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RESEARCH ARTICLE

Agri-4-All: A Framework for Blockchain Based Agricultural Food Supply Chains in the Era of Fourth Industrial Revolution

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ABSTRACT Blockchain, smart contracts, and the Internet of Things (IoT) are essential technologies for the business process re-engineering of supply chains in the era of Industry 4.0. The agricultural food supply chain is one of the research areas where these disruptive technologies can play a crucial role in automating business processes, providing real-time goods monitoring, and securing transactions. With the help of blockchain, smart contracts, and the IoT, a product's health and environment can be monitored throughout the supply chain. In this study, we have critically examined the relevance of these technologies through various activities of the agriculture supply chain using the approach of Business Process Modeling (BPM). The blockchain and smart contracts-based findings of the BPM were then incorporated along various layers of the Reference Architecture for Modeling Industry 4.0 (RAMI 4.0). This enabled us to introduce the IoT, blockchain, and smart contract based smart agriculture framework, Agri-4-All. Agri-4-All can be used to automate the intra-organizational and inter-organizational processes of the agricultural supply chain. We developed, deployed, and tested the intra-organizational and inter-organizational smart contracts written in the Solidity language for a typical scenario related to the agriculture supply chain. Our hybrid smart algorithms implemented using Ganache and Truffle suite reduce the gas cost in our proposed intra-organizational smart contracts by 13.89 times as compared to the traditional smart contract-based model.

INDEX TERMS Agriculture supply chain, blockchain, IoT devices, Internet of Things, smart contracts, RAMI 4.0.

I. INTRODUCTION

Supply chain management (SCM) [1], despite its maturity, is continually being rebuilt by disruptive technologies like the Internet of Things (IoT), blockchain, and smart contracts. Globalization and intricate regulatory policies have made supply chains complex. Information management systems for supply chains are generally centralized, requiring entities to trust one broker with sensitive data and information. Centralized information systems have the disadvantage of a single point of failure and are more susceptible to hacking and other attacks.

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Customers always demand better quality products delivered on time and at the right price, which is a big challenge in supply chain management [2]. Consumers also demand visibility and traceability to keep track of their orders. Traceability, or tracking a product through all supply chain stages, is more of a demand than a request, as almost every customer wants to know the product's origin and ingredients. Maintaining supply chain visibility and tracking shipments become tough when multiple carriers, third-party logistics providers, and modes of transportation are used [3]. Lack of traceability can create blind spots in the supply chain and weaken the customer's trust, which can eventually cause lower sales and lead to less profit. Transportation delays and poor storage practices in warehouses are common causes that can affect the

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safety and quality of products. Lack of communication also has a significant impact on the supply chain because there are several parties involved that have little or no knowledge of other entities' actions [4]. Poor communication among parties may cause inefficiency, leading to trust issues among suppliers and customers. If the supply chain operates globally, trust issues get much worse.

Blockchain is the solution to the majority of supply chain problems, such as information sharing between parties, data tampering, and lack of transparency. Blockchain technology, popularized by Satoshi Nakamoto's Bitcoin [5], has gained attraction in the financial world and is altering the dynamics of centralized systems. Transparency is one of the blockchain's promises, as copies of data are shared across the entire network and each blockchain node is required to keep a replica of that shared data [6]. Blockchain also plays a vital role in removing third-party involvement, as it did in Bitcoin: anyone can make transactions with any other member of the blockchain network without the involvement of third party trust managers and banks. No third-party involvement means we can save time, remove extra costs, and reduce risk factors. Blockchain increases trust as untrusted parties can do business without hesitation. Blockchain also reduces the risk of data tampering, fraud, and cybercrimes due to its transparency and immutability [7], [8]. Data and information sharing through blockchain can enable different levels of transparency in the supply chain, facilitating better product selection for customers. In the finance part of supply chain management, blockchain can help customers and companies adopt a common digital currency as an alternative to traditional money transfers. In our previous research [9], we proposed multi-processing mining techniques that could be used to make the payment system quicker and more secure for supply chain stakeholders.

With the assistance of IoT sensors, the product flow through the whole supply chain from farming, warehousing, transportation, and retailing to end consumers can be monitored. Many IoT reference architectures have been proposed for the development of IoT-based products and business models, including Reference Architectural Model Industrie 4.0 (RAMI 4.0) [10], Industrial Internet Reference Architecture (IIRA) [11], and Internet of Things Architecture (IoT-A) [12].

We have observed that there is no comprehensive framework for supply chain management (see Table 1) that takes into account disruptive technologies, i.e., IoT, blockchain, and smart contracts altogether. In addition, there is a gap in terms of Industry 4.0 compliant frameworks for the agricultural supply chain. To fill in this gap, we carried out an analysis of a typical agricultural supply chain using a BPMN model and highlighted the activities that can be automated with the help of IoT, blockchain, and smart contracts. The existing Industry 4.0 reference architectures do not incorporate blockchain and smart contracts in their design. We have selected the most elaborated Industry 4.0 reference architecture, RAMI 4.0, and mapped the BPMN model activities onto its axes. We identified various pieces of information pertaining to blockchain and smart contracts in the agriculture supply chain. This enabled us to propose a blockchain- and smart contract-based, industry 4.0-compliant framework for the agricultural supply chain, i.e., Agri-4-All. The motivation behind the name Agri-4-All is that all supply chain stakeholders share a blockchain enabled Industry 4.0 platform to communicate and share valuable information with each other. The use of blockchain and smart contracts in Agri-4-All incurs additional costs. We performed cost analysis across the supply chain and introduced enhancements leading to an improved cost-effective hybrid model for intra-organizational business processes.

The scientific contribution of this paper includes the following:

- Agri-4-All: An IoT, blockchain, and smart contract based Industry 4.0 compliant framework for the automation of intra-organizational and inter-organizational processes in a typical agriculture supply chain,
- Cost analysis of the typical intra-organizational and inter-organizational smart contracts employed in the framework.

The rest of the paper is organized as follows: Section II covers the related work, and methodology is described in Section III. Section IV explains the IoT, blockchain, and smart contract-based business process model of the smart agriculture supply chain. Industry 4.0-based agricultural supply chains are discussed in Section V. Section VI elaborates the proposed layered framework Agri-4-All for smart agricultural supply chains in Industry 4.0. A case study based on the Agri-4-All framework is discussed in VII and experiments with inter-organizational and intra-organizational solidity smart contracts are presented in Section VIII. Finally Section IX concludes the paper.

II. RELATED WORK

Manufacturing, and its allied industries as well as value-creation processes are going through a novel digital transformation propelled by "Industry 4.0." Manufacturers and supply chain stakeholders are incorporating IoT, blockchain, cloud computing, analytics, and machine learning to re-engineer their business processes.

The Internet of Things can assist in automating the supply chain with the help of carriers and vehicles equipped with various sensors, actuators, and addressing devices. A use case related to pharmacology has been discussed in [13]. As keeping the medicines between the required levels of temperature and humidity is of prime importance, it is suggested that IoT sensors can be used to monitor the environmental parameters during the supply. The authors also discuss the role of blockchain and smart contracts in the pharmaceutical supply chain, but smart contracts have a limited usage of temperature monitoring in the system. Authors in [14] focus on IoT-based traceability of perishable food in a supply chain and propose a user-friendly traceability system. The authors

TABLE 1. Technology oriented food supply chain frameworks.

Publications	Industry 4.0	Internet of Things	Blockchain	Smart Contracts
Casino et al. [15]	✗	✗	✓	✓
Hu et al. [16]	✗	✓	✓	✓
Bai et al. [17]	✗	✓	✓	✗
Awan et al. [18]	✗	✓	✓	✓
Guido et al. [19]	✗	✗	✓	✗
Iqbal et al. [20]	✗	✓	✓	✗
Salah et al. [21]	✗	✗	✓	✓
Casado-Vara et al. [22]	✗	✗	✓	✗
Tian et al. [23]	✗	✓	✓	✓
Proposed Framework (Agri-4-All)	✓	✓	✓	✓

present a conceptual framework, but technical details related to blockchain and smart contracts are not provided.

