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# Development of a Blockchain Technology Framework for Agri-food Supply Chain Management

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***Abstract***

*Supply chain management involves effectively managing the movement of goods and services all the way from their origin as raw materials to their delivery to the final consumer. It involves all the steps involved in transforming, transporting, and delivering products to meet customer demand. In agri-food supply chain management, producers, distributors, and consumers are demanding greater transparency in the food sector due to a rise in agricultural mislabeling and negligent handling of non-perishable items. Current research studies on traceability solutions sometimes do not offer dependable farm-to-consumer histories of products due to information spread among several divisions and the tendency to store incorrect data. This research delves into a novel blockchain-based framework specifically designed to improve traceability within agri-food supply chains. The proposed model offers a multi-faceted approach, incorporating several innovative features such as four-tiered architecture. This structured design likely organizes the framework into distinct layers, each handling specific functionalities within the system. Parallel side chains: these could act as secondary ledgers that manage high-volume transactions or store non-critical data, potentially improving scalability and transaction processing speed. Zero-knowledge proofs: This integration allows participants to verify ownership or compliance with regulations without revealing sensitive underlying data, enhancing privacy and trust within the network. InterPlanetary File System: By leveraging this system, the framework can efficiently store large data files. The study adopts a systematic literature review approach to gather insights from both academic and practitioner literature, comprehensively reviewed existing academic literature, industry reports, and white papers to understand the current state of knowledge on blockchain technology in agri-food supply chain management. Object-oriented analysis and design (OOAD) approach was employed for the analysis, Microsoft Visio was used as the platform for the design of the high-level model of the proposed system, and the unified modeling language was used for system modeling. The result contributes to the existing knowledge by offering a robust and scalable architecture that addresses critical challenges in the agri-food sector.*

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**Keywords:** Blockchain, agri-food supply chain, zero-knowledge proofs, InterPlanetary File System (IPFS), framework

## INTRODUCTION

Modern consumers demand transparency and trust in the origin and quality of their food. However, traditional agri-food supply chains are often plagued by information asymmetry, limited visibility, and vulnerability to fraud. Blockchain technology emerges as a promising solution due to its inherent immutability, security, and distributed ledger capabilities [1]. Blockchain technology is built on the concept of a distributed, replicated, and

 

immutable digital ledger that allows parties to conduct trustful and transparent transactions without the need for a central authority or intermediary. So far, its most widespread application has been in payment system applications, such as Bitcoin. This innovative technology is predicted to add considerable commercial value to a variety of industries, including supply chain management (SCM), where it can improve visibility, responsibility, and trust in interorganizational business collaboration [2]. Some of the challenges identified in agri-food supply chain management are information opacity – lack of transparency in data regarding food origin, processing methods, and storage conditions; traceability issues – difficulty in tracking food products throughout the supply chain from farm to fork, hindering incident response and contamination control; fraudulent activities – potential for counterfeiting, product substitution, and manipulation of documentation chains [3–5]. This paper proposes a novel blockchain-based framework specifically designed for the agri-food supply chain, incorporating innovative features to address existing limitations.

## RELATED WORK

Chu and Pham [6] reported that blockchain technology successfully enhances supply chain efficiency by assuring traceability, transparency, and efficiency from farmer to customer. The study reviews the research on vertical coordination in supply chains and its mechanisms and proposes a paradigm using blockchain technology to address coordination challenges. Feng et al. [7] review blockchain technology, identify solutions for food traceability, highlight benefits and challenges, and propose an architecture design framework and suitability assessment for researchers and practitioners. The study helps improve food traceability by designing and implementing blockchain-based traceability solutions. The study offers essential information for researchers and practitioners on blockchain-based food traceability management, positively impacting food sustainability. Ramkumar et al. [8] reported that the current trace and authenticity solutions for agri-food distribution networks are built on centralized architectures, which can lead to serious problems like data security, manipulation, and vulnerabilities at standard points. The implementation of decentralized trust-free networks is achieved using blockchain technology, which serve as the foundation for cryptocurrencies. The digitalization incorporates aspects such as fault tolerance, data integrity, visibility, and comprehensive tracing of recorded transactional data. It also includes unified digital information of property resources and independent transactions implementations. The study presents an Agri-Block IoT framework, a fully decentralized blockchain-powered platform designed to manage a worldwide agri-food distribution network. It enables seamless integration of IoT technologies that generate and utilize digital data throughout the distribution process. Patel et al. [9] reported that more than 15% of global agri-food trade consists of livestock goods. The rising global demand for food has heightened the vulnerability of food safety. Enhancements in the quality of food, the transit of cold chain, and preservation methods are necessary to ensure the safety of cattle products. However, despite the food safety and regulation authorities requiring comprehensive food traceability from the origin to the consumer, this requirement is often disregarded in traditional supply chains through manipulation of transit papers and bill invoices.

