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Blockchain Technology as a Tool to Make Supply Chains More Resilient and Sustainable

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ABSTRACT

Supply Chain Management (SCM) is a critical part of all businesses that dictates their success and customer satisfaction. The COVID-19 pandemic and other disruptions exposed critical shortcomings in SCM, such as material and labor scarcity, high freight prices, and demand forecasting complexities. These developments have called for an urgent need to explore ways to make supply chains more resilient. Digital technologies like blockchain, QR codes, and RFID tags are recognized for enhancing transparency and traceability. The paper focuses on enhancing the resilience of supply chains, emphasizing transparency and reliability. It presents a case study of a regional Australian food processing company and evaluates a blockchain-based SCM model to address its upstream supply chain and logistics issues. A smart contract of the proposed model is validated via simulation on Remix IDE. The model promotes total quality by facilitating real-time tracking for rapid fault identification, enabling timely, cost-efficient procurement of raw materials and inventory, and reducing waste. The framework enshrines the principles of the green supply chain, crucial for the SDGs of the UN's 2030 Agenda.

Keywords: *blockchain, supply chains, resilience, sustainability, traceability*

1. INTRODUCTION

In today's competitive business world, supply chain management (SCM) isn't just a backstage player anymore - it's one of the main factors fueling success and customer satisfaction. The philosophy of delivering high-quality goods and services using the best resources at an economically viable cost has been the hallmark of business good practices for ages. The procurement of these resources has been guided by supply chains, which were originally defined as a series of synchronized and related entities, processes, resources, information, and technology from the delivery of the source materials to the delivery of the finished products to customers (Closs and McGarrell, 2004). Early supply chains were largely confined to a local territory or zone or a country at least from resource procurement to product manufacture, and then subsequently to be exposed to select markets around the world. Such supply chains possessed some level of inherent reliability and trust, regulated by well-defined policies and guidelines, but the profits were low (Tokar and Swink, 2019).

New business models began to emerge in the mid-1980s to maximize profits through a reduction of costs related to material, cheap labor, logistics, etc. These models ushered in an era where manufacturing was moved offshore to countries with ready access to resources, labor, and larger consumer markets (or in closer proximity), ultimately termed the 4th era of globalization. This simultaneously saw the transformation of the multinational corporation (MNC) to a global corporation, to sell the same goods in the same way everywhere (Levitt, 1983). While globalization has seen a progressive increase in the flow of products and services across international borders, economic globalization has seen a rapid increase in the interdependence of world economics, resulting in the need for continuous expansion and integration of markets, setting off an irreversible expectation of constant expansion.

In this respect, the food processing industries are subject to several other unique challenges in establishing and maintaining reliable and robust supply chains, which are usually long and complex, and sometimes fragile as a breakdown can have detrimental consequences for environmental, social, and governance (ESG) goals. Agriculture produces needs careful and deft handling, from harvesting to packaging and transporting for downstream processing as some produce could be perishable (Salah et al., 2019). Perishability does not just result in wastage but can have serious consequences for the entire upstream (farmers) and downstream (customers) supply chain. It is imperative that businesses identify and anticipate such disruptions in a timely fashion so that waste and inventory costs are minimized simultaneously (Alkaabi et al., 2020).

From a best practice perspective (Chen and Chen, 2023), a supply chain typically includes real-time inventory and production planning, current technological support, reliable and trustworthy suppliers, robust vendor, and customer relations. Further, there is a paramount need for an efficient product distribution network to entail the least cost of production, faster product delivery, minimal inventory costs and management, increased sales, competitive advantage, and customer satisfaction.

Supply chains have advanced and become more complex with changes in business models over the decades. The advancement of not just manufacturing technology but also information technology and its management, generation, storage, and seamless transmission and access across the world has had a great impact on economic globalization. Despite its benefits of transforming our lives, it has its challenges and perils, often becoming susceptible to the butterfly effect. These have been aptly demonstrated by the COVID-19 pandemic (Shetu and Karim, 2023), wars, and in some cases, the role of climate change which have widely disrupted supply chains across the world, inevitably leading to macroeconomic imbalances across the globe (Kova´cs and Falagara Sigala, 2021). Such disruptions and their socio-economic impacts have brought into focus the apparent lack of robust and reliable supply chains in nearly all types of industries.

While traditional supply chains focus on production and delivery, the advancements toward Industry 4.0 and the digital world empowered by modern systems prioritize sustainability, data security, and privacy alongside economic efficiency leading to an emerging paradigm shift (Abdul Rahman *et al.*, 2023). This requires a holistic technological approach encompassing environmental and social considerations throughout the entire life cycle. However, complex supply chains face security vulnerabilities that threaten their integrity.

