Enhancing Transparency and Efficiency in Agricultural Supply Chain Management through Blockchain Integration: A Smart Contract Approach using Remix Solidity IDE

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***Abstract*—In the intricate ecosystem of the food supply chain, involving farmers, producers, distributors, retailers, and consumers, effective supply chain management (SCM) is paramount for streamlined exchange of goods and information among stakeholders. However, traditional SCM faces challenges such as limited transparency, privacy concerns, lack of real-time updates on demand fluctuations, traceability issues, quality control lapses, dispute resolution inefficiencies, and waning participant confidence. Addressing these challenges, our research proposes an innovative approach by integrating blockchain technology into the food supply chain. Leveraging the Ethereum platform's distributed ledger technology, our system incorporates smart contracts tailored to the nuances of the food supply chain. These smart contracts aim to simplify and enhance management across various stages including manufacturing, distribution, retail, and procurement. By harnessing the Ethereum blockchain, we ensure heightened transparency throughout the journey of food items from farm to plate. Our system facilitates effective monitoring of food items, stringent quality control measures, prevention of transaction repudiation, and agile adaptation to supply and demand dynamics. Furthermore, the integration of blockchain technology fosters accountability and trust among participants in the food supply chain. In the latter sections of our paper, we undertake a comprehensive evaluation of the proposed blockchain structure, assessing its alignment with the distinctive requirements of the food supply chain. Through this analysis, we demonstrate the potential of blockchain technology to address current challenges and significantly enhance the efficiency, reliability, and transparency of food supply chain management procedures.**

I. Introduction

The agricultural sector holds a critical role in global economies, providing essential goods to meet the needs of a continuously expanding population. The effectiveness of the agricultural supply chain is vital for the smooth exchange of information and goods among stakeholders, including farmers, producers, distributors, retailers, and consumers. However, traditional supply chain management (SCM) processes in agriculture encounter challenges related to transparency, traceability, quality assurance, and trust among participants [1].

As depicted in Figure 1, the conventional agricultural supply chain involves multiple stages, commencing with raw material suppliers providing inputs to farmers for cultivation, progressing through production, packaging, distribution to retailers, and reaching end consumers. In this intricate network, existing SCM frameworks often rely on paper agreements, resulting in non-transparent processes among suppliers, carriers, producers, distributors, and retailers. This lack of transparency complicates the tracking of contract breaches, management of perishable products, anticipation of demand uncertainties, and the realization of real-time tracking and tracing of agricultural products.

There is increasing interest in using blockchain technology to address these issues and improve the agricultural supply chain's efficiency. Blockchain, which was first unveiled by S. Nakamoto in 2008 as a decentralized peer-to-peer electronic cash system, has developed into a game-changing technology that may be used in a wide range of sectors. Blockchain's distributed and decentralized ledger features are beneficial to the agricultural industry since they allow for real-time record tracking, data immutability, user privacy, and overall increased efficiency.

Industry estimations indicate that blockchain would create a substantial amount of commercial value, estimated to be \$176 billion by 2025 and \$3.1 trillion by 2030. The decentralized nature of blockchain, enabled by encryption, consensus processes, and block referencing, presents it as a viable remedy for the issues confronting the agricultural supply chain. Blockchain ensures auditability and tracking of agricultural product manufacturing and supply information by enabling traceable and irreversible transactions through the use of smart contracts, which are self-executing contracts with programmed terms.