Chan et al. [10] introduce a methodology for implementing a traceable and transparent SCM system in the agri-food sector in Malaysia, utilizing blockchain technology. Many scholars argue that the present SCM system has various vulnerabilities, particularly when multiple enterprise resource planning (ERP) systems are used to centralize SCM. Therefore, there is a restriction on the extent to which data can be openly accessed and tracked. The study proposed that the utilization of blockchain technology can potentially mitigate the constraint by enhancing transparency and traceability in supply chain management. This is due to the decentralized nature of blockchain technology. The study focuses on the utilization of "pepper" as a domain within the agricultural and food industry. The analysis suggests that permissioned blockchain is more suitable than permissionless blockchain. Dayana and Kalpana [11] presented an enhanced system for food cultivation traceability which utilizes blockchain technology to ensure safety, agreement, distributed ledger, immediate payment, and decentralization. This system focuses on agri-crops and farmers, aiming to minimize costs in the food processing system and establish trust. Smart contracts are crucial in the agriculture insurance industry. Agricultural

 

insurance utilizing blockchain technology involves recording significant weather events and corresponding payouts on a smart contract. This contract is linked to mobile wallets and receives real-time weather updates from field sensors and nearby weather stations. This system ensures that prompt payouts are made in the event of natural disasters like floods or droughts.

Raza et al. [12] reported that blockchain, smart contracts, and the internet of things (IoT) are crucial technologies for the re-engineering of supply chains in the era of Industry 4.0. Disruptive technologies can significantly contribute to automating corporate procedures, ensuring real-time monitoring of items, and securing transactions in the agricultural food supply chain. By utilizing blockchain technology, smart contracts, and IoT, it is possible to continuously monitor the condition of a product and its impact on the environment at every stage of the supply chain. The study rigorously assessed the significance of these technologies by analyzing different operations within the agriculture supply chain, employing the methodology of business process modeling (BPM). The findings of the BPM, which were based on blockchain and smart contracts, were subsequently integrated into several levels of the Reference Architecture for Modeling Industry 4.0 (RAMI 4.0). Patel et al. [9] presented a food traceability framework driven by blockchain technology depicted as a three-layered process. The physical flow layer represents the actual food supply chain, via which food products are transported from the producer to the customer. The second flow layer involves the implementation of a digital record system that enables simultaneous data recording of the physical flow layer. This is achieved by the utilization of diverse sensors, radiofrequency identification (RFID), quick response (QR) code, and other digital technologies. The third tier of the flow consists of a digital blockchain infrastructure network that utilizes a smart contract to verify the data recorded in the second layer. This verification process involves all participating entities and is achieved using a consensus mechanism.

Bhat et al. [13] reported that frequent occurrences of fraudulent activities indicate a lack of transparency in agricultural supply chains, which leads to concerns about financial losses, erosion of customer trust, and a decrease in business brand value. To establish a trading environment that is both efficient and dependable, it is necessary to make numerous basic alterations to the current supply chain architecture. There is widespread agreement that blockchain technology has the potential to enhance transparency in agriculture-food supply chains. Consumers currently have an expectation for food production systems that are both safe and sustainable, as well as fair. To fulfil these expectations, firms are employing blockchains and the internet of things. To improve the efficiency of agri-food supply chains, new approaches have emerged that integrate blockchains with advanced technologies of Industry 5.0, such as blockchain technology, big data, IoT, RFID, near field communication (NFC), and others.

## METHODOLOGY

### Framework Analysis

The study used system analysis and design methodology and analyzed/designed the model of the new architecture. The study adopts a systematic literature review approach to gather insights from both academic and practitioner literature, comprehensively reviewed existing academic literature, industry reports, and white papers to understand the current state of knowledge on blockchain technology in agri-food SCM.

