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Blockchain-Based Smart Agri-Food Supply Chain Management System with User-Centric Design for Enhanced Consumer Trust

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Abstract

Existing blockchain-based solutions for agri-food supply chains primarily focus on internal traceability and efficiency while neglecting consumer-facing functionalities. Building consumer trust requires not only a secure and transparent supply chain but also user-friendly interfaces for easy access to product information and journey tracking. This study addresses this gap by implementing a blockchain-based agri-food supply chain system with a user-centric design. Beyond internal transparency, the system features an intuitive consumer interface that allows users to easily access product information. Consumers can readily access detailed information about a product, such as origin, production methods, and certifications. Track product journey to ensure data privacy while allowing consumers to verify key stages of the product's journey through the supply chain. The system facilitates product authentication and fosters trust and brand loyalty among consumers. A literature review was conducted to assess the current state of blockchain technology in agri-food supply chain management. This study adopted an exploratory/experimental research design. Relevant sources such as Scopus, Web of Science, Google Scholar, and ScienceDirect were searched, key findings were synthesized, and gaps in the existing literature were identified. Ganache (Ethereum) served as the blockchain platform, Solidity programming language was used to develop a smart contract, and Remix IDE was used for testing and deployment of the smart contract. ReactJS, Node.js, and VSCode were used for user interface development. The Indian agriculture crop production data and Ondo State Cocoa and Cassava production data, sourced from Kaggle, were used. The proposed system demonstrates flexibility and improvement in managing agri-food supply chains and enhancing transparency, traceability, and trust across all stakeholders. Performance evaluation shows 0–500 transactions processed in 0–4 s, 0–10% latency, 0–5% block time creation, and 0–30% energy consumption. To facilitate widespread adoption, it is recommended to encourage the adoption of blockchain technology within the agri-food supply chain to enhance transparency, traceability, and efficiency.

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Keywords: Agri-food supply chain, blockchain, system, transparency, user-centric

INTRODUCTION

The increasing consumer demand for transparency and assurance regarding the origin and quality of food has prompted significant shifts in the agri-food supply chain. Traditional supply chains often struggle to meet these expectations because of challenges such as information asymmetry, limited traceability, and susceptibility to fraud [1–3]. These issues undermine consumer trust and pose risks to food safety and quality. As consumers become more aware of these challenges, they seek greater transparency in food sources, necessitating innovative solutions that can effectively address these concerns [4, 5]. Blockchain technology has emerged as a transformative solution for enhancing transparency and traceability in agri-food supply chains. Its decentralized and immutable nature allows the creation of a transparent and auditable record of transactions, which can significantly improve trust and accountability among stakeholders [6–8]. The application of blockchain extends beyond mere record-keeping; it can facilitate the integration of Internet of Things (IoT) devices, enabling the real-time monitoring of food products throughout the supply chain [9, 10]. This integration not only enhances traceability but also helps identify instances of fraud and ensures compliance with food safety standards [11, 12]. Moreover, the implementation of blockchain technology can empower consumers by providing detailed product information, verifiable product journeys, and authenticity verification mechanisms [13, 14]. This user-centric approach is crucial for fostering consumer trust, as it allows individuals to make informed decisions based on reliable data regarding the food they consume. Research indicates that blockchain can effectively address the critical issues of transparency and traceability, thereby contributing to the development of a more resilient and sustainable agri-food system [15, 1]. The proposed blockchain-based system for agri-food supply chain management emphasizes not only the internal optimization of supply chain processes but also the enhancement of the consumer experience. By prioritizing a user-centric design, this study aims to build a robust system that not only meets regulatory requirements but also aligns with consumer expectations for transparency and quality assurance. This holistic approach is essential for establishing a trustworthy agri-food ecosystem that can adapt to the evolving demands of consumers and other stakeholders.