This study presents a novel framework—specifically, one built on the Ethereum platform—for agricultural supply chain management that makes use of blockchain technology. In order to handle the particular intricacies of the agricultural

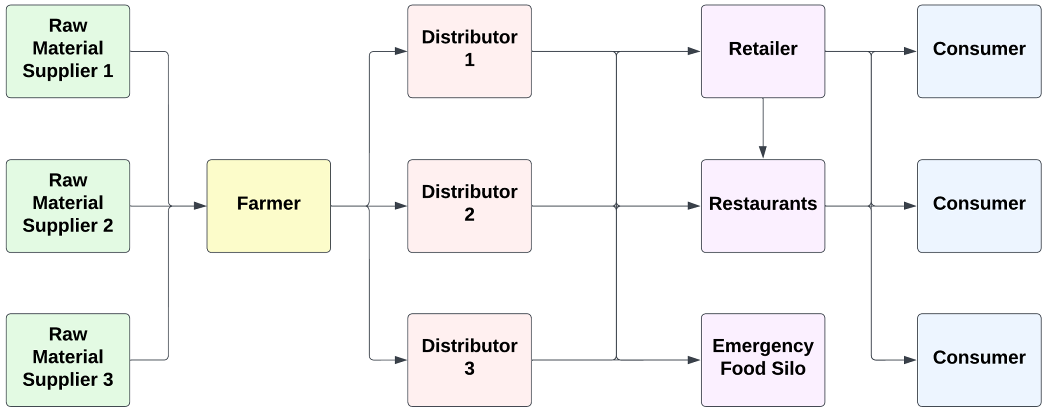

Fig. 1. Agricultural supply chain process.

supply chain, which includes phases like raw material supply, agriculture, logistics, distribution, retail, and end-user transactions, our system integrates smart contracts. In addition to promoting trust among participants, the suggested framework seeks to achieve user privacy, transparency in supplied product information, tracking of agricultural products, quality control, non-repudiation, and demand forecasting utilizing machine learning techniques.

This paper's later sections (Section II) identify research gaps by examining current frameworks for agricultural supply chain management. Then, in Section III, we show our suggested structure and provide information on the smart contracts created for the different phases of the agricultural supply chain. Section IV offers a thorough examination of the suggested framework's ability to satisfy the unique needs of agricultural supply chain management. Section V contains closing thoughts [1] [2].

II. Related Work

Blockchain technology has emerged as a promising solution to address various challenges in supply chain management, particularly in the agricultural sector. This section presents a comprehensive overview of relevant literature that contributes to the understanding and application of blockchain integration in enhancing transparency and efficiency in agricultural supply chain management.

Rogerson and Parry [3] investigate blockchain's applications beyond cryptocurrencies, specifically its role in enhancing trust and visibility within supply chains. Their research, using case studies from the food industry, highlights blockchain's potential impact on products like baby food. Challenges identified include concerns about technology trust and consumer willingness to pay. The study underscores the practical utility of blockchain in building trust and providing visibility, supported by evidence from real-world cases. The literature review underscores the significance of traceability and visibility in supply chains, showcasing four firms through case studies that exemplify blockchain applications for improved visibility, authenticity, and sustainability, offering valuable insights.

In their discussion of the growing use of IoT in agri-food supply chains, Caro, Ali, Vecchio, and Giaffreda [4] stress the need for trustworthy and open traceability systems. Single points of failure and data integrity are problems with the centralized IoT-based solutions that are currently in use. The decentralized blockchain-based traceability solution AgriBlockIoT, which seamlessly integrates IoT devices, is introduced by the authors. In their study, they construct this method on Ethereum and Hyperledger Sawtooth blockchains and assess it using a farm-to-fork use case. The study compares latency, CPU load, and network consumption across the two solutions with a focus on performance indicators. The results show that Ethereum is not as good as Hyperledger Sawtooth. The debate on decentralized traceability systems in agri-food supply chains is furthered by this study.

Shahid, Almogren, Javaid, Al-Zahrani, Ziaur, and Alam [5] address challenges in tracking data provenance and maintaining traceability in traditional centralized Agri-Food supply chains. They propose a comprehensive blockchain-based solution utilizing Ethereum's blockchain and smart contracts to enhance transparency, accountability, and traceability. The system records all transactions on the blockchain, uploading data to the Interplanetary File Storage System (IPFS) to ensure a secure and efficient solution. The study encompasses smart contract algorithms, simulations, and performance evaluations, emphasizing gas consumption, mining time, and deployment costs. Their work contributes to developing a reliable system for traceability, trust, and delivery mechanisms in Agri-Food supply chains.

