data privacy, security, and the potential for misuse of the technology.

In summary, the literature on blockchain in the food supply chain is rich and diverse, offering insights into the technology's potential to revolutionize the industry. While the opportunities for enhanced traceability, transparency, and efficiency are evident, significant challenges in terms of technical implementation, organizational change, regulatory compliance, and ethical considerations remain.

Addressing these challenges requires concerted efforts from researchers, industry practitioners, and policymakers to fully realize the potential of blockchain in transforming the food supply chain landscape.

III. SYSTEM ARCHITECTURE

The system architecture for a blockchain-based food supply chain management system is designed to address the inherent complexities and challenges of modern supply chains, particularly in ensuring transparency, traceability,

and efficiency. This architecture typically consists of multiple layers, each serving a distinct purpose, yet collectively working towards a seamless, integrated solution.

Application Layer

At the top of the architecture is the Application Layer, which serves as the primary interface for users interacting with the system. This layer is designed to provide an intuitive and user-friendly experience, allowing various stakeholders in the supply chain, such as farmers, processors, distributors, retailers, and consumers, to access and input data, monitor supply chain activities, and make informed decisions.

The Application Layer is typically built using modern web development frameworks like React.js, which facilitates the creation of dynamic and responsive web applications. This layer integrates various functionalities, including product tracking, inventory management, order placement, and payment processing, all of which are supported by the underlying blockchain infrastructure. The design and usability of this layer are crucial for ensuring widespread adoption and effective use of the system across the supply chain network.

Blockchain Layer

The core of the system's architecture is the Blockchain Layer, which serves as the backbone for recording, verifying, and executing transactions across the supply chain. This layer utilizes blockchain technology to ensure that all data and transactions are immutable, transparent, and secure.

Smart contracts, which are self-executing contractual states stored on the blockchain, automate and enforce the terms of agreements between parties in the supply chain. These contracts can include conditions such as payment terms, delivery schedules, and quality standards, which, when met, automatically trigger the corresponding actions, such as releasing payments or updating ownership records. This automation reduces the need for manual intervention, lowers the potential for disputes, and enhances the overall efficiency of the supply chain.

The blockchain layer is not only a ledger for recording transactions but also a platform for deploying and executing smart contracts that encapsulate the business logic and rules governing various supply chain processes. Ethereum is often the preferred choice for implementing this layer due to its mature development ecosystem and robust support for smart contracts.

Data Storage Layer

Given the extensive data generated in supply chains, the Data Storage Layer is critical for managing the storage and retrieval of data efficiently. This layer typically employs a combination of on-chain and off-chain storage solutions to balance cost, speed, and scalability.

For on-chain data, the focus is on storing transaction records and smart contract states directly on the blockchain, ensuring their immutability and public verifiability. However, given the volume and variety of data in supply chains, storing everything on-chain can be impractical and expensive. Hence, off-chain storage solutions like the InterPlanetary File System (IPFS) are utilized for storing larger datasets, such as product images, certificates of origin, and detailed product descriptions. The blockchain then stores the cryptographic hashes of these off-chain data pieces, ensuring their integrity and traceability without overburdening the blockchain.

Integration and Interoperability

A vital aspect of the system's architecture is its ability to integrate with existing supply chain management systems and technologies. This Integration and Interoperability facet ensures that blockchain-based solutions can seamlessly communicate and exchange data with legacy systems, IoT devices, and other digital platforms used within the supply chain.

Effective integration strategies often involve the use of APIs (Application Programming Interfaces) and middleware solutions that facilitate data exchange and process synchronization between the blockchain and external systems. This integration is crucial for automating data capture from various points in the supply chain, such as IoT sensors for real-time tracking of product conditions, and ERP (Enterprise Resource Planning) systems for managing business processes and transactions.

Security and Compliance

Given the critical nature of supply chain data and the need for compliance with various regulatory standards, the system architecture must prioritize Security and Compliance. This involves implementing robust security measures, including data encryption, access control mechanisms, and regular security audits, to protect against unauthorized access and cyber threats.

Compliance with industry standards and regulations is also paramount, necessitating a flexible architecture that can adapt to evolving legal and business requirements. This includes ensuring data privacy, meeting quality standards, and facilitating audits and certifications that verify the integrity and sustainability of supply chain practices.