RELATED WORK

Oriekhoe et al. [16] outlined a strategic framework for implementing blockchain in food supply chains, emphasizing the need for stakeholder collaboration and investment in infrastructure. This framework addresses the technical and regulatory challenges that often hinder the successful implementation of these systems. Mao and Zhang [18] proposed a digital quality monitoring and traceability system for fresh agricultural products, which underscores the importance of real-time data collection and monitoring in enhancing food safety and consumer satisfaction. Kayikci et al. [15] explored the opportunities and impediments of blockchain technology in the context of Industry 4.0, providing insights into how blockchain can resolve major challenges in the food industry, such as trust and accountability issues. Their systematic literature review highlights the need for further research into the technological and human-related challenges that must be addressed for successful blockchain implementation. Yogarajan et al. [12] conducted a systematic literature review, identifying research gaps and future directions in the adoption of blockchain technology in agri-food supply chains. Rana et al. [19] asserted that blockchain technology can markedly enhance food safety by delivering real-time data regarding food attributes and the companies responsible for their production and distribution. Tiscini et al. [20], in their investigation, illustrated how blockchain technology facilitates the monitoring of cultivation practices, processing methods, and logistical operations, thereby bolstering consumer confidence in food safety. In a similar vein, Akella et al. [21] highlighted the potential of blockchain to streamline supply chains by removing intermediaries and ensuring product safety, which ultimately cultivates consumer trust. This perspective is echoed by Mohammed et al. [22], who contend that conventional logistics systems frequently lack the transparency and traceability features that consumers increasingly demand. Sharma et al. [1] presented an empirical analysis of the factors driving blockchain adoption in agri-food supply chains, underscoring the critical role of digitalization for all stakeholders involved. They observed that while blockchain technology is still in its nascent stages of adoption, its potential for enhancing traceability and accountability is substantial. Supporting this view, Dugyala et al. [23] identified key challenges within food supply chains, such as inadequate record-keeping and a lack of standardization, which blockchain can effectively address. Their review suggests that integrating blockchain with complementary technologies, such as the IoT, can significantly improve the overall efficiency and transparency of food supply chains. Sharma et al. [1] proposed a strategic framework for implementing blockchain in food supply chains, emphasizing the necessity of stakeholder collaboration and investment in infrastructure. This framework addresses the technical and regulatory obstacles that often impede successful implementation. Gandhi Maniam et al. [24] contributed to this discourse by advocating for a digital quality monitoring and traceability system for fresh agricultural products, highlighting the importance of real-time data collection and monitoring to enhance food safety and consumer satisfaction. Munir et al. [25] investigated the opportunities and challenges associated with blockchain technology within the context of Industry 4.0, providing insights into how blockchain can address significant issues in the food industry, including trust and accountability.

Their systematic review emphasizes the need for further research into both technological and human-related challenges that must be overcome for successful blockchain implementation. Akella et al. [21] provided a systematic review of the barriers and enablers of blockchain adoption in smart and sustainable agriculture, identifying 18 key factors that facilitate its implementation. Furthermore, Mohammed et al. [22] explored the impact of blockchain on ethical sourcing and supply chain transparency in Ghana's agricultural and cocoa sectors, demonstrating its potential to enhance ethics. Dugyala et al. [23] analyzed the factors influencing blockchain adoption in the Indian agricultural supply chain, revealing unique dimensions related to perceived efficiency and ethical considerations. This nuanced understanding of blockchain adoption is essential for agricultural stakeholders. Munir et al. [25] discussed the economic, environmental, and social perspectives of blockchain adoption for sustainable supply chain management, emphasizing its transformative capabilities. In summary, the literature indicates that although blockchain technology presents significant opportunities for improving transparency, traceability, and consumer trust in agri-food supply chains, challenges related to implementation and standardization persist.

Awan et al. [26] presented a blockchain-based smart contract framework, as shown in Figure 1. The framework provides a foundation for further exploration of blockchain applications in the agri-food sector and highlights the need for empirical research to assess its impact on food safety and supply chain performance. This study was motivated by the fact that existing blockchain-based solutions for agri-food supply chains primarily focus on internal traceability and efficiency, neglecting consumer-facing functionalities. Building consumer trust requires not only a secure and transparent supply chain but also user-friendly interfaces for easy access to product information and journey tracking.

METHODOLOGY

This study adopted an exploratory/experimental research design. This combined approach enabled a comprehensive evaluation of the proposed blockchain-based framework's potential to enhance traceability, transparency, and consumer trust in the agri-food supply chain.

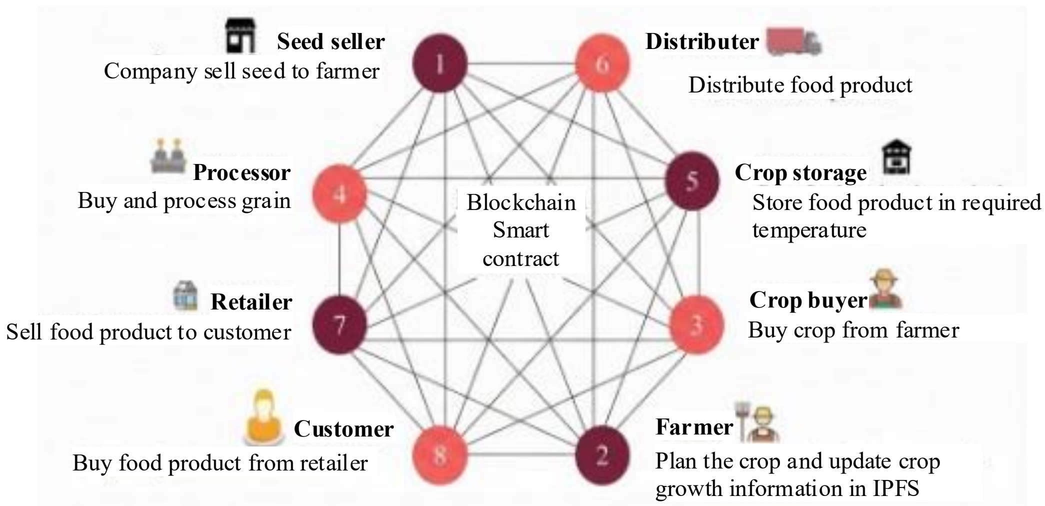

Figure 1. Blockchain-based smart agri-food supply chain frameworks.