Nakamoto(2008) [6] introduced the concept of blockchain through the seminal paper "Bitcoin: A Peer-to-Peer Electronic Cash System." This foundational work laid the groundwork for decentralized, transparent, and secure transactions, serving as the basis for subsequent research in blockchain technology.

Christidis and Devetsikiotis (2016) [7] explored the potential of blockchain and smart contracts for the Internet of Things

(IoT). Their study demonstrated the applicability of blockchain in enhancing data integrity, security, and automation, which are crucial aspects for improving supply chain transparency and efficiency.

Iansiti and Lakhani (2017) [8] provided insights into the broader implications of blockchain technology in their article ”The Truth About Blockchain” published in Harvard Business Review. They discussed how blockchain can revolutionize various industries, including supply chain management, by enabling trust, transparency, and efficiency.

Wang et al. (2018) [9] proposed a framework for blockchain-based industrial control systems security, emphasizing the importance of secure data exchange and verification mechanisms in supply chain operations. Their work contributes to addressing security concerns in agricultural supply chain management.

Tapscott and Tapscott (2016) [10] explored the transformative potential of blockchain technology in their book ”Blockchain Revolution.” They discussed how blockchain can streamline business processes, including supply chain management, by eliminating intermediaries and enhancing transparency.

Wang et al. (2019) [11] proposed a blockchain-based data traceability and verifiable computation scheme specifically tailored for supply chain applications. Their research contributes to ensuring data integrity and trustworthiness in agricultural supply chain management processes.

Kshetri (2018) [12] examined the potential of blockchain technology to address socioeconomic challenges, particularly in the Global South. His study discusses how blockchain can empower marginalized communities and improve transparency and accountability in supply chain operations.

Crosby et al. (2016) [13] provided a comprehensive overview of blockchain technology and its applications beyond Bitcoin in their article ”Blockchain Technology: Beyond Bitcoin.” Their work highlights the diverse potential applications of blockchain, including supply chain management in the agricultural sector.

However, the existing proposals lack the incorporation of transparency, leading to a lack of trust between farmers, distributors, and customers. Data integrity has also been overlooked in previous research efforts. Our paper addresses these challenges, aiming to overcome the deficiencies identified in the current literature.

III. Proposed Agriculture Supply Chain Management incorporating blockchain

A. Framework

The proposition section is divided into the framework part showing the framework and their design components and the algorithm part which includes all the steps followed to get output desired.

1) Objective and Design Objectives: The primary aim of the envisioned agricultural supply chain management framework is to establish a decentralized and reliable system that ensures transparency, traceability, and efficiency throughout the agricultural supply chain. The framework is meticulously crafted to address crucial requirements such as user privacy, data transparency, immutability, high availability, and real-time tracking. Additionally, the system strives to effectively manage crop quality and facilitate demand forecasting to enhance crisis preparedness.

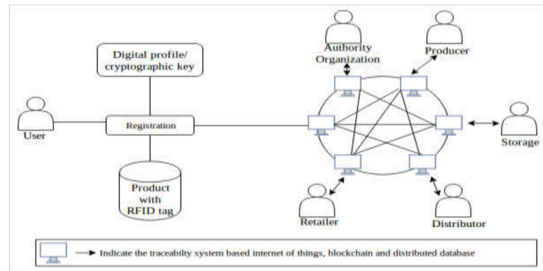

Fig. 2. Conceptual framework.