To emphasize the importance of blockchain in the supply chain, the authors in [24] conducted an online survey to get the opinion of logistics professionals about barriers, facilitators, and the general prospects of blockchain. Based on the survey, the authors conclude that blockchain will have a huge impact on the logistics industry and should be considered as a game-changer. The authors of [25] emphasize that transparency in supply chain management is the most important but difficult-to-address issue due to its complexities.

In articles [26], [27], [28], [29], [30], the enormous potential of blockchain is discussed, which will disrupt the current supply chain management in the production, marketing, purchasing, and consumption of foods. Tian et al. [31] have discussed the importance of RFID for product tracking, as supply chain traceability is becoming increasingly important. The pros and cons of using RFID in tandem with blockchain have been analyzed in detail, and the authors conclude that such a system would be critical in solving the food safety problem in China. The authors in [32] investigate how blockchain can optimize the supply chain and insist that visibility through tracking should be provided in each supply chain process. Casada-Vera et al. [22] argued that the current supply chain, which is a linear economic model, has some disadvantages, like the relationship between participants in the supply chain and the lack of information about the item's origin. The authors propose a new blockchain model, eliminating many problems associated with the present supply chain. Nakasumi et al. [33], [34], and [35] highlighted that serial numbers and bar codes could also be stored on the blockchain and that valuable information about the manufacturing, delivery, and maintenance of products can also be shared with suppliers and vendors through blockchain-based systems. In [36], the introduction of blockchain in business processes is discussed. Kshetri et al. [37] discussed how blockchain would affect organizational processes, especially the supply chain. They also highlighted supply chain objectives that could be affected, including cost, sustainability, and risk reduction. The majority of studies on the smart agriculture supply chain concurred that disruptive technologies may completely transform conventional supply chains; however, they did not employ Industry 4.0 methodologies.

We have carried out a comparative analysis of the technology-oriented conceptual frameworks in supply chains which is summarized in Table 1.

Now we elaborate the findings of our comparative analysis. The authors in [15] proposed a blockchain and smart contract-based framework for traceability purposes in the dairy supply chain. The authors developed smart contracts for this purpose and tested the effectiveness of these smart contracts with the help of Ganache and Truffle. The proposed model is solely based on blockchain, and not much emphasis has been put on IoT and Industry 4.0 practices. In [16] authors proposed a blockchain and edge computing-based layered framework to address trust issues among organic food supply chain stakeholders. The framework allowed geographically dispersed small and medium-sized farms to participate in any supply chain. Although the framework includes IoT and blockchain, it does not describe the basic smart contract structure and does not follow Industry 4.0 practices. The authors of [17] proposed a non-cooperative game model based on blockchain and IoT to identify and isolate malicious sensors in the agriculture green supply chain. The model also helped in filtering out malicious data from the gathered information. The model did not include any smart contracts for traceability and provenance. In [18], authors proposed a futuristic IoT with a blockchain model to address the present supply chains issues such as centralization and communication. The main focus of the model is to tackle sensor nodes' energy consumption, and for this purpose, the authors also proposed an energy-efficient clustering protocol. In [19] a simple blockchain framework for the traceability of olive oil in a supply chain is proposed. The authors discussed the value addition of blockchain in this supply chain to some extent, but there is no discussion about IoT or smart contracts in the proposed framework. Authors in [20] proposed an IoT-based framework to guard agriculture farms against animals throughout the life cycle of crops. This IoT model detects animals and activates a repelling and notifying system (RPS), which produces human-safe ultrasonic waves to repel them. The RPS information is then communicated to other

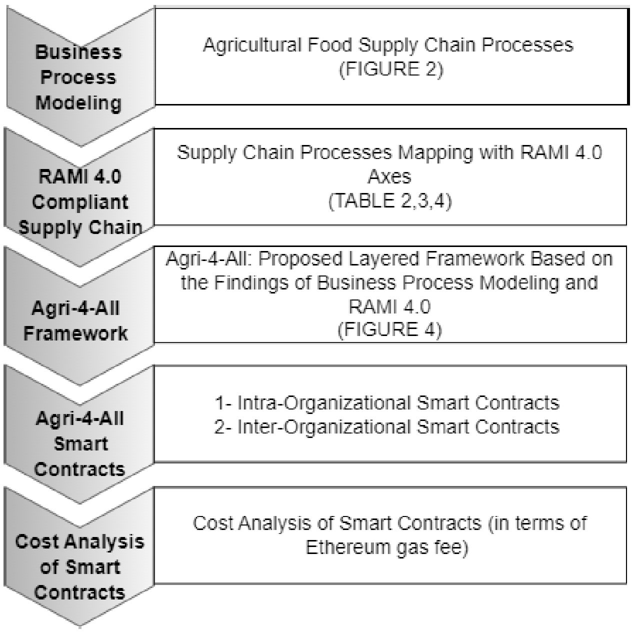

FIGURE 1. Methodology.

supply chain stakeholders with the help of a blockchain. No use of smart contracts is discussed in the paper. In [21], authors proposed a blockchain- and smart contract-based detailed framework for the traceability of soybeans in a supply chain. The authors developed Ethereum smart contracts for tractability but did not highlight the use of IoT. Authors in [22] highlighted the ways in which blockchain can improve traditional supply chains. But the authors have not discussed the role of IoT or smart contracts. The authors in [23] proposed a blockchain and IoT-based traceability system for food safety but did not provide technical details about the smart contracts and IoT in the proposed model.

We notice that none of the studies in Table 1 has focused on IoT, blockchain, smart contracts, and Industry 4.0 altogether in their conceptual frameworks. Our proposed framework aims at comprising IoT, blockchain, and smart contracts in a comprehensive fashion while being compliant with Industry 4.0 at the same time.

III. METHODOLOGY

The research methodology of the paper is depicted in Figure 1. The technology-oriented information about the agricultural supply chain is extracted from a BPMN model, as shown in Figure 2. We observe that the agricultural supply chain is comprised of two types of processes: intra-organizational processes within an organization and inter-organizational processes between supply chain organizations. Both types of processes can be automated with the help of smart contracts and are distinguished in the BPMN model with dotted and solid rectangles. The extracted information is then mapped on to a well-known Industry 4.0 framework, RAMI 4.0. Tables 2, 3 and 4 present the mapped information. An IoT, blockchain, and smart contract-based layered conceptual framework 'Agri-4-All' is then proposed in Figure 4. The intra-organizational and inter-organizational smart contracts are constructed for the mentioned processes. The smart contracts are then tested and a hybrid model is proposed to minimize the gas fee consumption in intra-organizational smart contracts.

IV. BUSINESS PROCESS MODEL OF AGRICULTURAL FOOD SUPPLY CHAIN

Supply chain management can be defined as delivering the right product in the right quantity to the right place at the right time to the right customers. An agriculture supply chain consists of farmers, warehouses, transporters, retailers, and customers. A smart agriculture supply chain must have IoT devices whose data could be used to automate inter- and intra-organizational processes.

In this section, a smart agriculture supply chain model is designed using Business Process Modeling Notation (BPMN) [38]. The BPMN model fetches all of the major processes in farming, warehousing, transportation, and retailing where IoT, blockchain, and smart contracts could play a role. The business process model is shown in Figure 2.

A. FARMING

Farming is the primary and essential step of food production in the form of fruits, vegetables, and crops. Until harvesting, an IoT-based smart monitoring system monitors the field and crops. A smart monitoring system helps in providing timely information about field maintenance, fertilization, and if there is a need for pesticides, herbicides, insecticides, or fungicides. This system also updates the perfect harvesting time based on the grain, fruit, or vegetable moisture level. Alerts generated by sensors and the actions taken based on these alerts can be stored on the blockchain for customer satisfaction.

B. WAREHOUSING

Warehousing means storing goods or products that will be sold or distributed. For a small business, warehousing can be done in a room, garage, or basement. But for warehousing in a larger business, one must rent or own a building designed for storage. Like smart farming, IoT and blockchain could play a vital role in smart warehousing. Based on the nature of the product, the temperature, light, and humidity are controlled in the warehouses using an IoT sensor-based smart storage system. Sensor alerts and actions taken in smart storage systems should be recorded on the blockchain.