A related literature review was conducted to assess the current state of blockchain in agri-food supply chain management. Relevant sources such as Scopus, Web of Science, Google Scholar, and ScienceDirect were searched, key findings were synthesized, and gaps in the existing literature were identified.

The researcher installed an Open-source Ganache Ethereum framework and Remix Integrated Development Environment on a PC running Windows 10 OS (64-bit) with 4GB of RAM, Core^{TM} i5 CPU @2.20Ghz, and 500GB HDD, and used Solidity as the programming language of choice to develop and deploy the smart contract on the blockchain. ReactJS, Node.js, and VSCode were used for the user interface development. The Indian agriculture crop production data and Ondo State Cocoa and Cassava production data, sourced from Kaggle, were used to test the performance of the proposed system.

Developmental Framework

The implementation of this study is based on our proposed architectural model that offers a conceptual overview of the core components and their interactions within a blockchain-based agri-food supply chain management system, as illustrated in Figure 2.

The researcher employed a flowchart and represented the general high-level flow of data and actions within the system, as shown in Figure 3.

Components Integration, Testing, and Validation

The researcher took the following steps to integrate the Ganache blockchain framework into the components of agri-food supply chains, as depicted in Figure 4. Ganache is a valuable tool for testing and validating blockchain-based agri-food supply chain solutions.

1. Ganache was set up as a local blockchain network with the desired settings.
2. Smart contracts were developed with functionalities representing the entities in the agri-food supply chain operations.
3. Smart contracts were deployed to the Ganache network.
4. The operation of the system was simulated using test cases for various scenarios.
5. The functionalities of the system were validated to verify its correct behavior and data accuracy.
6. The system performance was measured using an improved key performance indicator.

A smart contract that enhances transparency, traceability, and compliance in the agri-food supply chain was developed and deployed in this study, as depicted in Figure 5.

RESULTS AND DISCUSSION

The study results show a robust, user-friendly interface with a sign-up process that is essential for a blockchain-based agri-food supply chain platform. It establishes user identity, verifies roles, and provides a foundation for secure interactions within the developed system. The key elements of the user sign-up page are full name, email address, phone number, address, and role selection. Clear options for user roles (farmer, distributor, retailer, consumer), which also include a brief description of each role to assist users in making the correct choice, as depicted in Figure 6.

Figure 7 shows the state/stage of the product that represents its current position in the agri-food supply chain operations (e.g., produced, shipped, received, sold, and consumed). Effectively displaying this information is crucial for ensuring transparency and trust. Status Label, such as a clear and concise text label indicating the current product state, for example, "Product State: Shipped," combined with other visual elements for better clarity. A visual representation of the product state using icons and symbols. For instance, a green checkmark for "produced," a truck for "shipped,"

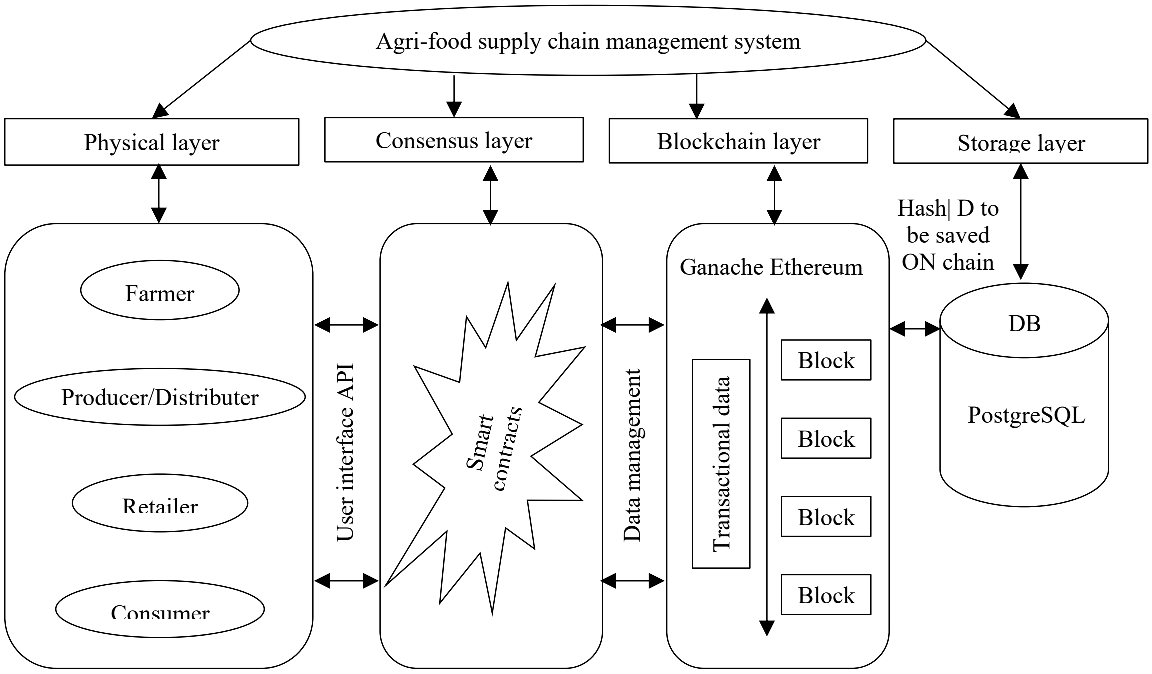

Figure 2. Model of an agri-food blockchain-based framework [17].