The artful assembly of existing technologies, such as cryptographic hashing functions, decentralized networks, and consensus mechanisms, constituted the foundation of blockchain technology in 2008 and led us into a whole new digital era (Nakamoto and Bitcoin, 2008). Although the technology was initially used in fiscal applications, it quickly proved to be highly promising. Consequently, during its evolution over three generations, researchers began exploring its potential application across various domains, including financial services (OBAID *et al.*, 2021), logistics (Goyal *et al.*, 2022), identity management (Das *et al.*, 2023), Internet-of-Things (IoT) (Issa *et al.*, 2023), insurance services (Trivedi, 2023), food industry (Singh and Sharma, 2023), rural development (Enayati *et al.*, 2024), health and well-being (Mardiansyah *et al.*, 2022), and telecommunication (Enayati *et al.*, 2022) among others. these unique attributes and merits of blockchain make it valuable for a diverse range of applications.

Blockchain technology serves as a robust security measure for supply chain management, offering a decentralized and tamper-resistant platform for storing and exchanging crucial information across various supply chain layers. It enables the recording of diverse product information, spanning from raw materials and their origin to production, logistics, distribution, and sales. The immutability of blockchain ensures that once information is recorded, it cannot be altered without consensus, enhancing the reliability of the entire supply chain data ecosystem.

This study aims to address the challenges faced by an Australian food processing company in its supply chain management system. Consequently, it proposes a conceptual blockchain-based framework for real-time product tracking in supply chains, which can be generalized to other use cases for addressing the urgent need for increased resilience exposed by challenges such as the COVID-19 pandemic and the war in Ukraine (Israfilov *et al.*, 2023; Sodhi and Tang, 2021). This framework incorporates the principles of the green supply chain such as resource efficiency, environmental responsibility, transparency, collaboration, and innovation, serving as a blockchain-based innovative solution and communication hub between various stakeholders, both within and external to a supply chain. Its emphasis on transparency, reliability, and coordination among stakeholders, aligns with the UN's 2030 Agenda sustainable development goals (Nations, 2015).

Utilizing a qualitative research methodology the study answers the following questions:

- **RQ1**: How can the vulnerabilities of the complex supply chains in the food processing industries in Australia be overcome using blockchain technology?
- **RQ2**: What blockchain-based solution can tackle the identified challenges in the food supply chain management system under study?

The structure of the paper is organized as follows: In Section 2, the paper delineates the fundamental aspects of an ideal sustainable supply chain management system and elucidates how blockchain technology can serve as a robust security measure. This section also proposes a blockchain-based supply chain management system. Section 3 provides an overview of the case study and outlines the methods employed to address the research questions. The proposed solution to the identified challenges faced by the company in the study is presented in Section 4. Section 5 provides the simulation of a smart contract from the proposed model. Finally, Section 6 concludes the paper by summarizing its key points and discussing possible future directions for this study.

2. LITERATURE REVIEW

2.1. The Basic Facets of a Supply Chain

It is important to understand the fundamental nature of supply chains before trying to optimize or transform any system. **Figure 1** shows a typical supply chain which can be construed as an orderly system of manufacturing and selling tangible and intangible products and services to consumers. It consists of suppliers, producers, distributors, vendors, and retailers involved in developing, marketing, financing, and delivery of final products, facilitating the transfer of data/information and cash flow as well, at strategic points. It is seen that the complexity of a supply chain is a function of the number and levels of interdependencies at every stage of the supply chain. Interdependencies, principally, dictate the reliability of each stage and, in the process, its overall integrity and robustness, which in turn, are a function of the product/service integrity and quality. Since modern supply chains are highly information-intensive and computerized, they are highly susceptible to a range of security concerns, since information sharing is a critical aspect of the whole business process. Integrating sustainable practices has gained paramount importance amid the optimization of supply chains. Sustainable supply chain systems aspire not only to enhance operational effectiveness but also to mitigate their adverse impacts on the environment while upholding ethical standards (Afghah *et al.*, 2023). The demand for robust, eco-friendly, and socially responsible systems is becoming more evident as supply networks evolve, and achieving a harmonious balance among economic objectives, and ecological and social considerations is increasingly imperative.