2) Design of the Proposed Framework: The proposed framework, illustrated in Figure 2, utilizes smart contracts to govern interactions among raw material suppliers, manufacturers, distributors, and retailers. Capitalizing on the Ethereum blockchain’s capabilities for executing autonomous smart contracts, the framework orchestrates a sequence of transactions and notifications through pseudocode:

1) **Raw Material Submission:** Suppliers update the distributed ledger technology (DLT1) with stock information by providing the supply aggregator contract with raw material specifics.
   - Update information about available raw materials for every vendor.
   - Transmit a notification to the supply aggregator agreement.
2) **Manufacturer’s Demand Forecast:** Manufacturers forecast their demand, initiating transactions through the raw material purchase contract.
   - Assign the manufacturer the raw material.
   - Update accounts and ownership.
   - Alert the logistics department regarding transportation.
3) **Quality Checking:** Upon raw material arrival, quality checking contracts are invoked to ensure proper quality and quantity, with transportation costs calculated and deducted accordingly.
   - For each stage (manufacturer, distributor, retailer):
     – Check quality and quantity.
     – Update accounts and ownership.
     – Calculate and deduct transportation costs.
4) **Distributor and Retailer Transactions (Stock and Crop Purchase Contracts):** Distributors and retailers engage in transactions facilitated by stock and crop purchase contracts.
   - For each distributor/retailer:
     – Assign the crop to the distributor/retailer.

- Update accounts and ownership.
- Notify logistics for transportation.

3) Proposed Smart Contracts for Agricultural Supply Chain Management: The suggested framework's smart contracts are designed to monitor different phases of the agricultural supply chain. Important contracts that provide seamless interactions and data updates include the Quality Checking Contract, the Raw Material Purchase Contract, and the Supply Aggregator Contract.

To sum up, the proposed architecture for managing the agricultural supply chain makes use of smart contracts and blockchain technology to improve efficiency, traceability, and transparency. As a fundamental component, the Solidity code that is offered implements crucial features for overseeing the agricultural supply chain.

B. ALGORITHM FOR AGRICULTURE SUPPLY CHAIN

Initialization:

```
Contract CropManagement:
   // State variables
   owner: address
   cropCount: uint256

   // Struct to represent crop
   struct Crop:
      farmer: address
      cropName: string
      quantity: uint256
      status: string

   // Mapping to store crops
   crops: mapping(uint256 => Crop)

   // Events
   event CropAdded(
      uint256 indexed cropId,
      address indexed farmer,
      string cropName,
      uint256 quantity,
      string status
   )
   event CropDetails(
      uint256 indexed cropId,
      address indexed farmer,
      string cropName,
      uint256 quantity,
      string status
   )

   // Modifier to restrict access to owner-
       only functions
   modifier onlyOwner():
      require(msg.sender == owner, "Only owner
           can call this function")
      _

   // Constructor to set owner and initialize
       cropCount
   constructor():
      owner = msg.sender
      cropCount = 0

   // Function to add a new crop
   function addCrop(string memory _cropName,
       uint256 _quantity) external:
      require(_quantity > 0, "Quantity must be
           greater than zero")
      cropCount++
      crops[cropCount] = Crop(msg.sender,
          _cropName, _quantity, "Planted")
      emit CropAdded(cropCount, msg.sender,
          _cropName, _quantity, "Planted")
      emit CropDetails(cropCount, msg.sender,
          _cropName, _quantity, "Planted")

   // Function to harvest a crop
   function harvestCrop(uint256 _cropId)
       external onlyOwner():
      require(_cropId > 0 && _cropId <=
          cropCount, "Invalid crop ID")
      crops[_cropId].status = "Harvested"

   // Function to distribute a crop
   function distributeCrop(uint256 _cropId,
       uint256 _quantity) external onlyOwner()
      :
      require(_cropId > 0 && _cropId <=
          cropCount, "Invalid crop ID")
      require(_quantity > 0 && _quantity <=
          crops[_cropId].quantity, "Invalid
          quantity")
      crops[_cropId].status = "Distributed"
      crops[_cropId].quantity -= _quantity

   // Function to purchase a crop
   function purchaseCrop(uint256 _cropId,
       uint256 _quantity) external:
      require(_cropId > 0 && _cropId <=
          cropCount, "Invalid crop ID")
      require(_quantity > 0 && _quantity <=
          crops[_cropId].quantity, "Invalid
          quantity")
      crops[_cropId].status = "Purchased"
      crops[_cropId].quantity -= _quantity

   // Function to get details of a crop
   function getCropDetails(uint256 _cropId)
       external view returns (address, string
       memory, uint256, string memory):
      require(_cropId > 0 && _cropId <=
          cropCount, "Invalid crop ID")
      Crop memory crop = crops[_cropId]
      return (crop.farmer, crop.cropName, crop
          .quantity, crop.status)
```