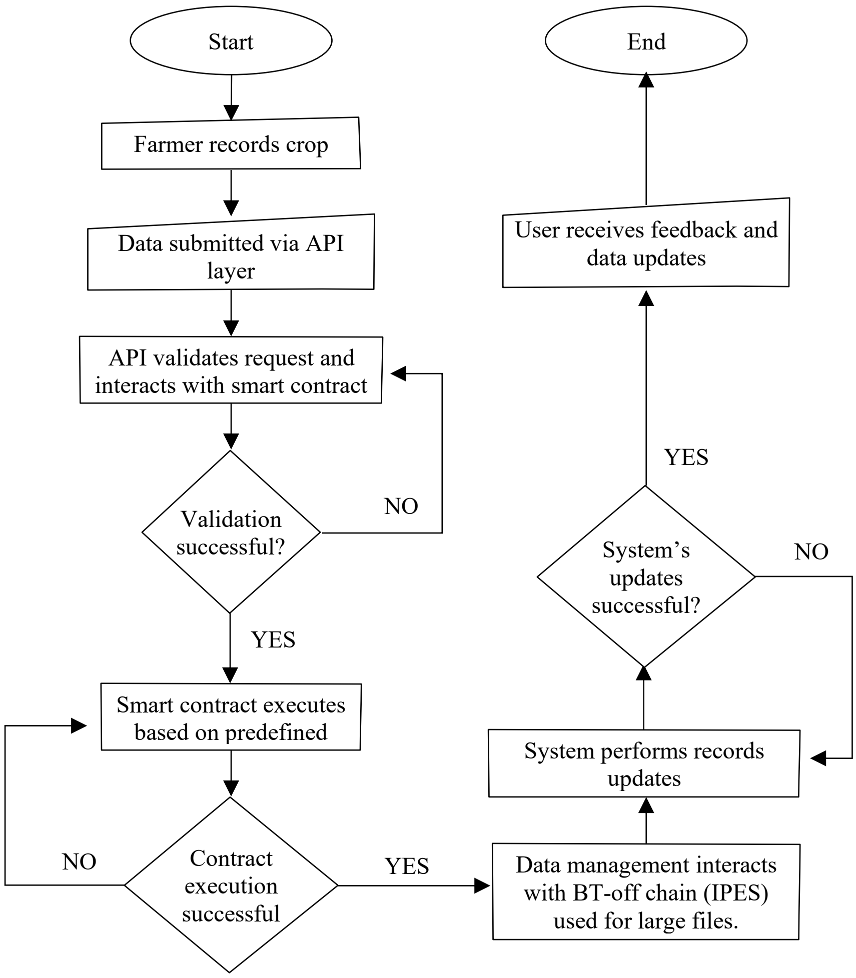

Figure 3. Program flowchart of the proposed framework.