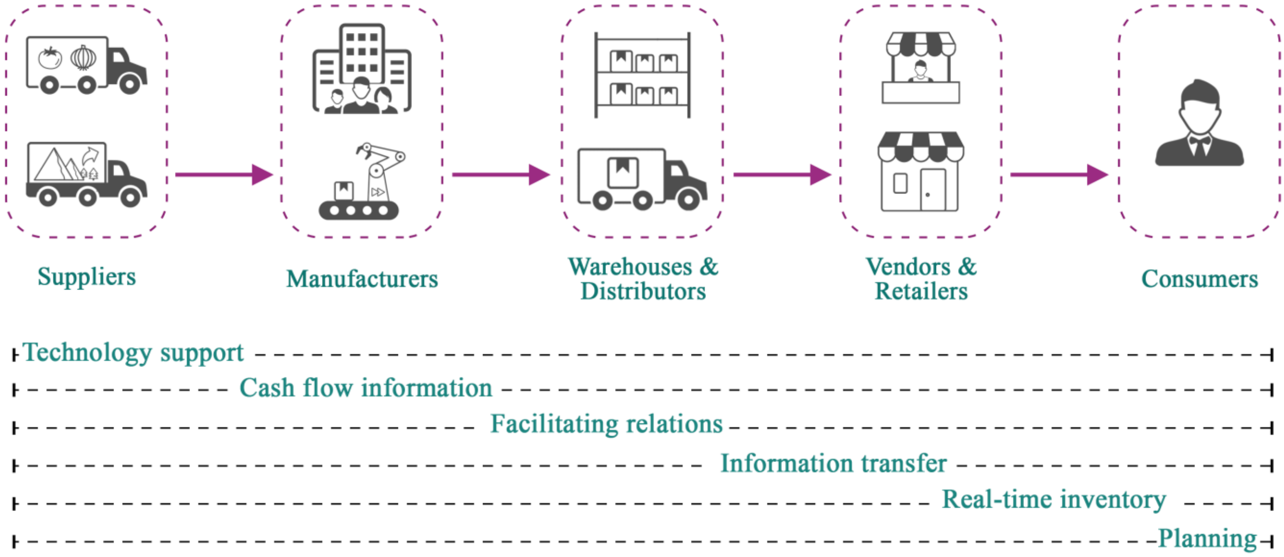

Figure 1 The basic facets of a typical supply chain

Supply chains originally focused on efficient production and delivery only. However, there has been a paradigm shift in how SCs are now designed with the growing importance of environmental issues and sustainability challenges (Seitz and Wells, 2006). Sustainable supply chain management (SSCM) represents a holistic approach, integrating environmentally and financially viable practices throughout the supply chain life cycle, ranging from product design and development to material selection (Ferreira Jr *et al.*, 2022). This transformation is propelled by the changing landscape of customer requirements, pushing manufacturers toward immediate benefits without compromising environmental and societal well-being (Liu *et al.*, 2023). The essence of SSCM lies in considering the triple bottom line of the sustainable development concept, i.e., economic, environmental, and social objectives while meeting stakeholder and customer requirements (Seuring and Müller, 2008). It demands explicit consideration of the social and environmental impact, encompassing the management of raw materials, services, and the entire product life cycle (Johnson *et al.*, 2021; Zhu *et al.*, 2005).

SSCM incorporates practices such as environmentally friendly packaging, end-of-life (EOL) product return, recycling, and waste disposal, emphasizing the importance of eco-friendly handling throughout the supply chain (Zhu *et al.*, 2005). Carter and Rogers (Carter and Rogers, 2008) define SSCM as the strategic integration of an organization's social, environmental, and economic goals, aiming to improve long-term economic performance across its supply chains. It thus involves designing, organizing, coordinating, and controlling supply chains for long-term economic viability without harm to social or environmental systems (Pagell and Shevchenko, 2014). However, the reliable operation of large and complex supply chains comprised of numerous interconnected entities will inevitably face some security, privacy, trust, and other concerns that may put the whole supply chain at risk and make it highly vulnerable (Fatima *et al.*, 2024). The next section discusses the potential of blockchain technology to address the above-mentioned concerns.

2.2. Blockchain Technology as a Reliable Information Hub

Blockchain employs decentralized servers (i.e., nodes) instead of a central server, enhancing resistance to cyberattacks and minimizing single points of failure. It leverages layers of cryptography and links data blocks, contributing to enhanced data security and integrity. Furthermore, the information stored in data blocks is immutable, meaning it cannot be altered without notifying all other participants. Additionally, blockchain provides clarity and transparency to all stakeholders, enabling each participant to examine the data's origin and access the system's latest status without requiring the knowledge of other stakeholders. Blockchain's trust building capabilities eliminate the need for entities to establish trust before engaging in cooperation, a process that traditionally required a considerable amount of time before the technology's advent.