C. TRANSPORTATION

Transportation/logistics means distributing the goods from warehouses to shops or retailers. The products from warehouses are transported using trucks, rails, ships, and planes. Some products need a controlled environment, so monitoring the temperature, light, humidity, and other necessary factors during the transportation is necessary. IoT and smart contracts could play a vital role in monitoring the temperature, light, and humidity during the transportation of goods. A smart

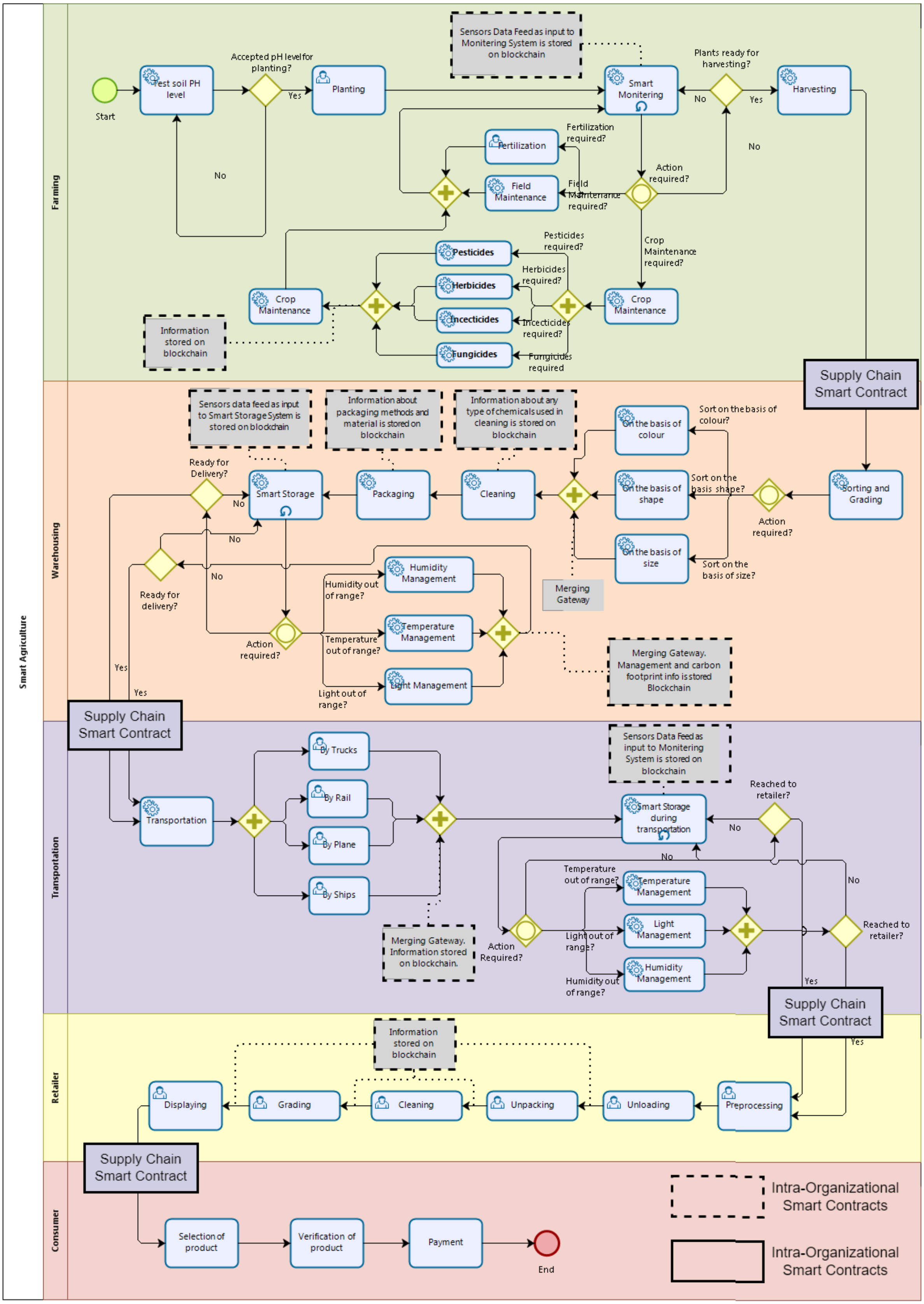

FIGURE 2. **Business process model of agricultural supply chain.**

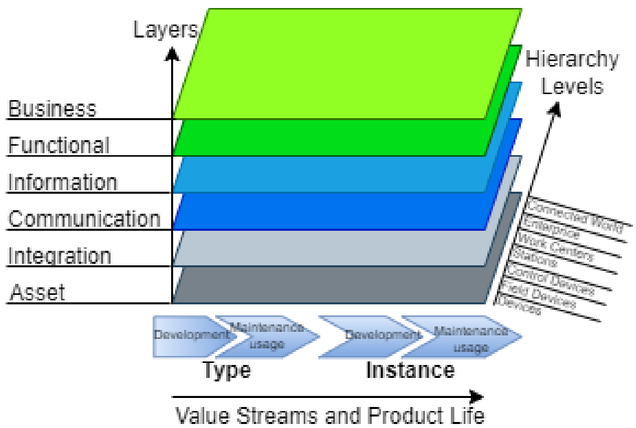

FIGURE 3. RAMI 4.0 reference model.

storage system similar to warehousing can monitor and control the desired factors and ensure the safety and quality of products during the transportation phase.

D. RETAILING

Once the products reach the retailer, they are unloaded, unpacked, cleaned, and graded based on customer demands. All the pre-processing information could be stored on the blockchain for better transparency.

The customers can select and verify the product with the help of the provenance property of the blockchain, as the necessary supply chain information about the product is stored on the blockchain.

We have highlighted the intra-organizational processes in each organization with dotted rectangles and the inter-organizational processes with solid rectangles in Figure 2. As the sensors' data in every phase of the supply chain are very important, we have demonstrated the role of intra-organizational solidity smart contracts that can facilitate the stakeholders' ability to put and get the sensor data on a Ganache blockchain network.

V. SMART AGRICULTURE IN CONTEXT OF INDUSTRY 4.0

Reference Architectural Model Industrie 4.0 or simply RAMI 4.0 [10] is a three-dimensional model which addresses the Industrie 4.0 [39], [40] processes in a structured manner. RAMI 4.0 maps all the participants involved in the connected industry on its three axes: layers, hierarchy levels, and product life cycle & value stream. A typical RAMI 4.0 reference model is given in Figure 3. The fetched information in the BPMN model is aligned with the RAMI 4.0 axis in this section.

A. AXIS I: LAYERS

There are six layers in axis I of RAMI 4.0. These layers of the vertical axis define the decomposition of a system into its properties. In Table 2, all the layers of RAMI 4.0 and their implications for smart agriculture are elaborated.

From the BPMN model, any IoT-enabled vegetable, crop, or fruit comes under the asset layer. Other important layers are the information and functional layers, in which decisions are made with the help of smart contracts and information is stored on the blockchain for tracing and transparency. The related information that comes from the BPMN model to the AXIS I layers is highlighted with bold characters in Table 2.

TABLE 2. RAMI 4.0 axis I – layers.

Layers	Description	RAMI 4.0 Layers Detail in Smart Agriculture
Business Layer	Business strategy, business environment, business goals	Price strategies, **cost analysis**, profit and Loss
Functional Layer	Production rules, processing, system control	Smart farming, smart warehousing, smart transportation etc
Information Layer	Necessary data, execution of event-related rules, formal description of rules, event pre-processing	**Decoding of the sensor's data, decisions rules (Smart Contracts), information storage on blockchain**
Communication Layer	making the information from asset and integration layers to upper layers	ZigBee [41], Bluetooth, Wibree [42], WiFi, 5G [43]
Integration Layer	Transition from real to digital world, assets in the form which can be processed by computer, events generated from assets	Tag readers, RFID readers, barcode readers
Asset Layer	Physical things in the world, documents, diagrams, archives	Agricultural food products with readable tags, RFID chips, IoT sensors, products manual

B. AXIS II: HIERARCHY LEVELS

There are seven hierarchy levels on axis II of RAMI 4.0. These levels describe different functionalities within the factory. In Table 3, all the hierarchical levels of RAMI 4.0 and their implications for smart agriculture are elaborated.