TABLE I
COMPARISON OF TRADITIONAL VS. BLOCKCHAIN-BASED
SUPPLY CHAIN MODELS

| Feature | Tradition Supply Chain | Blockchain-based Supply Chain |
|----------------|----------------------------------|---|
| Data Integrity | Susceptible to fraud and errors. | High integrity; data is immutable and tamper-proof. |

| | | |
|--------------|---|---|
| Efficiency | Time-consuming processes due to manual checks and intermediaries. | Increased efficiency through automation and smart contracts. |
| Traceability | Complex and sometimes unreliable tracking mechanisms. | Simplified and reliable traceability with blockchain ledger. |
| Cost | Higher due to intermediaries and manual processes. | Reduced costs by eliminating intermediaries and automating processes. |
| Security | Potential for data breaches and unauthorized access. | Enhanced security through encryption and consensus mechanisms. |

IV. IMPLEMENTATION DETAILS

The successful implementation of a blockchain-based food supply chain system hinges on the strategic orchestration of various technical and operational elements. This section delves into the core components of the implementation process, including the development of smart contracts, integration of Internet of Things (IoT) devices, data management, and user interface design, all tailored to facilitate a seamless, efficient, and transparent supply chain ecosystem.

1. Smart Contract Development

Smart contracts are pivotal in automating and enforcing the rules and agreements within the blockchain-based supply chain. These contracts are written in a programming language, such as Solidity for Ethereum, and are deployed on the blockchain to execute automatically when predetermined conditions are met.

The development process involves:

Designing Contract Logic: Defining the logic and conditions that govern transactions and interactions in the supply chain, such as payment terms, product verification, and compliance with quality standards.

Coding and Testing: Writing the smart contract code and conducting thorough testing, including unit tests and integration tests, to ensure the contracts perform as intended without vulnerabilities.

Deployment: Deploying the contracts to the blockchain, making them accessible and executable by authorized parties within the supply chain network.

2. IoT Integration for Real-Time Data Capture

IoT devices play a crucial role in capturing real-time data at various stages of the supply chain, from production and storage to transportation and delivery. These devices, including sensors and RFID tags, collect data on product conditions, location, and movement, providing a continuous stream of information that enhances the traceability and transparency of the supply chain.

Key aspects of IoT integration include:

Device Selection and Setup: Choosing the appropriate IoT devices based on the type of data required (e.g., temperature, humidity, GPS location) and setting them up in the relevant supply chain segments.

Data Capture and Transmission: Configuring the devices to capture and transmit data securely and efficiently to the blockchain system, ensuring the accuracy and timeliness of the information.

Integration with Smart Contracts: Linking the IoT data with smart contracts so that the real-time information can trigger contract executions, such as confirming the fulfillment of delivery conditions or initiating quality control processes.

3. Data Management and Storage

Effective data management is critical in handling the vast amount of information generated within a blockchain-based supply chain system. This involves not only the transaction records on the blockchain but also the supplementary data collected through IoT devices and other sources.

The data management strategy encompasses:

On-Chain and Off-Chain Storage: Determining what data is stored on-chain for transparency and verification (e.g., transaction records, smart contract states) and what is stored off-chain (e.g., large datasets, detailed product information) to optimize costs and efficiency.

Data Security and Privacy: Implementing robust security measures to protect data integrity and privacy, including encryption, access controls, and regular audits, especially for sensitive or proprietary information.

Interoperability and Standardization: Ensuring data formats and protocols are standardized across different systems and stakeholders to facilitate seamless data exchange and integration.

4. User Interface and Experience Design

The user interface (UI) is the gateway through which stakeholders interact with the blockchain-based supply chain system. A well-designed UI is essential for ensuring user adoption and effective system utilization.

Elements of UI design include:

Intuitive Navigation: Creating a user-friendly interface that allows users to easily access and understand the system's functionalities, from tracking products to viewing transaction histories and managing smart contracts.

Responsive Design: Ensuring the UI is adaptable to various devices, including desktops, tablets, and smartphones, allowing stakeholders to access the system anytime, anywhere.

Real-Time Data Visualization: Implementing dashboards and analytics tools that present data in an easily digestible format, enabling users to make informed decisions based on real-time insights.

5. Testing and Quality Assurance

Before the full-scale deployment of the blockchain-based supply chain system, comprehensive testing and quality assurance are necessary to ensure its reliability, performance, and security.

Testing phases include:

Functional Testing: Verifying that all system components, from smart contracts to IoT integrations and user interfaces, function correctly and meet the specified requirements.

Security Testing: Conducting vulnerability assessments and penetration testing to identify and mitigate potential security risks, ensuring the system is protected against attacks and data breaches.