The data records including raw materials' origin, production information, policy adherence, logistics, distribution, and sales consist of comprehensive data, including contributor identities and timestamps, fostering accountability and transparency. Importantly, this shared ledger system extends beyond internal stakeholders; external entities like governmental bodies, Non-governmental Organizations (NGOs), insurance companies, and certifiers can contribute to and strategically access relevant data.

The integration of blockchain technology into supply chain systems aligns with the principles of Industry 5.0, utilizing advanced technologies for sustainable supply chain management. This integration enhances the reliability, efficiency, and security of information exchange among stakeholders in sustainable supply chains (Musamih et al., 2021; Wang et al., 2023). Particularly relevant to industries aiming to showcase the superior quality of their methods and products to customers (Smith, 2008), blockchain, through smart contracts, facilitates automation in asserting, certifying, and executing market operations, contributing to increased efficiency and security within the supply chain (Hsiao and Sung, 2022). The pivotal elements of transparency, efficiency, and security are crucial in understanding why blockchain is instrumental in enhancing supply chain management (Thompson and Rust, 2023). This research underscores the importance of traceability, and transparency, highlighting blockchain's role in improving overall supply chain performance (Paliwal et al., 2020). By providing consumers with comprehensive access to information about products or services, from ethical considerations to production and logistics details, blockchain contributes to a more informed and accountable supply chain ecosystem (Perboli et al., 2018).

3. METHODS AND MATERIALS

3.1. Supply Chain Issues at an Australin Food Processing Company

This research began as a funded study to address a pressing issue in the supply chain management field. It adopts an applied research approach, aiming to find practical solutions to enhance the supply chain management system at an Australian food processing company. The company was founded in regional Australia in 1958 and rose to become a major supplier of processed foods all over Australia using its patented Instant Quick Freeze (IQF) technology. The company's basic business process involves the procurement of fresh produce such as zucchini, sweet potatoes, capsicum, and tomatoes from farmers, and holding them in their inventory for processing. Once they are converted into desired finished products, they are packed and shipped to various sellers. The business process can thus be succinctly divided into three distinct supply chains, viz., upstream supply chain (procurement), internal, and downstream (delivery to consumers). In the initial interviews, the company's supply chain manager underscored several concerns with their upstream supply chain, which constituted about 20 different farmers who were local and from other parts of the state supplying varying quantities of produce at different times of the month. The manager explained that she used internal software systems to identify fresh produce demand based on existing inventory. She then called each farmer and placed an order one month before it was required. The company also held a 3-month floating inventory using its IQF technology. However, following the order placement, the supply chain manager made time-consuming individual follow-up calls to suppliers on a weekly basis just to get updates on the order status. As she frustratingly pointed out, it wasn't until almost the dispatch day that the manager or the company received any clear information about what would actually be delivered. This lack of clarity created too many uncertainties.

Another issue with the dispatch was the varying quantities of produce received in at least 30% of the orders. Farmers tended to send more produce than requested. For example, if the company ordered 6,000 kilograms of zucchini, they would end up receiving an additional 500 kilograms or even 1,000 kilograms, which harmed the company's internal processing plans. This mismatch in supply and demand had adverse consequences. The excess stock became waste, requiring additional time and effort for disposal and cleanup. This experience highlighted the following important issues around the company's upstream supply chain:

- **Lack of transparency and traceability while sourcing produce:** The unreliable delivery system and intermittent traceability of deliveries contribute to a lack of transparency in the origin and movement of produce within the supply chain.
- **Poor storage practices:** The use of the Instant Quick Freeze method leads to challenges, especially with soft produce, causing them to become watery due to prolonged freezing, resulting in significant wastage.
- **Too much inventory:** Maintaining a 3-month inventory of produce, thawed as required, leads to challenges, such as increased wastage due to prolonged inventory holding and the need for extensive storage facilities.
- **Poor communication between vendors, subcontractors, and the company:** Subcontracting operations introduce an additional layer of communication, contributing to challenges in coordinating and ensuring timely services, resulting in increased paperwork.
- **Additional costs associated with subcontracting:** Relying on subcontractors due to low supply chain reliability incurs additional costs and complexities, affecting the overall efficiency and cost-effectiveness of the supply chain.
- **Largely manual handling of all paperwork:** The majority of paperwork being manual and carried by truck drivers introduces inefficiencies, potential errors, and increased labor requirements in handling documentation throughout the supply chain.