From the BMPN model, it is evident that IoT, blockchain, and smart contracts are the main pillars of a smart supply chain system, and in AXIS II, the control devices, stations, work centers, enterprises, and connected world form a hierarchy that deals with the related IoT sensors' information and its storage on a common blockchain system. A mapping

TABLE 3. RAMI 4.0 axis II – hierarchy levels.

Hierarchy Levels	Description	RAMI 4.0 Hierarchical Levels Detail in Smart Agriculture
Connected World	Interlink between stakeholders, suppliers, customers, and products, interlink between all the systems involved in production	**IoT devices and supply chain stakeholders based blockchain network**
Enterprise	Business management software, production planning, service delivery, marketing and sales, financial modules, retail	**Blockchain and smart contract based system for order information, delivery status, item descriptions, product statistics**
Work Centers	Manufacturing information, defines the production state, renovation of raw materials to refined goods	**Blockchain based storage**
Stations	Activities to examine the operation of events and processes	**Examination of smart contracts and smart contract-based systems**
Control Devices	Brain of manufacturing, programmable logic controller, control systems, and GUI	**Smart Contracts and Smart Algorithms**
Field Devices	Electronic devices used for detecting and identifying components	Sensors, actuators, tags, and cameras
Product	A factory product	Vegetables, fruits, crops, and other consumable agricultural food products

of information from the BPMN to AXIS II of RAMI 4.0 is provided in Table 3.

C. AXIS III: LIFE CYCLE AND VALUE STREAM

The horizontal axis shows the product life cycle based on IEC 62890 [44]. Table 4 shows the life cycle and value stream of smart agriculture. This axis deals with the actual supply chain system.

TABLE 4. RAMI 4.0 axis III – smart agriculture life cycle and value stream.

Type		Instances	
Development	Maintenance Usage	Production	Maintenance Usage
Land preparation, and real-time crop and atmosphere monitoring using sensors	**Field and crops Maintenance, pest and herb control, fertilization to maintain crop life and health, the adaptation of latest technologies, i.e., blockchain, IoT and smart contracts**	Crop, fruit or vegetable identification using RFID or other readers	Information manual of an agricultural product

VI. AGRI-4-ALL: A LAYERED FRAMEWORK FOR SMART AGRICULTURAL SUPPLY CHAINS IN INDUSTRY 4.0

Section V highlights the need of a systematic framework for the agricultural supply chain that utilizes latest technologies to fill the gaps in traditional supply chain systems. For this purpose, we propose a disruptive technology-based multi-layered framework depicted in Figure 4.

A. ASSET LAYER

This layer deals with the actual assets, i.e., IoT-equipped crops, fruits, and vegetables, through their journey in the supply chain. IoT devices attached to the assets help capture the information, i.e., the current state and movement of the assets in a supply chain.

B. COMMUNICATION LAYER

To connect IoT devices with the infrastructure, we need communication protocols, i.e., ZigBee, LoRaWAN, SIGFOX, Bluetooth, and 5G. Communication protocols should be chosen carefully; they depend on many factors. One can choose 5G for fast communication or Bluetooth as a communication protocol if deployed sensors are close to each other.

C. INTEGRATION & SERVICE INFRASTRUCTURE LAYER

It is one of the most important layers of the framework. A blockchain system including smart contracts, consensus protocols, membership, and events is designed and developed here. Here, blockchain stakeholders' authentication and authorization are also done. Moreover, stakeholder and goods certificates are also awarded.

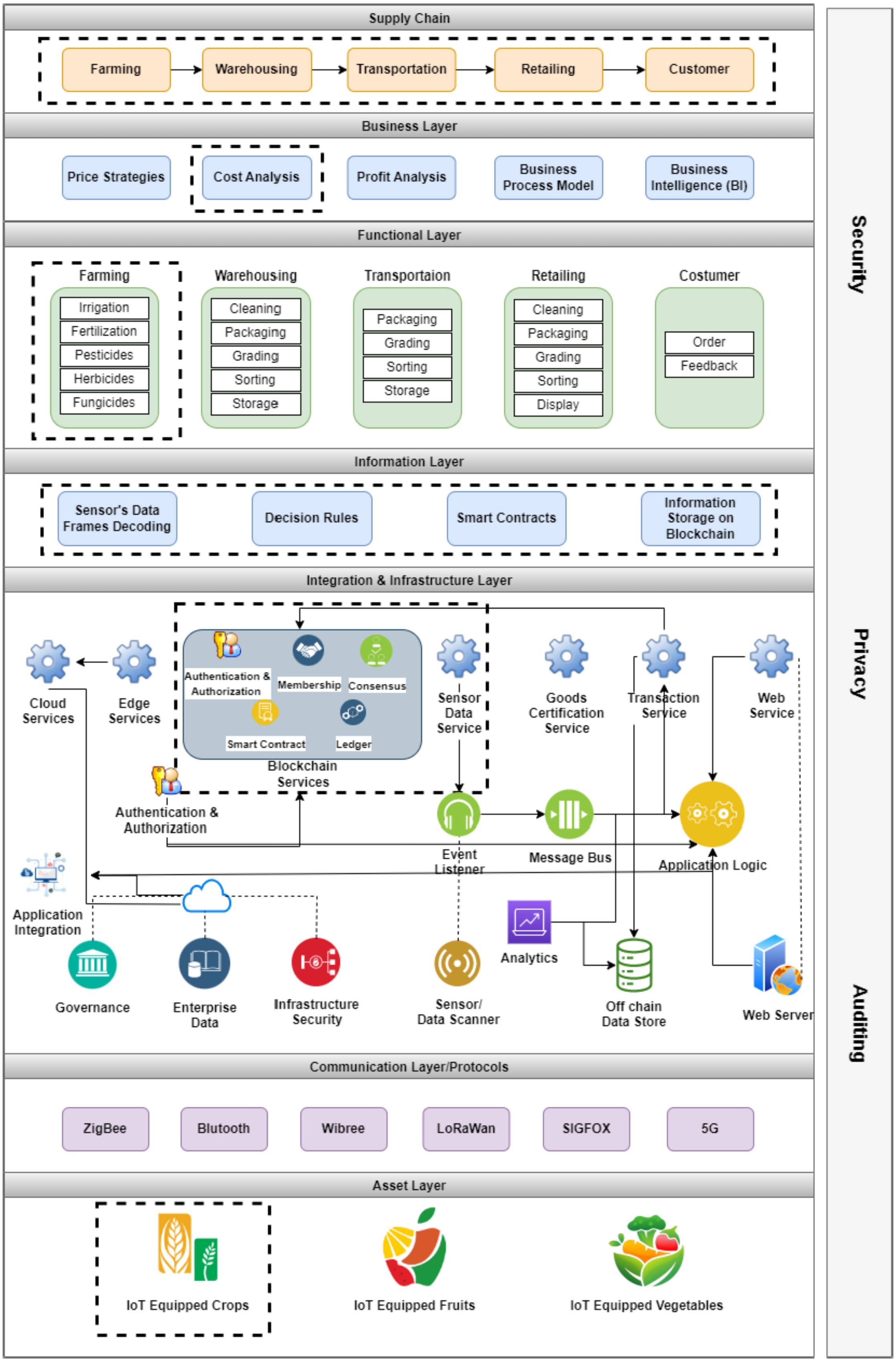

FIGURE 4. Agri-4-All: Framework for smart agriculture supply chain.

Blockchain, a digital and decentralized ledger, is used to keep the transaction records between the blockchain nodes. Public [45], private [45], and permissioned blockchain [46] systems provide different features for different types of businesses. If parties want to maintain their privacy, the HyperLedger Fabric-based blockchain system is appropriate because it has a channel feature that allows multiple parties to communicate privately through a channel [47]. Ethereum [48] is another blockchain ledger that allows smart contracts and transactions to be stored on it.

Smart contracts [49] are translations of an agreement between a buyer and seller in a programming language. Smart contracts are auto-executable programs that are stored on a blockchain. With the help of smart contracts, parties can do business without the involvement of a third party, so smart contracts eliminate trust issues. Smart contracts are also helpful in automating the business processes of an organization.