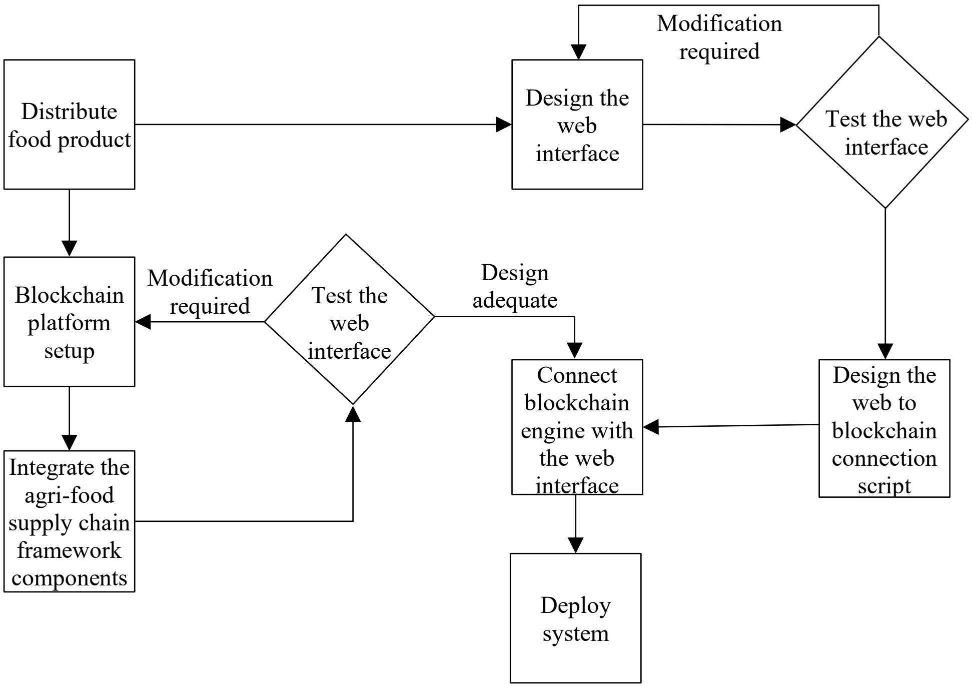

Figure 4. Methodology workflow.

```
    function transferFarmer(uint256 _productId) public {    infinite gas
        require(_productId > 0 && _productId <= productCtr, "Invalid product ID");
        uint256 _id = findFarmer(msg.sender);
        require(_id > 0, "Farmer not found");
        require(products[_productId].state == STATE.Created, "Product not in Created state");
        products[_productId].farmerId = _id;
        products[_productId].state = STATE.Farmer;
    }

    function transferDistributor(uint256 _productId) public {    infinite gas
        require(_productId > 0 && _productId <= productCtr, "Invalid product ID");
        uint256 _id = findDistributor(msg.sender);
        require(_id > 0, "Distributor not found");
        require(products[_productId].state == STATE.Farmer, "Product not in Farmer state");
        products[_productId].distributorId = _id;
        products[_productId].state = STATE.Dispatched;
    }

    function transferRetailer(uint256 _productId) public {    infinite gas
        require(_productId > 0 && _productId <= productCtr, "Invalid product ID");
        uint256 _id = findRetailer(msg.sender);
        require(_id > 0, "Retailer not found");
        require(products[_productId].state == STATE.Dispatched, "Product not in Dispatched state");
```

Figure 5. The smart contract function.

The system operational performance and evaluation of the developed and deployed smart contract in an agri-food supply chain study showed improved efficiency, effectiveness, and security. The key metrics include transaction speed, which was evaluated in 0–4 s and 0–25000 calls; the time taken to execute smart contract functions and scalability, which assessed the contract's ability to handle increasing transaction volumes; gas consumption, which measures the computational cost of contract operations; and security, which identifies vulnerabilities and assesses the contract's resilience to attacks, as shown in Figures 8 and 9.

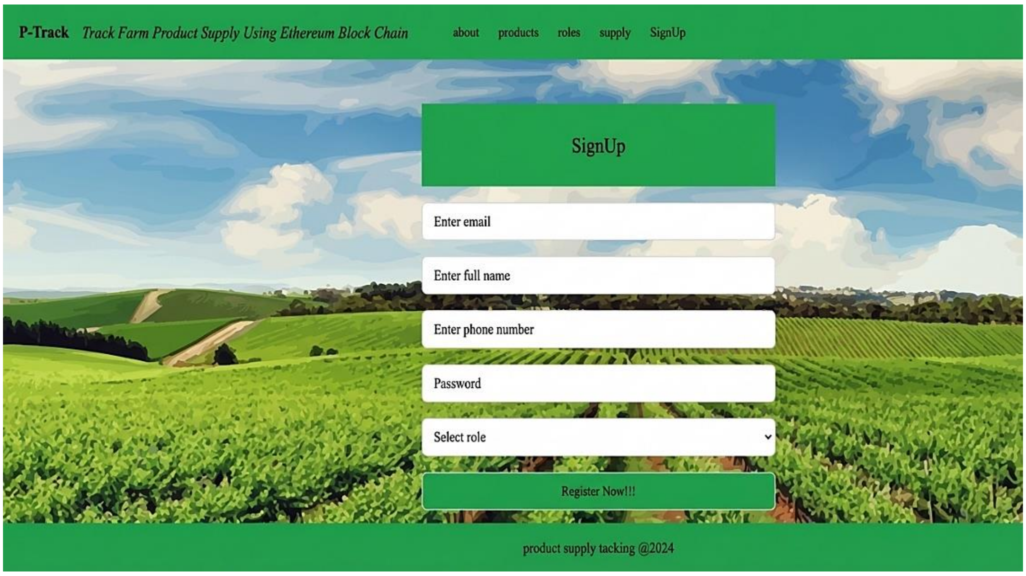

Figure 6. The user sign-up page.