3.2. Data Collection and Analysis

To gather information on the challenges faced by the company, the research team conducted semi-structured qualitative interviews with key personnel from the Supply Chain Management (SCM) section at the studied company. The initial two interviews were online sessions between the company's supply chain manager and the research team. To delve deeper into problem identification, the research team conducted four additional on-site visits to the company. Each visit lasted approximately half a day and included observing procedures at the factory. During this period, the team also conducted three more online interviews with the company's SCM personnel, bringing the total number of online interviews to five.

Furthermore, discussions with relevant upstream stakeholders, including interactions with various personnel and raw material suppliers, provided valuable insights into the supply chain's complexities. Additionally, the research team maintained ongoing communication with key personnel from the food processing company's SCM section via email. This communication ensured they captured any required information beyond what was already provided during interviews and visits.

Reports were generated for each interview to keep the research team members updated and to be used during the data processing phase before designing solutions for the identified challenges. In the next phase, the qualitative information collected was manually analyzed (McAleavy, 2020) to identify the causes of the issues reported by the company under study. Table 1 lists the semi-structured qualitative questions used in the initial phase of the study. Relevant documents, such as reports on delivered raw materials from various logistics and suppliers, were also analyzed to ensure that the designed solution aligns as closely as possible with conventional procedures.

Table 1 Semi-structured Interview Questions and Corresponding Themes
*DIFOT: Delivery in Full on Time

No.	Question	Theme
1	What challenges hinder the company from delivering products 'in full' and 'on time'?	* DIFOT
2	What is the frequency at which the challenges occur?	DIFOT
3	How much are the challenges related to on-site and external delays?	DIFOT
4	Do these occur in a combined form or individually or both (cannot deliver full and on time, can deliver full but not on time, cannot deliver full but on time, etc.)?	DIFOT
5	Does existing inventory control influence the occurring challenges?	DIFOT
6	Which part of the supply chain is the most required part for traceability?	Traceability
7	What are the feasible options to include electronic tracking approaches?	Traceability
8	Who constitutes the other stakeholders both upstream and downstream in your supply chain?	Traceability
9	What are the sources or reasons leading to waste?	Waste reduction
10	What do you do with the wasted materials?	Waste reduction
11	In which sections and procedures do you require automation?	Automation
12	How open is the company to the next-generation (AI-based) document automation platforms?	Automation
13	What specific information do you communicate with each stakeholder?	Automation

4. RESULTS

Four distinct themes have emerged during the study (see Table 1), viz., Delivery in Full on Time (DIFOT) as a key performance indicator (KPI) to measure the efficiency and effectiveness of the delivery process, traceability focusing on tracking and documenting the movement of goods and materials throughout the entire supply chain, waste reduction for minimizing waste generated throughout the supply chain by optimizing processes and resources, and automation referring to using technology to automate tasks within the supply chain, improving efficiency and reducing human error.

The company's philosophy and mission of DIFOT are largely dependent on its relationship with both upstream suppliers and downstream consumers. The present study, however, discusses issues pertaining to the upstream supply chain as the company uses a manual and conventional interaction with farmers as already stated. This places a lot of stress on the internal processes of the company and requires urgent attention.

The following are some quotes from the interview with the SCM manager at the company that contributed to the findings of this study:

- **Traceability:**

  ”Being in this industry traceability is a major part of our quality requirement. So, we need to follow it from the raw materials coming into our factory, how we temperature record everything, and we put that into a finished product.”

  ”We find that some of the biggest problems in our supply chain management system are transport, extensive paperwork, and lack of traceability.”

  ”I spoke with so many big transport companies, but there is no electronic tracking system, they only have an electronic portal where you can book your jobs in, but that is it! There is no traceability of where did your cargo go, after departure and we have been told the reason is the cargo goes through several carriers to reach the destination.”

- **Automation:**

  ”I would like to see this technology be part of our ERP system, where we can have the industry transport people can communicate with us and also, we can import and export manifests.”

  ”We are trying to reduce our paper footprint but still get the traceability, so, I am interested to see how your program would turn this around because the industry needs it.”

- **Waste reduction, DIFOT, and traceability:**

  ”Yesterday I had a scenario where raw material came in and it was all good on paper but when we checked the raw materials all was rotting, we did get back to our suppliers and said that we cannot use that in production, they replied that the raw materials should have been damaged due to raised temperature during the transport.”

  ”The logistic companies do not use electronic devices to record the temperature and only record on pieces of paper, there is no proper tracking of the status of the raw material in transit.”