### Design Tool

Microsoft Visio was used for drawing the architectural model of the proposed framework and the data flow diagram (DFD).

## ANALYSIS OF EXISTING BLOCKCHAIN-BASED AGRI-FOOD SUPPLY CHAIN

While significant advancements have been made in applying blockchain technology to agri-food supply chain management, some limitations persist in existing research as shown in Figure 1.

 

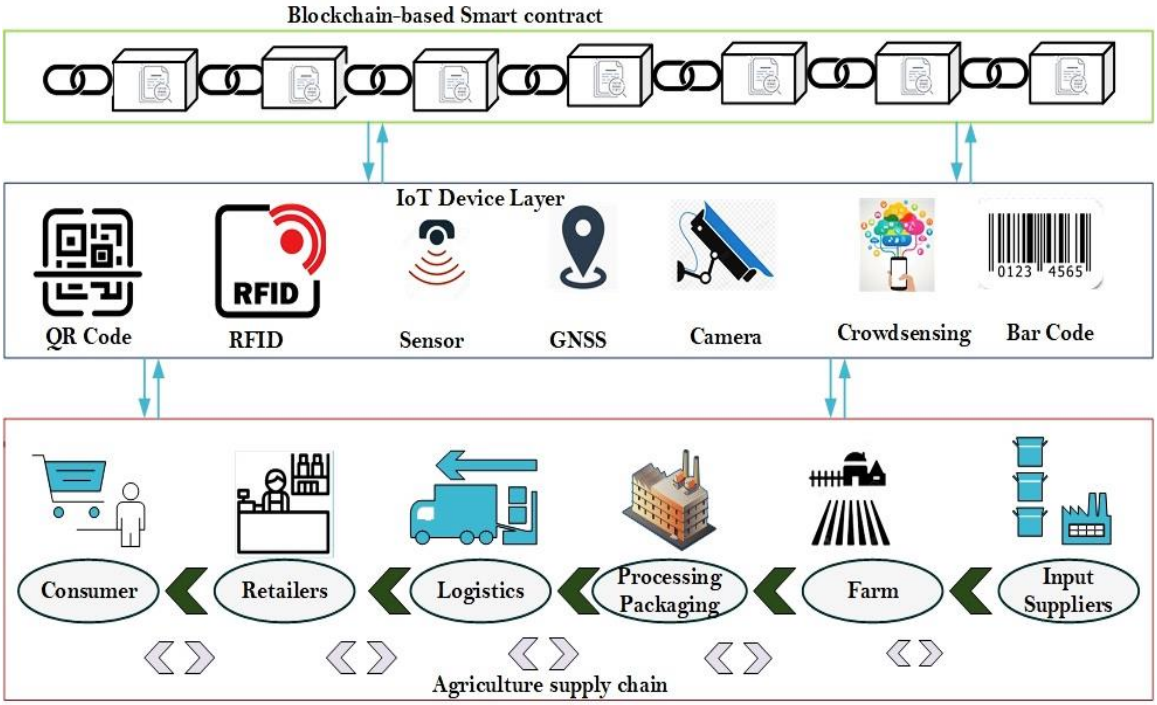


**Figure 1.** Blockchain-based smart agri-supply chain [13].

**Limited Focus on Specific Privacy Concerns**

- Current research often focuses on generic privacy-preserving techniques without addressing the specific privacy needs of different stakeholders in the agri-food supply chain.
- Farmers might be concerned about revealing farm locations or proprietary production methods, while processors might want to protect trade secrets related to their processing techniques.
- Existing solutions may not offer granular control over data visibility, potentially hindering wider adoption by participants who require stricter privacy safeguards for specific types of information.
- Existing blockchain platforms for agri-food SCM often operate as siloed systems, hindering interoperability and data exchange between different platforms.
- Integrating these platforms with existing enterprise resource planning (ERP) systems used by participants can be complex and require significant development effort.
- Current research primarily focuses on addressing challenges within the supply chain itself, with less emphasis on user-friendly interfaces and functionalities for consumers.
- Building trust with consumers requires not only a robust and transparent supply chain but also user-centric interfaces that allow them to easily access product information and track its journey.