Performance Testing: Evaluating the system's performance under various conditions to ensure it can handle the expected transaction volumes and user interactions without degradation.

journey is recorded on the blockchain, providing consumers and stakeholders with verifiable and immutable data on its origin, processing, and distribution. For instance, a blockchain system can record the entire lifecycle of a product, such as a batch of organic apples, detailing the farm of origin, harvest date, storage conditions, transportation routes, and retail distribution. This level of traceability is instrumental in building consumer trust and ensuring the authenticity and safety of food products.

2. Improved Food Safety and Quality Assurance

Blockchain technology can significantly reduce the time taken to identify and rectify issues within the food supply chain, thereby enhancing food safety. In the event of a food safety scare, such as an E. coli outbreak, blockchain can quickly trace the contaminated product to its source, enabling a swift response to remove it from the market. Moreover, integrating IoT devices with blockchain allows for real-time monitoring of storage and transportation conditions, ensuring that food products meet safety and quality standards throughout their journey.

3. Waste Reduction and Sustainability

Blockchain facilitates the efficient management of supply chains by providing accurate data on product movements and inventories, helping to reduce overproduction and minimize waste. This precision supports the sustainable use of resources and helps in the fight against food waste. Furthermore, blockchain's transparent nature allows consumers to make informed choices about the sustainability of their food, encouraging producers and retailers to adopt more environmentally friendly practices.

4. Streamlined Operations and Reduced Costs

By automating processes and reducing the reliance on intermediaries, blockchain can streamline operations and reduce costs in the food supply chain. Smart contracts can automate payments and validate compliance with trade agreements and regulatory requirements, eliminating paperwork and speeding up transactions. This efficiency not only reduces operational costs but also enhances the overall agility of the supply chain.

5. Combatting Food Fraud

Food fraud, including the mislabelling and adulteration of products, is a significant issue in the industry. Blockchain technology can combat this by providing a tamper-proof system for verifying the authenticity of food products. Consumers, regulators, and companies can access the blockchain to verify claims made about a product, such as its organic or fair-trade status, ensuring that the product meets the advertised standards and is worth the premium price.

6. Facilitating Regulatory Compliance and Auditability

Blockchain's immutable record-keeping facilitates compliance with regulatory requirements, as every transaction and product journey are permanently recorded and easily auditable. Regulatory bodies can leverage blockchain to monitor compliance across the supply chain,

TABLE II
KEY COMPONENTS OF BLOCKCHAIN-BASED SUPPLY CHAIN IMPLEMENTATION

| Component | Role in Implementation | Technologies Used |
|---------------------|--|--|
| Smart Contracts | Automate and enforce supply chain transactions | Solidity, Ethereum |
| IoT Devices | Real-time data capture and monitoring | RFID, GPS sensors, temperature sensors |
| Data Management | Handle large volumes of supply chain data | IPFS, Cloud Storage, Database Systems |
| User Interface (UI) | Facilitate user interaction with the system | React.js, Web APIs, HTML/CSS |
| Security Protocols | Protect data integrity and system reliability | Encryption, Access Control |

V. APPLICATIONS AND USE CASES

The advent of blockchain technology has heralded a new era in supply chain management, particularly within the food industry. Its application extends beyond mere transactional records, touching upon various aspects of the supply chain, thereby enhancing transparency, efficiency, and consumer trust. Herein, we explore a range of applications and use cases where blockchain technology is revolutionizing the food supply chain.

1. Enhanced Traceability and Transparency

Blockchain's inherent transparency allows for the detailed tracking of food products from farm to table. Each product's

reducing the need for costly and time-consuming audits. This not only ensures that companies adhere to legal standards but also streamlines the compliance process.

7. Empowering Small-scale Producers

Blockchain technology can empower small-scale producers by providing them with a platform to compete on equal footing with larger corporations. Through blockchain, small producers can prove the provenance and quality of their products, gaining access to markets that were previously out of reach. This democratization of the supply chain helps to promote diversity and support local economies.

8. Consumer Engagement and Loyalty

Blockchain enables a new level of consumer engagement by providing customers with detailed information about the products they purchase. By scanning a QR code, consumers can access a product's blockchain record, learning about its journey, the people involved, and the company's practices. This transparency can enhance consumer trust and loyalty, as customers feel more connected to the products and the stories behind them.