  ”At the end of the day the proof of delivery is the key thing that we can show to the customers and make sure they received it in good condition and then get paid.”

  ”I definitely think we will get some value from participating in this blockchain because I used to work with a different industry, a gas industry, so we were using different things for tracking and tracing and transport. It is very interesting with the food industry where you need to have all of your papers ready and signed because if the product makes somebody sick the company can have serious problems, so I really think that blockchain might be able to help us in this matter and to help us to do the things more efficiently."

4.1. Upstream Supply Chain Model Using Blockchain Technology

Challenges that came to light were, uncertainties in decision-making due to the lack of reliable information, excessive manual procedures for recording the information leading to more human errors and unnecessary time consumption, lack of automated communication and follow-up processes, unknown status of the material in transit, and lack of a unified information format provided by the other stakeholders. To mitigate these challenges a logical design of the supply chain management system, leveraging blockchain technology and its smart contracts for optimizing planning, transparency, reliability, traceability, sustainability, and bottleneck prevention was created. The proposed framework is designed in alignment with the issues of the company to tackle the roots of its challenges as shown in **Figure 2**.

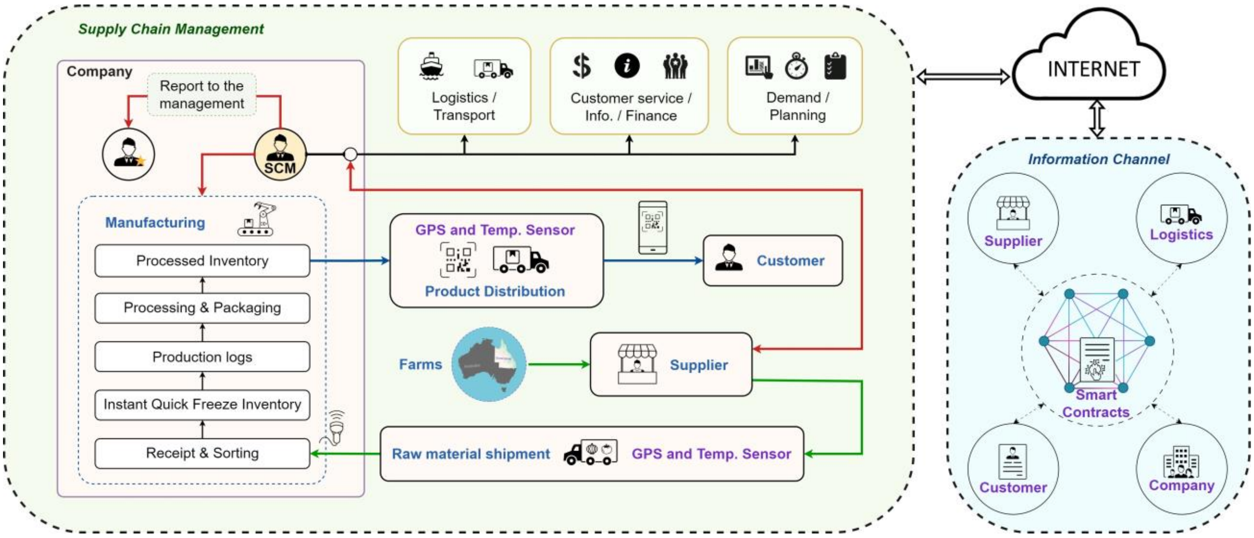

Figure 2 Logical design of the proposed blockchain-based supply chain management system.

It is comprised of two major sections that pertain to different concepts, working together to establish a holistic and efficient supply chain management system: the automated supply chain management system and a consortium of various organizations. Firstly, the automated supply chain management, aligned with the green supply chain concept in opposition to the linear supply chain, operates based on the principle that every part of the product ecosystem should act responsibly to achieve green supply chain goals, such as preventing unnecessary harm to the environment for a more sustainable approach. Responsible changes to adapt from a linear supply chain can start with avoiding over-exploitation and unnecessarily prolonged storage of raw materials and implementing changes in manufacturing planning and processes, such as more efficient designs to achieve zero waste and reduce material use, to name a few.

Secondly, the consortium comprises organizations that play various roles in the processes of procuring raw materials, manufacturing, and delivering a product to end-users while ensuring the accurate recording of information during these procedures. The holistic approach of securely and efficiently sharing information using blockchain technology aims to reduce bureaucracy, facilitate informed decision-making, increase trust in recorded information, automate procedures for faster processes, identify and prevent potential bottlenecks, foster trust between customers and manufacturers, and provide reliable information to end-users, business partners, and stakeholders. Blockchain technology acts as an information hub, connecting all components with automation capabilities through smart contracts to enhance the performance and reliability of the system.