IV. RESULTS OF THE EXPERIMENTS AND EVALUATION OF THE SUGGESTED FRAMEWORK

I. Experimental Setup

A thorough series of tests was carried out to assess the viability and effectiveness of the suggested Agriculture Supply Chain Management framework. The goal of the tests was to evaluate transaction speed with different participant counts. For testing, the Ethereum blockchain network was set up and deployed at NIT Goa. There were 40 participants in the experimental environment, which consisted of Ethereum Geth nodes with 20 supplier and 20 customer accounts. The

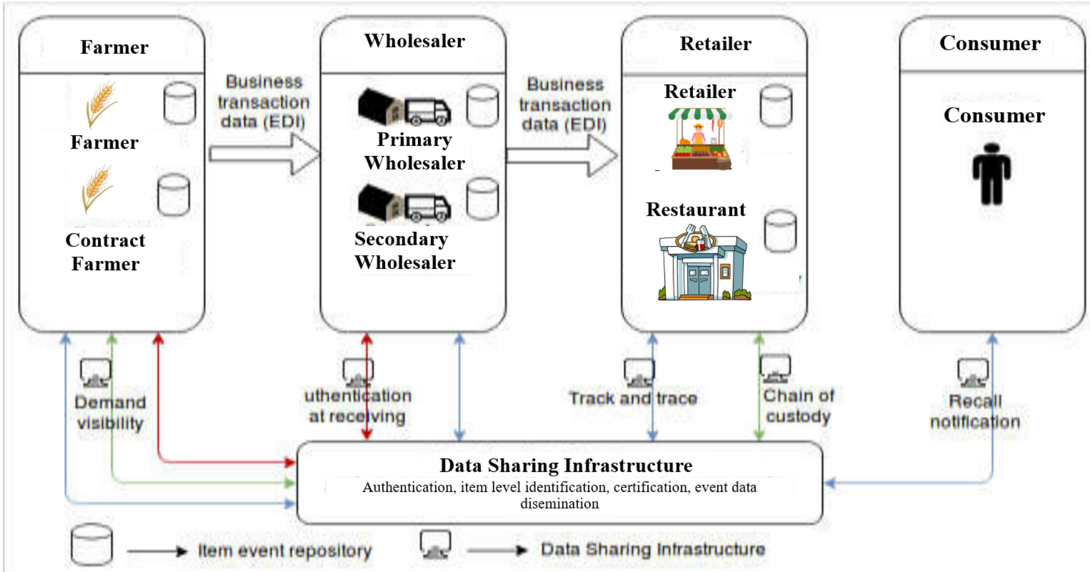

Fig. 3. Information flow.

necessary smart contracts were created in Solidity and verified with the Remix Solidity IDE, as explained in Section III.

II. Transaction Speed Analysis

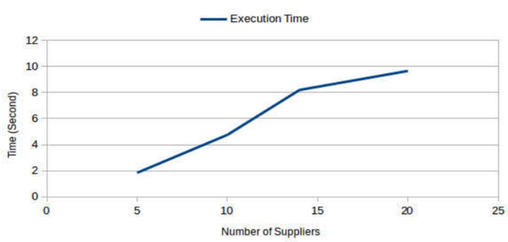

Fig. 4. Average execution time of supply aggregator.