Consensus is a method in which all the peer nodes of the blockchain network agree on the present state. Bitcoin uses a Proof of Work consensus protocol, whereas Ethereum makes use of both Proof of Work and Proof of Stake algorithms. Other consensus protocols are Proof of Authority, Proof of Burn, Proof of Elapsed Time, Byzantine Fault Tolerance, and Practical Byzantine Fault Tolerance. In our previous research work [9], we presented a survey on various consensus protocols.

Membership Service Provider is a blockchain component used for identity management [50]. It is used to provide and check the membership of the clients who are intended to join a blockchain network.

Authentication and authorization are essential parts of any blockchain-based system. Authentication means checking whether the entity that is trying to access a system is authentic or not, and authorization means checking the permissions that are given to users to access resources [51].

This layer also deals with service infrastructure, i.e., sensor data service, goods certification service, transaction service, and web service.

D. INFORMATION LAYER

This layer deals with data retrieved from IoT devices. After processing the sensor's data, different decisions are made through decision rules, smart algorithms, and smart contracts. Finally, the valuable information is stored on the blockchain, which can be accessed by any node of the supply chain network.

E. FUNCTIONAL LAYER

Information about all the key functionalities of supply chain organizations and stakeholders is gathered here. Activities of farming like cultivation, irrigation, harvesting, cleaning, grading, and storing of goods at different phases to get customer feedback are performed in this layer. The activities of other agricultural supply chain organizations are also given in this layer.

F. BUSINESS LAYER

The business layer deals with business strategy, business environment, price strategy, cost analysis, profit and loss analysis, business process modeling, business intelligence, and business goals.

G. SUPPLY CHAIN

This is the main agriculture supply chain, where a product is produced on agricultural farms and reaches the customer by moving through warehouses, transportation modes, and retailers.

H. SECURITY, PRIVACY, AND AUDITING

Security, privacy, and auditing of all the processes of all layers should be done at every stage.

It is seen that the proposed framework is aligned with the AXIS I layers of RAMI 4.0. The hierarchical levels of AXIS II of RAMI 4.0 are also accommodated in these layers, which start from the sensors deployed in a farm, warehouse, or transport vehicle to make a connected world with the help of a single, common information-sharing system, i.e., blockchain. All the sensors and stakeholders are part of this connected world, as all are connected with each other with the help of smart contracts and blockchain. AXIS III of RAMI 4.0 is actually a supply chain, which is shown in the Supply Chain layer of the framework.

VII. AGRI-4-ALL BASED CASE STUDY

We have chosen the tomato crop as a case study and analyzed its farming in detail. The soil moisture sensors, plant & leave sensors, and atmosphere and weather monitoring sensors of a tomato farm continuously give their values to intra-organizational smart contracts through a trusted gateway. Each inter-organizational smart contract then calculates the average sensor values and updates the intra-organizational blockchain regardless of the decision to start or stop any system, i.e. the irrigation system. The farmer of the tomato crop can also access an inter-organizational smart contract to sell his products and the transactions generated through this smart contract are stored on a separate inter-organizational blockchain. The inter-organizational smart contract and blockchain can also be accessed by other supply chain stakeholders.

The layer-by-layer breakdown of the tomato crop case study, mapped on the functions and features of each Agri-4-All layer, is shown in Figure 5. IoT-equipped tomato crop farms come under the asset layer. The communication layer helps in forwarding the sensors' data to the intra-organizational smart contracts, which are created and tested in the integration and infrastructure layer. The functional layer is responsible for creating the smart contract functions, i.e., irrigation, fertilization, and herbicide monitoring functions. The successful testing of smart contracts generates transactions that are stored on an intra-organizational blockchain ledger, which is created

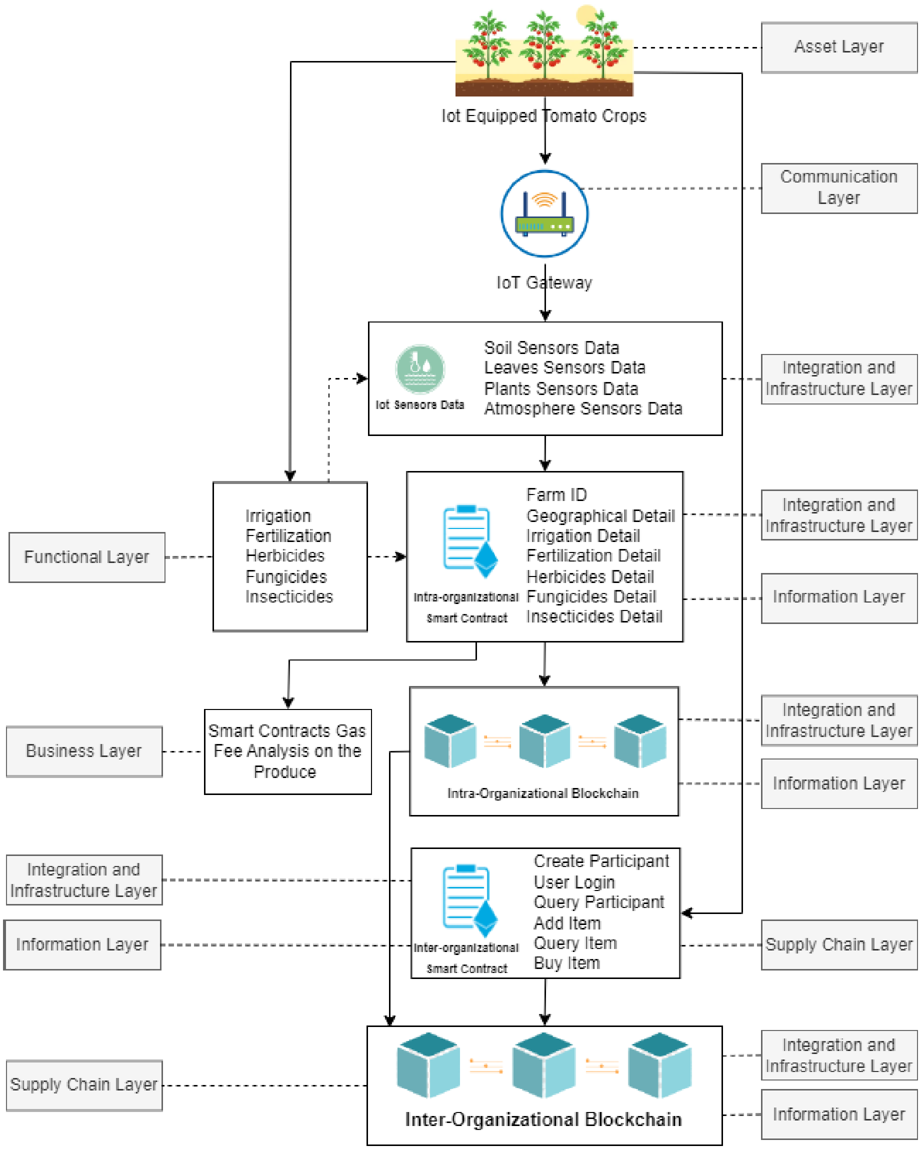

FIGURE 5. Agri-4-All based case study.

in the integration and infrastructure layer. For Farmers to sell crops, they need to access the inter-organizational smart contracts and blockchains, and the integration & infrastructure layer is responsible for the creation of inter-organizational blockchains and smart contracts. The information layer is responsible for storing valuable information on blockchain ledgers. Cost analysis, pricing strategies, and other business-related analyses are performed in the business layer.

Figure 4 likewise uses dotted rectangles to highlight the tomato crop-related information in the Agri-4-All layers.

VIII. EXPERIMENTS WITH AGRI-4-ALL SMART CONTRACTS

The experimental setup consists of two blockchains and two types of smart contracts. We named them intra-organizational and inter-organizational blockchains and smart contracts. Each organization in the supply chain has its intra-organizational blockchain, which can be updated by the execution of intra-organizational smart contracts. The information stored on the intra-organizational blockchain is then forwarded to the inter-organizational blockchain for transparency and traceability throughout the supply chain. When supply chain stakeholders have to interact with each other, they must have access to the inter-organizational blockchain. If stakeholders are interested in buying or selling a food product, they can use an inter-organizational smart contract that includes *addItem()*, *queryItem()* and *buyItem()* functions for these purposes. A detailed view of smart contracts and smart blockchain-based systems is given in Figure 6.