Furthermore, it shows a reorganized supply chain and operations for the company incorporating blockchain technology. It is comprised of two main components, viz., the Supply Chain and the Information Channel. As with any manufacturing organization, the Supply Chain Manager is the major interface between the upper management and the manufacturing department, internally, while also the principal communicator with suppliers and customers. The person is also responsible for undertaking demand forecasting, procurement planning, logistics and transport, financial planning, and customer service and liaison. As can be seen in the figure, the Supply Chain Manager is the trigger for all orders and interfaces directly with the suppliers (farmers). This is discussed in detail in section 4.2 and **Figure 5**. Once orders are placed, the details would be automatically captured and stored in a new information model database, as shown in **Figure 5**. This database can be used to keep a tally of all inventories at any given time, thereby saving valuable time for the supply chain manager. The suppliers would have access to a separate node of this database (external and secure) where they enter the details of the consignments at dispatch. This is critical to the internal production planning for the company as details such as harvest and packaging dates (which are currently not available from some suppliers) are vital to the stock rotation and management. RFID and temperature sensors would be embedded in pallets, providing real-time data for traceability and transparency.

Figure 3 illustrates the comparison between the company's conventional supply chain (A) and the upgraded version of the supply chain with the proposed framework (B). In the figure, the supplier is denoted as number 1, the logistics company and shipping trucks as number 2, the company's supply chain management office as number 3, the factory as number 4, the warehouses for storing manufactured products as number 5, and the customers as number 6. In the conventional system, all processes are manual, relying on extensive paperwork. Suppliers submit information in manual forms and various formats, and logistics lack real-time tracking during transit, relying on manual manifests. The upgraded system benefits from a unified data structure between the suppliers and the company, traceable logistic systems with real-time shipment status in transit, and automation of both intercompany and intracompany processes. These can be delivered via mobile or web applications with synced databases, GPS tracking systems, and IoT devices installed on the trucks communicating the real-time status of the products (Adeusi *et al.*, 2024; Ben-Daya *et al.*, 2019; Helo and Shamsuzzoha, 2020; Molano *et al.*, 2017; Suban *et al.*, 2021).