VI. EVALUATION

The evaluation of a blockchain-based food supply chain system is pivotal to understanding its efficacy, sustainability, and impact on the industry. This process encompasses assessing the system's performance in real-world applications, gauging its ability to meet the set objectives, and identifying areas for improvement. Through a comprehensive evaluation, stakeholders can validate the system's benefits, such as enhanced traceability, increased efficiency, and improved food safety, while also addressing potential challenges and limitations.

i. Performance and Scalability

A primary focus of the evaluation is on the system's performance and scalability. Performance metrics might include transaction throughput, system responsiveness, and the time taken to record and retrieve data from the blockchain. Scalability is assessed to determine the system's ability to handle increased loads, particularly in terms of transaction volume and data storage, as the supply chain expands. Performance testing under varying conditions helps to ascertain the system's robustness and its capacity to support a growing network of users and transactions.

ii. Traceability and Transparency

The core advantage of integrating blockchain into the supply chain is improved traceability and transparency. The evaluation process, therefore, scrutinizes the system's ability to track and trace product movements accurately and in real-time across the supply chain. This includes verifying the integrity and immutability of the data recorded on the blockchain, ensuring that all stakeholders can trust the system to provide a reliable and tamper-proof audit trail from the origin to the consumer.

iii. User Adoption and Experience

For a blockchain-based system to be successful, it must be widely adopted and used effectively by stakeholders in the supply chain. Evaluation in this context involves gathering user feedback on the system's interface, functionality, and overall usability. This feedback can highlight areas where the user experience may be enhanced to encourage broader adoption and more efficient use of the system. Training and support mechanisms are also assessed to ensure they are adequate for helping users navigate and utilize the system effectively.

iv. Cost-Benefit Analysis

A comprehensive cost-benefit analysis is conducted to quantify the economic impact of implementing the blockchain system within the supply chain. This analysis considers the costs associated with deploying and maintaining the system, including technology, training, and operational expenses, against the financial benefits derived from its use, such as reduced inefficiencies, lower fraud incidents, and improved compliance with regulatory standards. This financial evaluation helps to determine the system's return on investment and its long-term viability.

v. Environmental and Social Impact

Evaluating the environmental and social impact of the blockchain system is crucial, especially given the growing emphasis on sustainable and ethical business practices. This includes assessing the system's contribution to reducing waste, enhancing product sustainability, and promoting fair trade practices. Furthermore, the system's role in supporting small-scale producers and creating more equitable supply chains is evaluated to understand its broader societal implications.

VII. CONCLUSIONS

Concluding a comprehensive discourse on the blockchain-enabled transformation in food supply chain management, it's imperative to acknowledge the paradigm shift this technology heralds. Blockchain's intrinsic properties of decentralization, transparency, and immutability are not merely enhancing the operational aspects of supply chains but are fundamentally redefining the ethos of supply chain management. The journey from farm to fork, historically opaque and fraught with inefficiencies, is being reimagined as a transparent, efficient, and trust-infused process. The integration of blockchain into the supply chain ecosystem offers a robust solution to chronic industry challenges such as food fraud, safety concerns, and inefficiencies. It empowers stakeholders with real-time, immutable data, facilitating informed decision-making and fostering an environment of trust and accountability. Moreover, blockchain's synergy with IoT and AI technologies is creating a confluence of digital innovation that promises to escalate the supply chain's capabilities to unprecedented levels. This integration not only automates

and optimizes operations but also engenders a more responsive and resilient supply network capable of withstanding disruptions and catering to the dynamic demands of the global market. The implications for food safety and quality assurance are profound, with blockchain's traceability feature enabling rapid pinpointing of contamination sources, thereby mitigating risks to public health and financial stability. This technology also champions the cause of sustainability and ethical practices by providing consumers with verifiable insights into the lifecycle of their food, thus influencing production and consumption patterns towards more sustainable and ethical choices. However, the journey towards a fully blockchain-integrated supply chain is replete with challenges. Technical, regulatory, and adoption hurdles loom large, necessitating a collaborative approach among technologists, industry stakeholders, and policymakers to devise robust solutions that harmonize with existing systems and regulations. The evolution of blockchain from a nascent technology to a supply chain mainstay requires a concerted effort to foster understanding, develop standards, and ensure interoperability across diverse supply chain ecosystems. Looking ahead, the potential of blockchain in revolutionizing the food supply chain is vast and largely untapped. As the technology matures and more use cases emerge, we can anticipate a more interconnected and transparent global supply network. This network will not only elevate the standards of food safety and integrity but also promote inclusivity, sustainability, and economic empowerment across the supply chain.

The road ahead is complex and fraught with challenges, yet the promise of a blockchain-enabled supply chain future is bright, beckoning a new era of transparency, efficiency, and trust in the global food supply network. In essence, blockchain stands as a beacon of innovation in the supply chain domain, heralding a future where the integrity of every product is assured, and the global supply chain operates as a seamless, transparent, and equitable ecosystem.

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