A. Contract Execution Time for Supply Aggregator: The processing duration of the Supply Aggregator contract was evaluated by initiating transactions from various suppliers and customers. The experiments were progressively expanded, commencing with 5 suppliers and 5 customers. Additional tests augmented the participant count in increments of 5. As depicted in the figure, the execution time of the Supply Aggregator contract displayed an upward trajectory as the number of suppliers increased. On average, the contract required approximately 6 seconds to complete transactions for all 20 suppliers.

B. Execution Time for Crop Purchase Contract: Similarly, the execution time for the Crop Purchase contract was assessed by initiating transactions from 5 customers and incrementally increasing the participant count. The results, shown in Figure 5, indicated an average execution time of 12.64 seconds for the 20 customers.

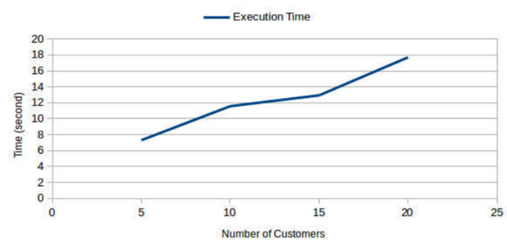

Fig. 5. Average execution time for purchase contract.

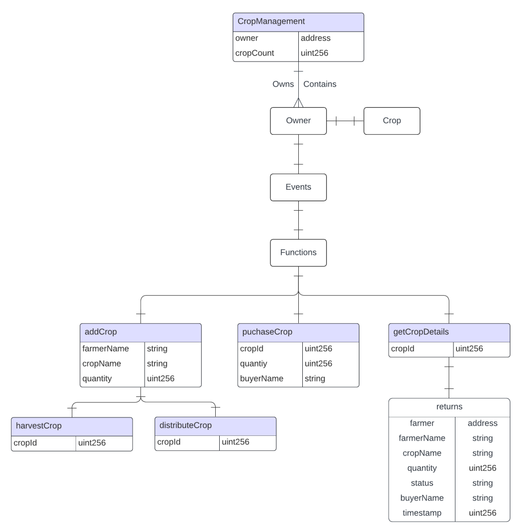

Fig. 6. Flow Diagram.

III. Framework Evaluation

The proposed framework demonstrates several key features that contribute to its viability in Agriculture Supply Chain

Management.

A. User Privacy: One of the most important requirements is privacy. By using externally owned accounts (EOAs), or faux identities, for participants, the suggested system protects user privacy. By using their specific EOA address to conduct transactions, each member ensures the privacy of their identity and crop stock details. The exclusive linkage of financial and medicine purchase/supply information to EOAs improves user privacy.

B. High Availability, Immutability, and Transparency of Data: By making all money transactions and medicine supply details transparent to participants, blockchain technology ensures data transparency. Immutability is guaranteed by using a distributed ledger since data on the blockchain cannot be changed without a lot of processing power. The suggested framework's decentralized design eliminates single points of failure and guarantees high data availability. Each transaction may be tracked back to its source thanks to the non-repudiation feature of digital signatures using private keys.

C. Crop and Demand-Supply Tracking in Real-Time: Real-time tracking of the crop supply is made possible by blockchain's timestamped sequential storage. At every step of the supply chain, smart contracts built into the framework run quantity and quality checks, guaranteeing precision and dependability. Blockchain's immutability makes it possible to use machine learning techniques to precisely estimate demand, which helps with disaster preparedness and prevention.

V. Conclusion

Our paper introduces an innovative Agricultural Supply Chain Management framework. Our system guarantees user privacy, data transparency, immutability, high availability, and real-time agricultural product tracing by utilizing the Ethereum blockchain and smart contracts. The experimental results are encouraging, laying the groundwork for a proof of concept. Future work may explore machine learning for demand prediction. While blockchain scalability remains a challenge, ongoing research aims to address this, paving the way for broader adoption in agriculture, mirroring success in pharmaceutical supply chains. The cross-industry collaboration promises a progressive future for supply chain management.

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