The experimental phases are divided into three parts: writing, deploying, and testing intra- and inter-organizational smart contracts. In these experiments, we have modelled farming-related intra-organizational smart contracts. Similar

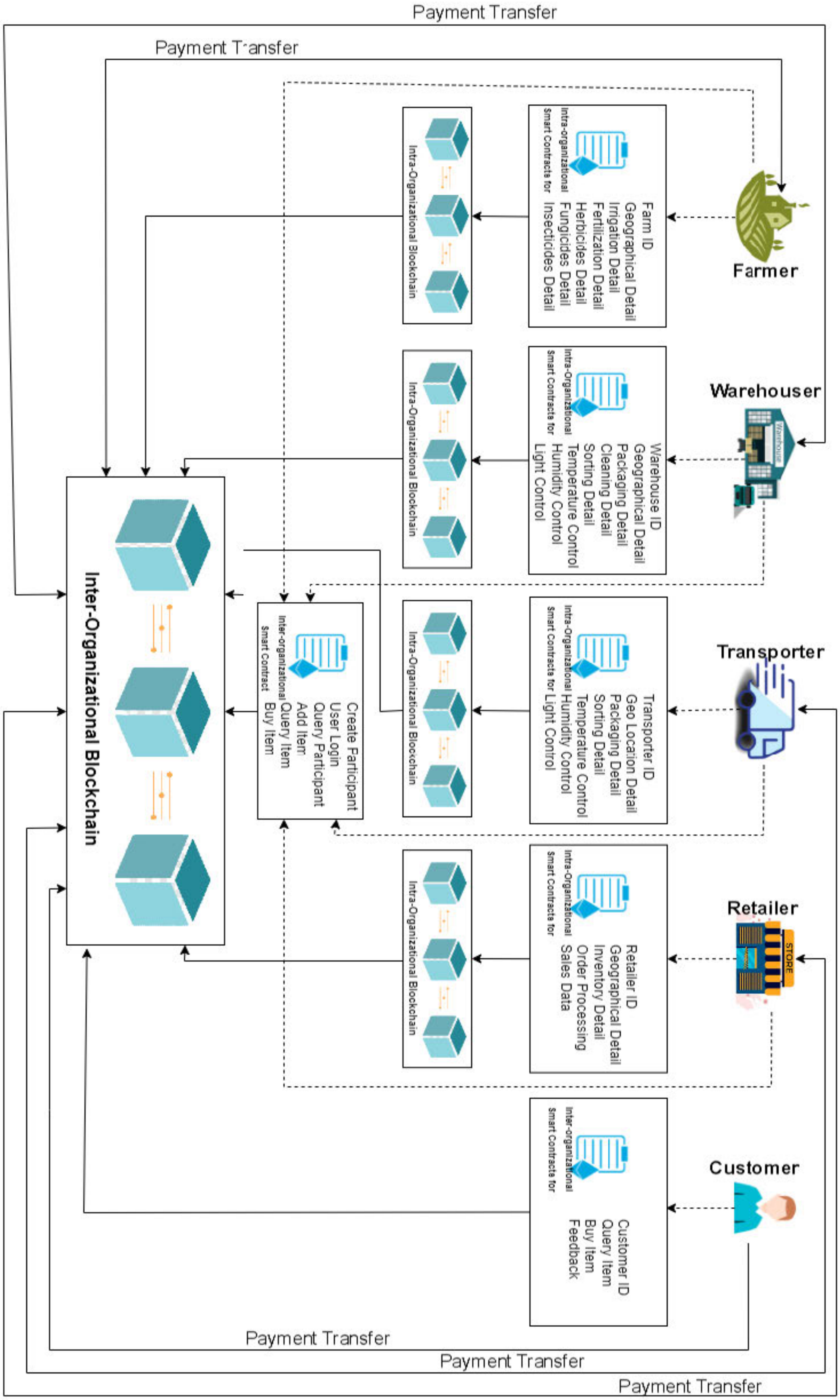

FIGURE 6. Inter and intra-organizational blockchain & smart contract infrastructure.

TABLE 5. Appropriate soil moisture levels by soil types [52].

Soil Type	Irrigation Not Required	Irrigation Required
Fine (Clay)	80-100	60-80
Medium (Loamy)	88-100	70-88
Coarse (Sandy)	90-100	80-90

contracts could also be written and deployed for warehousing, transportation, and retailing purposes.

A. SMART CONTRACTS' CONSTRUCTION

We discuss the Smart contracts' construction in two sections: intra- and inter-organizational smart contracts.

1) INTRA-ORGANIZATIONAL SMART CONTRACTS

Intra-organizational smart contracts are only used to update the intra-organizational blockchains with information related to the internal processes of an organization. These smart contracts are highlighted with dotted rectangles in the BPMN model in Figure 2. These smart contracts play a pivotal role in realizing Decentralized Autonomous Organizations (DAOs). A DAO runs solely on code without human intervention.

Consider farming in Figure 2: it could be automated using IoT and smart contracts. In smart farming, intra-organizational smart contracts continuously receive the data feeds from all deployed sensors and update the intra-organizational blockchain status with the latest information. Similarly, the transactions related to warehousing and transportation may also be stored on a separate blockchain for better transparency of its internal processes and operations.

As shown in Table 5, agricultural products typically require three types of soils [52]. And usually, the tomato crop is grown in loamy soil, which requires irrigation if the soil moisture level falls between 70-88.

Algorithm 1 explains the workings of the intra-organizational smart contract of the irrigation system of tomato crops. ASM_Value represents the average soil moisture sensor value in the algorithm.

Algorithms for fertilization, pesticides, etc. work similar to Algorithm 1.

2) INTER-ORGANIZATIONAL SMART CONTRACTS

The supply chain can be considered as a network of DAOs as these DAOs work together across the supply chain system. When these DAOs join a secured and transparent blockchain system, they can do business with the help of smart contracts.

The inter-organizational smart contract is used to buy and sell agricultural food. If any supply chain stakeholder, i.e., a farmer or warehouser, wants to access this smart contract, he must register and login to the blockchain system. On registering, he is assigned a membership through the integration and infrastructure layer of the Agri-4-All, while login authentication and authorization are also done through the same layer.

Algorithm 1 Smart Contract Based Irrigation

Result: Decision to Start/Stop Irrigation System and Update the Blockchain

ASM_Value =

$$(\sum_{i=1}^{n} Sensor_i)/n$$

```
Irrigation_Status = <START | STOP | IDLE>;
k1 = 70;
k2 = 88;
k3 = 100;
if k1 < ASM_Value < k2 then
    Irrigation_Status = START;
    Sensors_Value = ASM_Value
if k3 > ASM_Value > k2 then
    if Irrigation_Status = START then
        Irrigation_Status = STOP;
        Sensors_Value = ASM_Value
    else
        Irrigation_Status = IDLE;
        Sensors_Value = ASM_Value
```

After registering and logging in, the stakeholders can add the food items with sales prices to the blockchain ledger by accessing an inter-organizational smart contract function, *AddItem()*. Agricultural food items are assigned certification through the integration and infrastructure layer of Agri-4-All. Any other user can query the status of the item, i.e., whether it is for sale or not, through the *QueryItem()* function, and buy the item with the help of *BuyItem()* function. Once all the conditions are met, i.e., the product is delivered on time, and the buyer has enough currency in his wallet, the same function automatically transfers the funds to the seller's account and changes the ownership of the product to the buyer, as both the buyer and seller do have unique addresses on the blockchain.

All the transactions related to *CreateParticipant()*, *AddItem()* and *BuyItem()* are stored on the inter-organizational blockchain as all the functions change the state of the blockchain system. Functions like *QueryParticipant()* and *QueryItem()* do not change the state, so they do not consume any gas.

The inter-organizational smart contracts may implement at least these functions:

- ***createParticipant()***: This function receives the participant's name, password, address, and role as parameters and registers him in the system with a unique id. A participant structure and an array of data types are used to store a participant's data. The roles of participants are farmer, warehouser, retailer, and customer.
- ***queryParticipant()***: This function receives a unique id and returns the details of the participants.
- ***userLogin()***: This function takes the id, name, and password of a participant, and in the case of correct infor-

FIGURE 7. Smart contracts' deployment.