## HIGH-LEVEL MODEL OF THE PROPOSED BLOCK-CHAIN FRAMEWORK FOR AGRI-FOOD SUPPLY CHAIN MANAGEMENT

This proposed high-level architectural model provides a conceptual overview of the core components and their interactions within a blockchain-based agri-food SCM system are as depicted in Figures 2 and 3.

## RESULTS AND DISCUSSION

### Framework Functionality

The framework operates through the following stages:

1. *Data Entry:* Participants submit data related to their role in the supply chain, using zero-knowledge proofs (ZKPs) for sensitive information verification.
2. *Data Validation and Consensus:* Authorized nodes validate data integrity and reach consensus using a suitable Byzantine fault tolerance (BFT) consensus mechanism.

 

3. *Data Storage:* Critical data is stored on the blockchain for immutability and secure access, while large files are stored on InterPlanetary File System (IPFS) for efficient retrieval.
4. *Traceability and Visibility:* Consumers and stakeholders can access product history and track its journey through the supply chain, enhancing transparency and trust.

**Contribution to Knowledge**

This framework offers several significant contributions: The proposed blockchain-based framework for agri-food SCM aims to address the limitations identified in existing research by incorporating innovative features:

***Enhanced Privacy with Zero-Knowledge Proofs***

Unlike existing solutions with generic privacy measures, our framework leverages ZKPs to cater to the specific privacy needs of diverse stakeholders. Participants can demonstrate compliance with regulations or ownership of data (e.g., farm location) without revealing the underlying details. This granular control over data visibility fosters trust and encourages wider participation, particularly from privacy-conscious farmers and processors.

***Scalable Storage with InterPlanetary File System***

- Our framework recognizes the limitations of blockchain storage for large data files. By integrating IPFS, we ensure efficient and scalable storage of non-critical data like sensor readings or high-resolution product images.
- This approach optimizes blockchain storage for essential transactional data while maintaining accessibility to larger files through IPFS, addressing scalability concerns and reducing storage costs associated with maintaining the entire data set on-chain.

***User-Centric Design for Consumer Trust Building***

- The framework goes beyond internal supply chain transparency. We consider user-centric design principles to develop an intuitive interface for consumers.
- Consumers can easily access product information, track its journey through the supply chain using ZKP-verified data points, and verify product authenticity, fostering trust and brand loyalty.