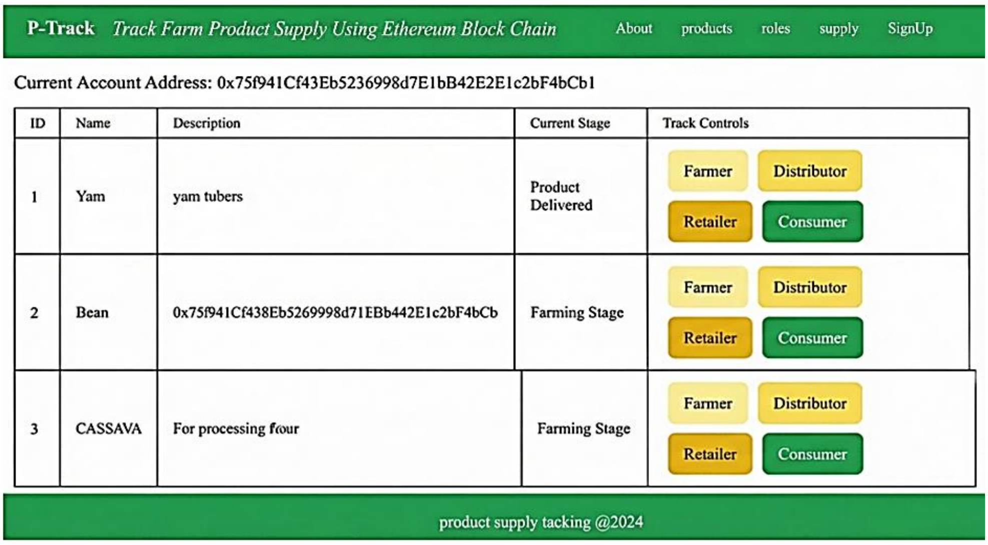

Figure 7. Visibility of the current stage/state of a product for tracking/traceability.

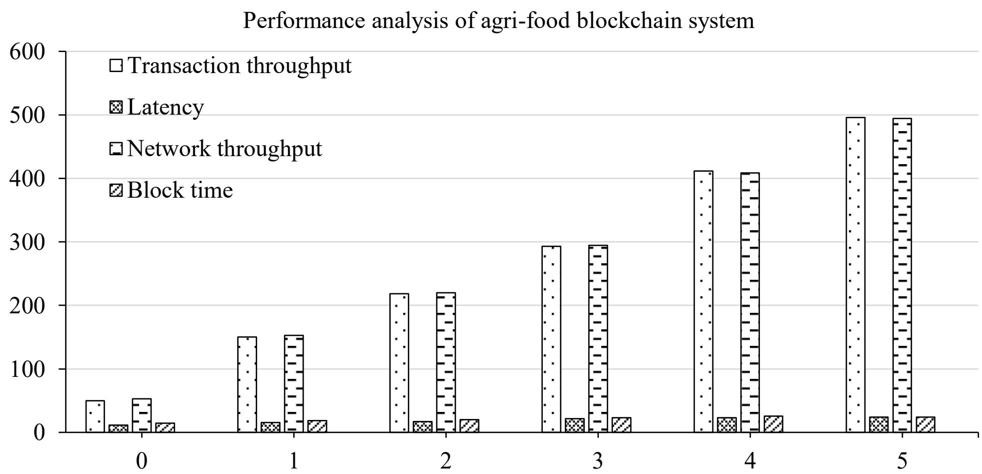

Figure 8. KPI metrics of the proposed system performance.

Comparison Analysis with Some Previous Studies

This analysis compares the performance of the proposed blockchain-based system with that of two previous studies by Awan et al. [26] and Mao and Zhang [18]. The key performance indicators (KPIs) evaluated include transaction throughput, latency, block time, and energy consumption, as depicted in Figures 10–13.

The proposed system demonstrated a transaction throughput comparable to that of previous studies. It processed between 0 and 500 transactions in 0–4 s, which is within the range (50–500 in 0–30 s) reported by Awan et al. [26] and (0–600 in 35 s) by Mao and Zhang [18], as shown in Figure 10.

The proposed system exhibited a significantly lower latency than those in previous studies. The average time for transaction confirmation was between 0 and 10%, compared to 0–50% in Awan et al. [26] and 0–60% in Mao and Zhang [18], as shown in Figures 11 and 12. This indicates that the proposed system is more responsive and efficient in processing the transactions.

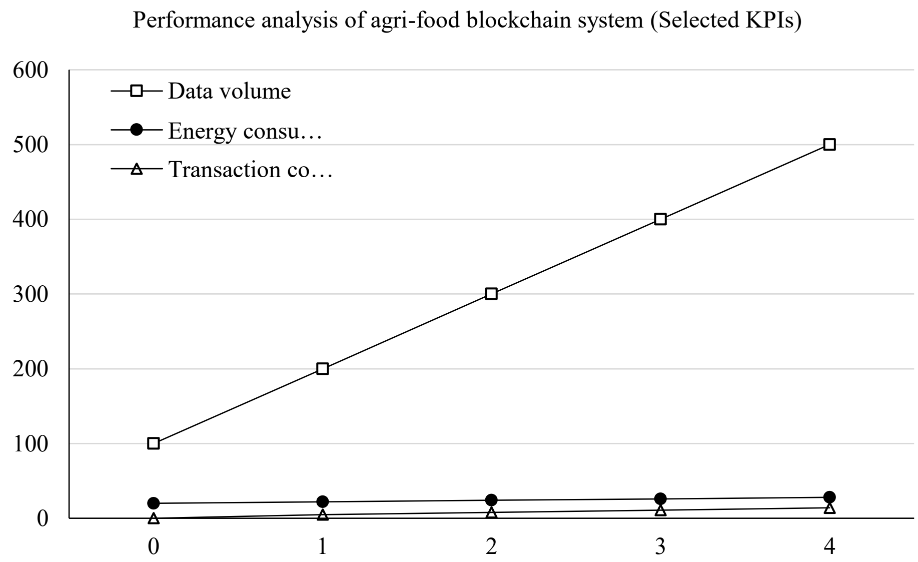

Figure 9. KPI metrics showing the performance of the blockchain system.