TABLE 6. Soil moisture sensors values of a farming field: When irrigation required.

Soil Moisture Sensors	Soil Moisture Value
Sensor 1	100
Sensor 2	72
Sensor 3	87
Sensor 4	90
Sensor 5	86
Sensor 6	78
Sensor 7	77
Sensor 8	73
Sensor 9	72
Sensor 10	78

mation, it gives the participant access to the functions of smart contracts.

- ***addItem()***: This function takes the item/product name and price as input and stores it in an array with a unique item id.
- ***queryItem***: This function takes a unique item as input and returns the details and status of a product. The statuses of an item could be ForSale, NotForSale, Sold, Shipped, and NotShipped.
- ***buyItem***: This function receives the item's unique id and address of the buyer and, after a few checks, changes the status and ownership of an item.

B. SMART CONTRACTS' DEPLOYMENT

We have deployed the Inter-organizational and inter-organizational smart contracts on the Ganache network using *truffle deploy* command, and the gas fees to deploy the smart contracts are computed, which is 483726 Wei 1818167 Wei, respectively. The addresses of intra-organizational (DAO) and inter-organizational (supply chain) deployed smart contracts are shown in figure 7.

C. SMART CONTRACTS' TESTING

Smart contracts testing is also divided into two sections: intra- and inter-organizational smart contract testing.

1) INTRA-ORGANIZATIONAL SMART CONTRACT's TESTING

For the testing of irrigation smart contracts, we created a scenario of 10 soil moisture sensors deployed in a tomato farm field, as shown in Table 6.

TABLE 7. Soil moisture sensors values of a farming field: When irrigation not required.

Soil Moisture Sensors	Soil Moisture Value
Sensor 1	88
Sensor 2	87
Sensor 3	85
Sensor 4	90
Sensor 5	92
Sensor 6	92
Sensor 7	88
Sensor 8	85
Sensor 9	92
Sensor 10	93

The average soil moisture computed by the information in Table 6 at a given time is 81.3. From Table 5, it is clear that irrigation is required in this field. The intra-organizational smart contract receives the sensor data, calculates the average, and starts the irrigation system. This smart contract updates the blockchain on a daily basis, regardless of the decision to start or stop the irrigation system. The same methodology is applied to all other sensors deployed in an agricultural field, but different smart contracts are used to update the blockchain for each type of sensor.

The intra-organizational smart contract for this scenario consumes 95,952 Wei in gas fees to update the status of the blockchain.

If we update the blockchain with the soil moisture level on a daily basis (after 24 hours) then a total of 14,392,800 Wei of the gas fee per season (5 months) is consumed for one farm field. A similar amount of gas fee should also be consumed for the fungicides, pesticides, and herbicide-related sensors data. So a combined gas fee of 71,964,000 is required to update the blockchain about soil moisture, fertilization detection, and plants & leaves sensors on daily basis for 5 months (150 days).

Total gas fee consumption for 150 days:

$$150 * 95,952 * 5 = 71,964,000 \quad (1)$$

whereas 1,000,000,000,000,000,000 Wei = 1 Ethereum

Blockchain systems face scalability issues with the increase in their size, so it's recommended to update them with only high-value information. The smart contracts should only update the blockchain with high-value information, i.e. when actual irrigation is applied. To address this issue, we tested our hybrid approach.

To understand the working of the hybrid approach, let's consider another scenario of 10 soil moisture level sensor data deployed in a Tomato field in Figure 7.

The average value of all sensors shown in Table 7 is 89.2. From Table 5, it is clear that irrigation is not required in that field. So it's unnecessary to update the blockchain, as it could create a blockchain scalability issue and consume additional gas fees.

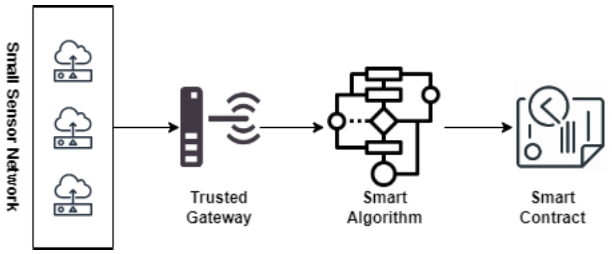

FIGURE 8. Hybrid model for smart farming.

To overcome the high gas fee and scalability issues, we proposed a hybrid approach of smart algorithms coupled with smart contracts, as shown in Figure 8. We suggest that smart algorithms should run on an internal system to make decisions, i.e., start/stop the irrigation system. And smart contracts should update the blockchain only with high-value information, i.e., sensor values and irrigation system status. In the hybrid approach, the decision to start/stop the irrigation system is carried out by the smart algorithm and the smart contract subsequently updates the blockchain with the current status of the irrigation system and sensor values.

Algorithm 2 explains the workings of a hybrid model for irrigation systems. For fertilization, fungicides, pesticides, and herbicides, the same type of model should be applied separately. ASMA_Value represents the average soil moisture sensor value gathered at any time interval.

Algorithm 2 Smart Algorithm for Hybrid Model

Result: Decision to Start/Stop Irrigation System
ASMA_Value =

$$(\sum_{i=1}^{n} Sensor_i)/n$$

IrrigationS_Status = <START | STOP | IDLE>;
SmartContract_Status = <EXECUTE>;
k1 = 70;
k2 = 88;
k3 = 100;
if $k1 < ASMA\_Value < k2$ **then**
  IrrigationS_Status = START;
  SmartContract_Status = EXECUTE
if $k3 > ASMA\_Value > k2$ **then**
  if $IrrigationS\_Status = START$ **then**
    IrrigationS_Status = STOP;
    SmartContract_Status = EXECUTE
  else
    Do Nothing

Algorithm 3 simply depicts a smart contract dependent on a smart algorithm. This Smart Contract just updates the blockchain with the current state of the irrigation system and average sensor values based on the decision made by the smart algorithm.

Algorithm 3 Smart Contract for Hybrid Model

Result: Update the Blockchain with Irrigation_Status and Sensor_Value
Irrigation_Status = IrrigationS_Status;
Sensors_Value = ASMA_Value;

TABLE 8. Soil and crop requirements for tomato.

Requirement	No. of Application Required per Season
Irrigation	18 Times [53]
Fertilization	10 Times [54]
Fungicides	20 Times [55]
Pesticides	3 Times [56]
Herbicides	3 Times [57]

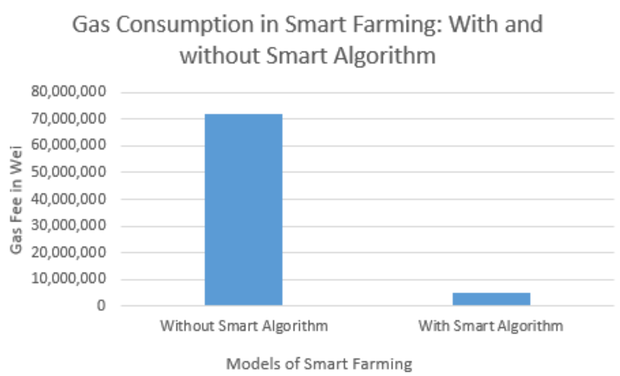

FIGURE 9. Gas fee in smart irrigation: With and without smart algorithm.

Table 8 gives details about the maximum number of irrigation, fertilization, fungicide, pesticide, and herbicide applications the tomato crop requires per season.

So by using a hybrid approach, instead of updating the blockchain daily (750 times per season), the blockchain will be updated just 54 times per tomato season (5 months), as shown in Table 8.

Total gas fee consumption if we use a hybrid model is computed in Equation 2:

$$54 * 95,952 = 5,181,408 \tag{2}$$

With the introduction of smart algorithms, the smart contract only updates the blockchain 54 times, which not only saves gas fees but also helps in solving the scalability issue of the blockchain. The same hybrid model can also be used in any other DAO, i.e., warehousing, transportation, and retailing. Figure 9 shows the comparison of gas consumption in the case of tomatoes with and without the introduction of the smart algorithm.