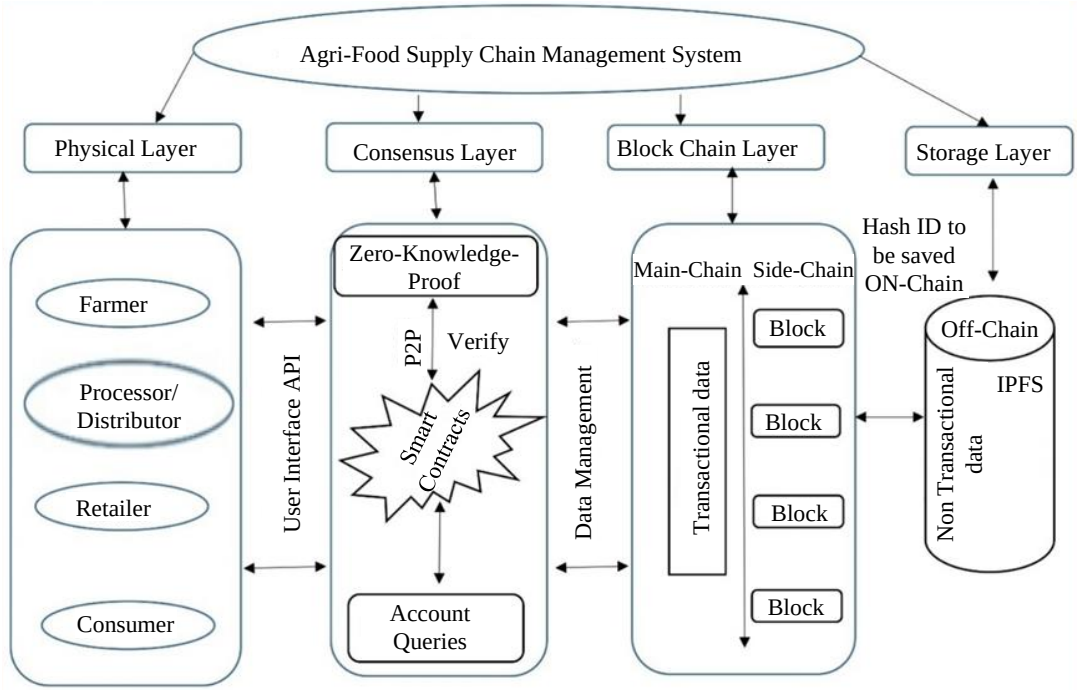


**Figure 2.** High-level architectural model of the proposed agri-food blockchain-based framework.

 

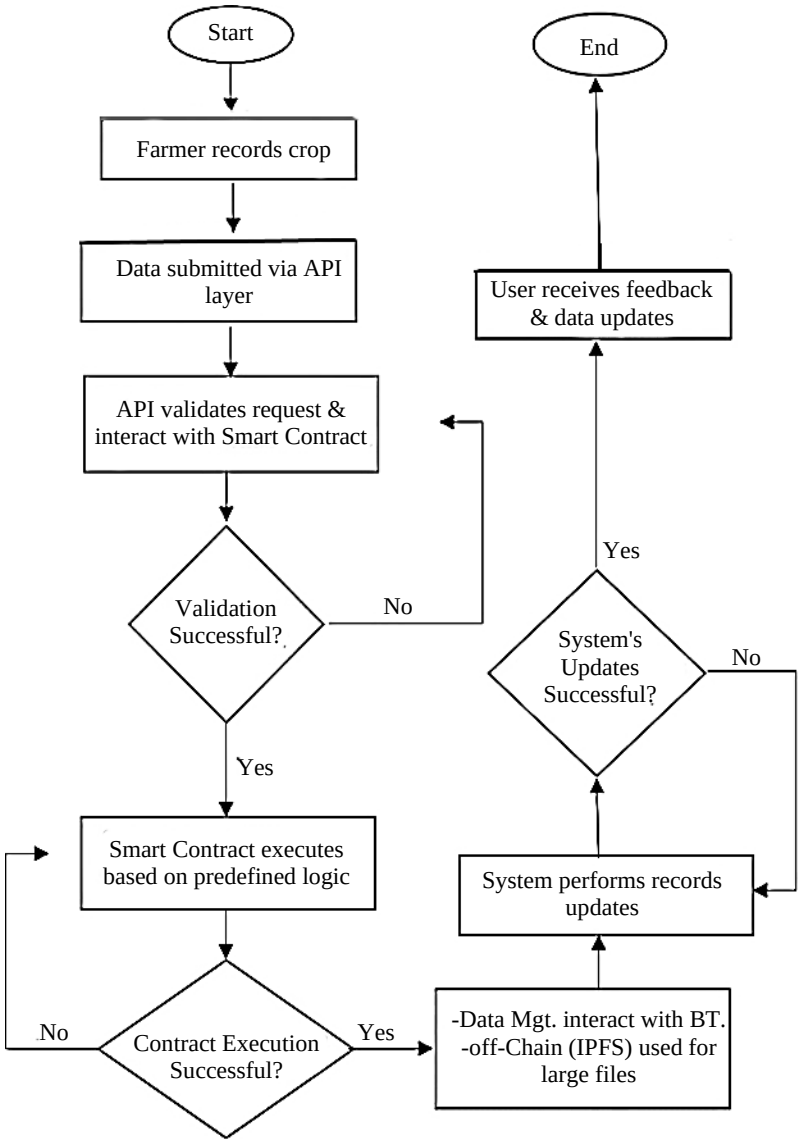


**Figure 3.** The program flowchart of the proposed framework.

## CONCLUSION, RECOMMENDATION, AND FUTURE WORK

The proposed blockchain-based framework, incorporating ZKPs and IPFS, presents a compelling solution for addressing critical challenges in the agri-food supply chain. It facilitates transparency, enhances traceability, and promotes trust among stakeholders, ultimately benefiting consumers, producers, and regulators alike. Additional investigation could delve into incorporating IoT devices for the real-time gathering of data and examining incentive structures to promote broader adoption within the agricultural and food industry.

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