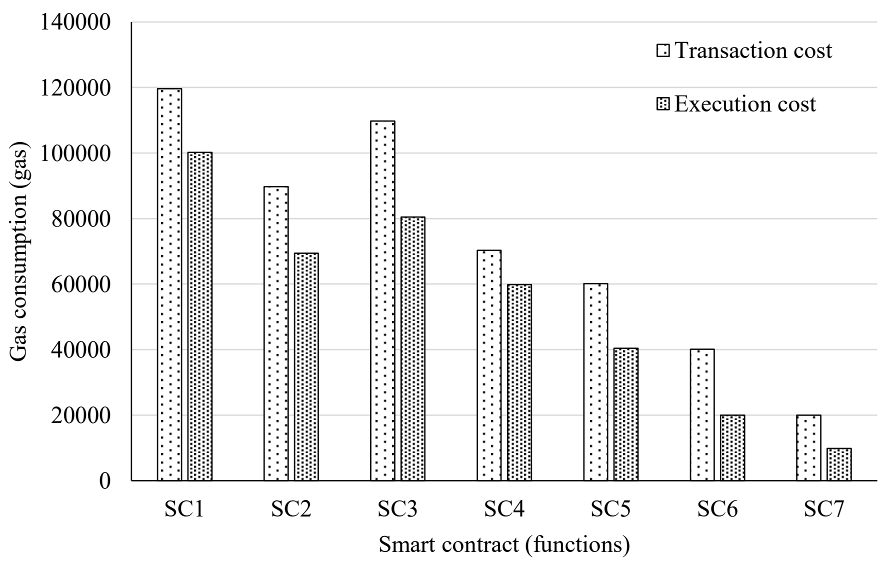

Figure 10. Smart contract transactions and gas consumption [26].

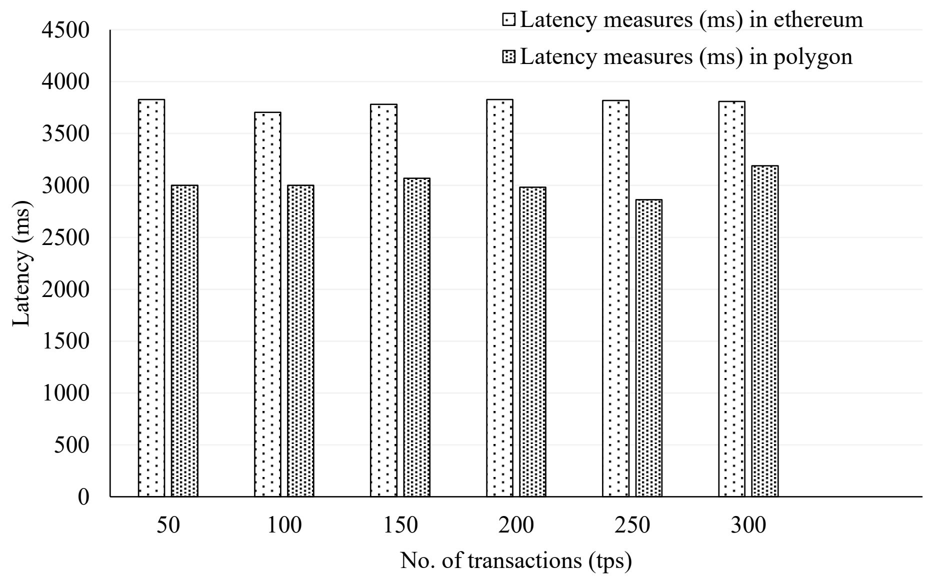

Figure 11. Latency measurements in different networks [26].