For the minimal cost of 5,181,408 Wei, the farmers can add significant value to their products. Not only does it add to transparency, but it also helps satisfy customers about the authenticity of the product. So using a blockchain system to update the processing of a product within an organization is a win-win for buyers and sellers in a supply chain.

TABLE 9. Costs of SupplyChain smart contract functions (Wie).

Function	Execution Fee
addItem()	118682 Wei
queryItem()	0 Wei
buyItem()	205710 Wei
createParticipant()	131107 Wei
queryParticipant()	0 Wei

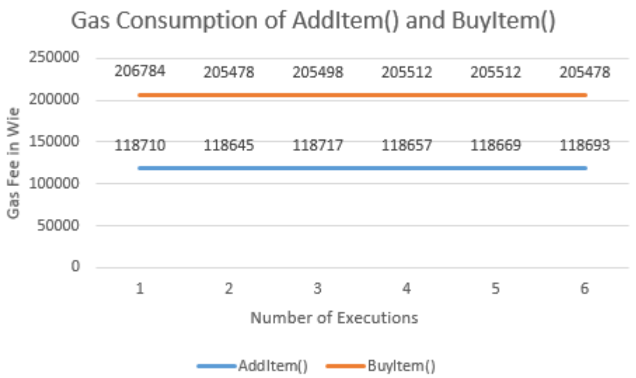

FIGURE 10. Gas fee consumption of AddItem() and BuyItem().

TABLE 10. Complexity analysis of inter-organizational smart contract functions.

Function	Complexity
addItem()	O(1)
createParticipant()	O(n)
buyItem()	O(n log n)

2) INTER-ORGANIZATIONAL SMART CONTRACT's TESTING

Table 9 demonstrates the average gas fee consumption of the inter-organizational smart contract. *addItem()*, *buyItem()* and *createParticipant()* functions consume gas fees as these functions change the state of the blockchain by creating and changing the information related to a new item and participant. The gas fees are computed by executing the functions ten times and taking the average of the gas fees consumed by each function.

If we compare the *AddItem()* and *BuyItem()* functions, we can observe that there is a big difference in the energy consumption of these functions. This is because *AddItem()* just used to add a new product with his sales price on the blockchain. While *BuyItem()* has a loop and a conditional structure in its functionality, it adds an extra cost to execute this function of the smart contract. Figure 10 shows the difference in gas fee consumption of both functions.

We conducted a complexity study of all the *addItem()*, *buyItem()*, and *createParticipant()* functions in Table 10 and Figure 11 and found that the time complexity of the *addItem()* and *createParticipant()* functions is O(1) and O(n) respectively. The time complexity of the *buyItem()* function is O (n log n).

Figure 12 displays the amount of gas used if a product is transported from a farmer to a customer. To list his produce for sale, the farmer uses the *addItem()* function. Other

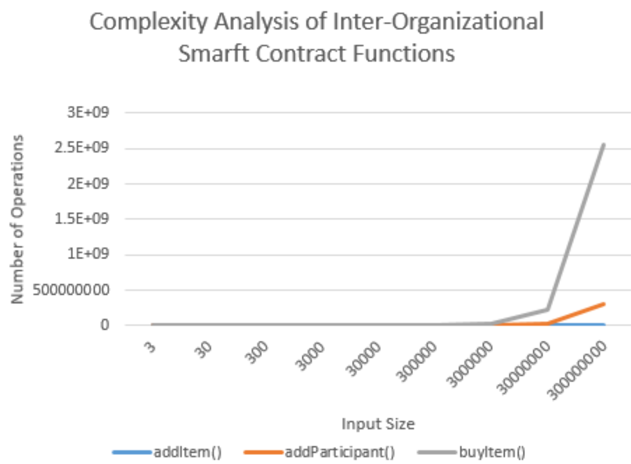

FIGURE 11. Complexity analysis of inter-organizational smart contract functions.

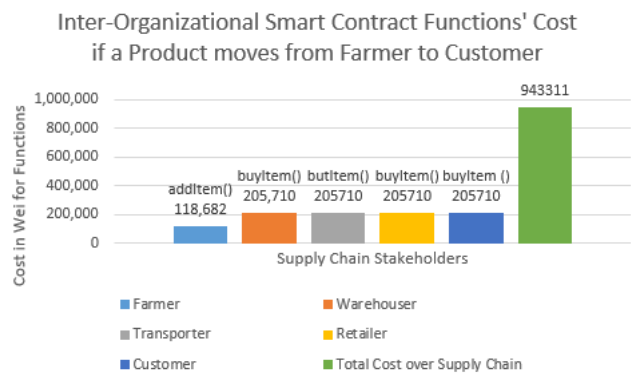

FIGURE 12. Total cost of a product movement in a supply chain: From farmer to customer.

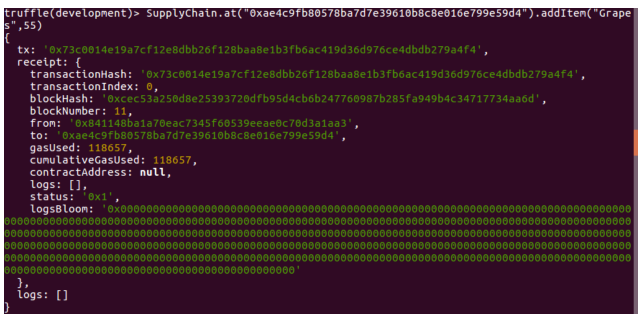

FIGURE 13. Smart contract testing using truffle console.

interested parties call the *buyItem()* function, which alters the product's ownership. The total gas cost of 943,311 Wei is minimal in comparison to the benefits that blockchain and smart contracts bring, such as transparency, immutability, and automation.

Truffle testing of *addItem()* function is shown in Figure 13. It contains all the necessary information related to the transaction generated through successful function testing, i.e., transaction address, transaction hash, block number, address of the node that invokes the function, address of the smart contracts that contain the function, and gas consumed in terms of Wie to test the function.

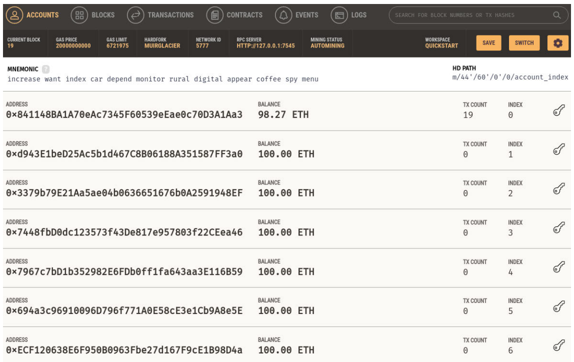

FIGURE 14. Ganache accounts.

FIGURE 15. Ganache transaction structure.

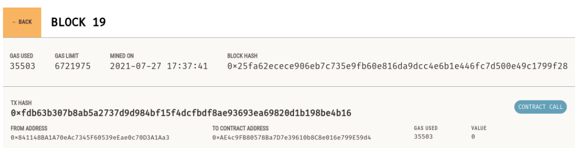

FIGURE 16. Ganache block structure.

Ganache GUI provides 10 accounts with 100 fake Ethereum, shown in Figure 14, which can be used to deploy and test smart contracts. Each account does have a private key and a record of several transactions. Ganache GUI also provides the information transaction structure shown in Figure 15. The block structure of Ganache GUI is shown in Figure 16.

IX. CONCLUSION

Traditional supply chains face limitations such as a lack of transparency, third parties' involvement, information security, and centralized information storage systems. With the advent of the latest technologies, i.e., IoT, blockchain, and smart contracts, most of these challenges can be addressed in an efficient manner. In this paper, we proposed a conceptual layered framework for the agricultural food supply chain that incorporates disruptive technologies to automate and digitize intra-organizational and inter-organizational processes of the supply chain. We performed experiments using the Ethereum smart contracts and observed that the gas fee consumption can be minimized in intra-organizational smart contracts through our improvised hybrid approach. We then reached the conclusion that with a little gas fee cost, a supply chain stakeholder can provide remarkable visibility to the customers in connection with the processing of a product across the supply chain. The limitation of our framework is that it does not address the interoperability of different types of inter-organizational blockchains and stakeholders' privacy issues in an appropriate manner. In future, we plan to work on a framework that can incorporate this interoperability issue.

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