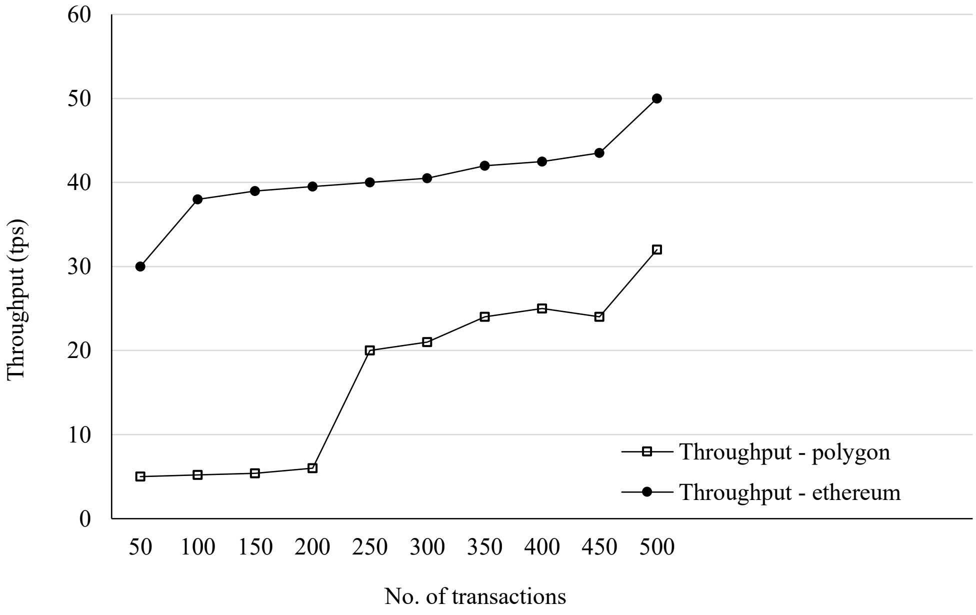

Figure 12. Transaction throughput [18].

The proposed system also had a lower block time creation compared with that in Mao and Zhang [18]. The average time to create a new block was between 0 and 50%, whereas Mao and Zhang [18] reported a range of 0–60%, as shown in Figure 13. This suggests that the proposed system is more efficient in generating new blocks on a blockchain.

The proposed system demonstrated energy consumption comparable to that of previous studies. It utilized between 0 and 30% of the total energy to process transactions, which is within the range (0–45%) reported by Awan et al. [26] and (0–55%) by Mao and Zhang [18], as shown in Figures 9 and 10. Overall, the proposed system shows promising performance improvements in terms of latency and block time while maintaining comparable levels of transaction throughput and energy consumption. These results suggest that the proposed system is a more efficient and scalable solution for blockchain-based applications in the agri-food supply chain.

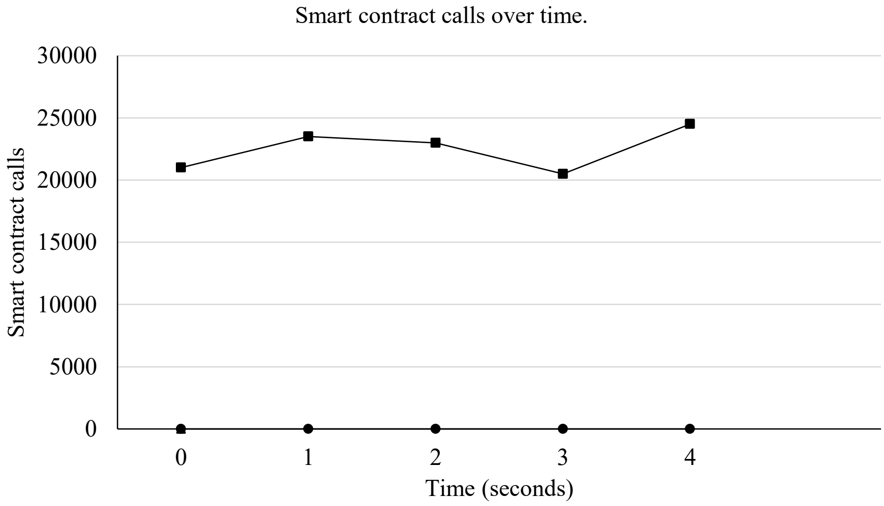

Figure 13. Number of block time and smart contract calls [18].

Contribution to Knowledge

This study contributes to the existing body of knowledge by offering a holistic integration of agri-food supply chain components that serves as new knowledge and a guide to agri-food supply chain operations, including traceability, transparency, and efficiency. This study provides valuable insights into the performance gains achieved, the development of a user-friendly interface, and the deployment of a functional smart contract, which contribute to the practical application of blockchain technology in the agri-food sector. This research expands the understanding of the potential of blockchain technology to revolutionize the agri-food supply chain by addressing key challenges and offering tangible solutions. This study bridges the gap between theoretical concepts and their practical implementation.

CONCLUSION, RECOMMENDATIONS, AND FUTURE WORK

This study aimed to address the challenges associated with blockchain adoption in agri-food supply chain management and develop a robust, user-friendly, and efficient blockchain-based solution. The study identified key obstacles hindering blockchain implementation in the agri-food sector, including interoperability, data privacy concerns, scalability limitations, and resistance to change, and proposed solutions. The researcher integrated blockchain framework components into the blockchain-based platform Ganache (Ethereum) for agri-food supply chain operations. The researcher developed a smart contract that automates various aspects of the agri-food supply chain traceability, including product creation, transfer, and ownership. A user-friendly interface was created to facilitate interactions among all supply chain stakeholders, improving usability and accessibility. Data from Indian agricultural production and cocoa/cassava data from Ondo State, sourced from Kaggle, were used, and a performance evaluation was conducted. The proposed system demonstrated improved performance in terms of transaction throughput (0–500 kpi), latency (0–10%), energy consumption (0–30%), and block time (0–50%) in 0–4 s compared to previous studies. Wider adoption of blockchain technology within the agri-food supply chain is recommended to enhance transparency, traceability, and efficiency. Although the system demonstrates promising results, future work is required to assess its long-term performance, address scalability challenges under extreme conditions, and explore additional use cases within the agri-food industry.

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