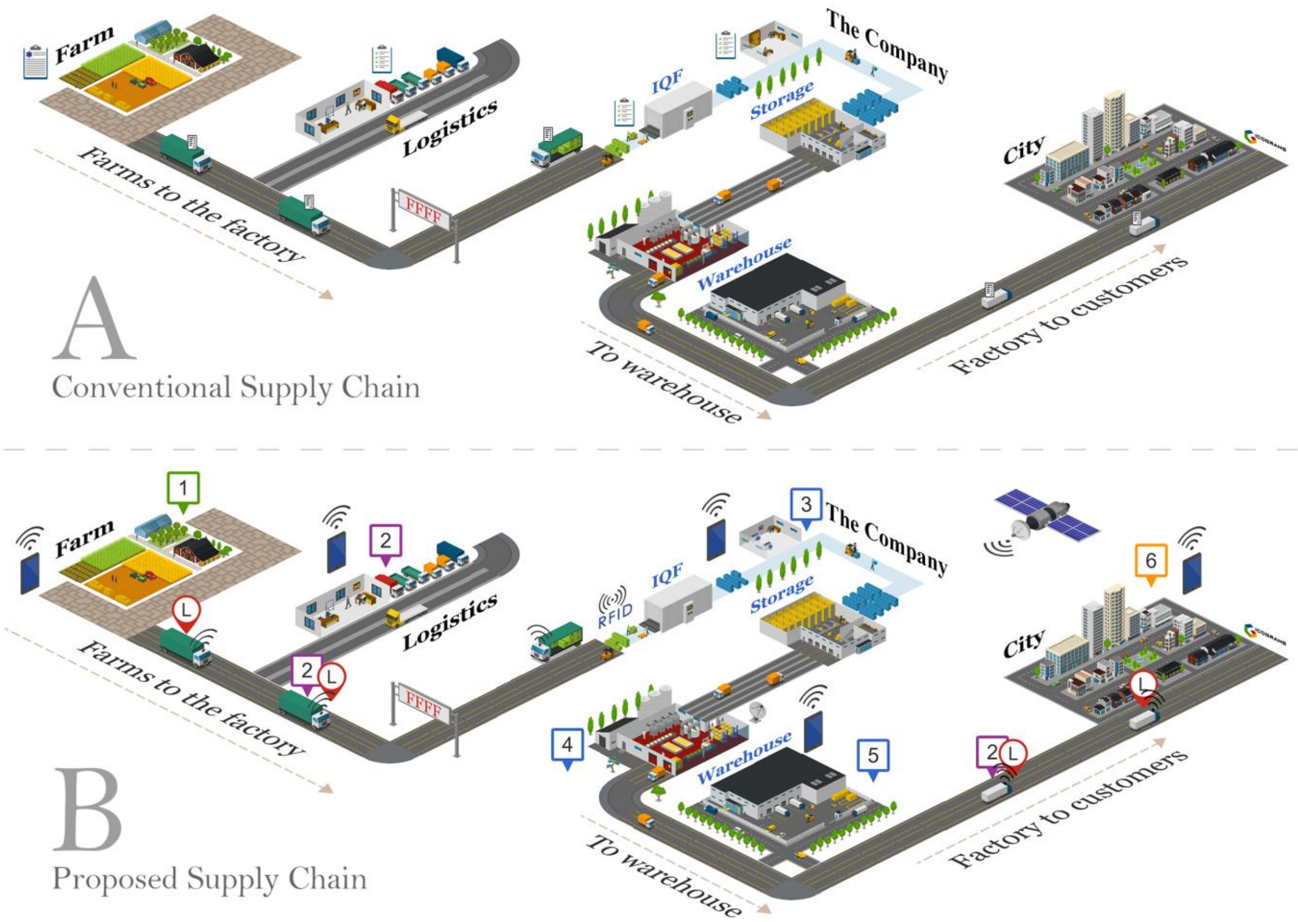

Figure 3 Supply chain model of the company under study, before and after adopting the framework. Designed with the *icograms* online service.

4.2. Creation of Blocks on the Ledger

While recording information on the blocks of the ledger, two types of information take separate paths to be encapsulated in a block. For instance, information meant to support end-users' rights, including details about the origin of the products, their raw materials, the manufacturing processes, and the policies followed by manufacturers during various procedures, should be recorded in a way that is accessible to end users. On the other hand, there is information that may not necessarily concern end-users, such as details of orders for raw materials, including the volume of ordered material and the date of clearing financial balances between business entities. **Figure 4** outlines the high-level flowchart that nodes should follow when creating an appropriate block.

It emphasizes that identifying the recipient of recorded information on the blockchain is pivotal for deciding how the information should be recorded and disseminated on the network. Therefore, the information should follow specific protocols before being encapsulated in the blocks. Publicly available information does not need to be encrypted to be accessed by a specific recipient. In this process, smart contracts autonomously execute required actions and share information with relevant entities and organizations. Certain sensitive information, including financial details, order and demand information, and the terms of contracts between entities, must be securely maintained and disclosed only to the intended recipients. The need for a supply chain management system with capabilities such as reliably and securely recording public and private information calls for a framework proficient in generating both publicly available blocks and private blocks on the ledger as needed.

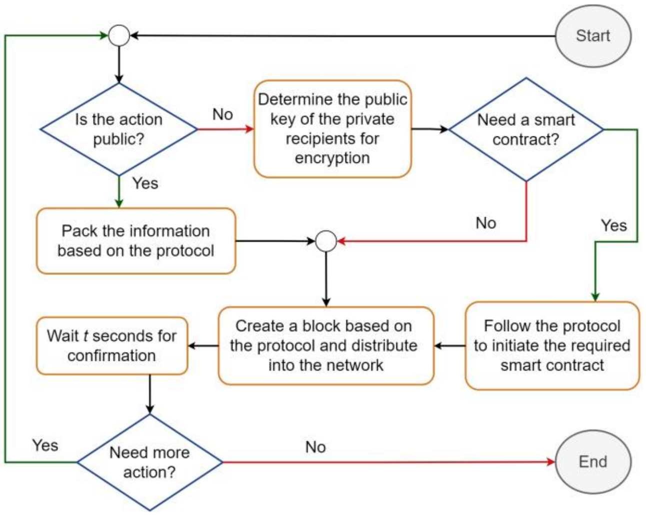

Figure 4 Block creation flowchart based on the recipient of the information.

Utilizing technologies can enhance the performance of the supply chain management system, such as cloud computing to improve data access efficiency (Anbuudayasankar *et al.*, 2020; Nair, 2012; Nair and Anbuudayasankar, 2016a), blockchain technology to enhance transparency and traceability (Darshan *et al.*, 2022; Kumar *et al.*, 2023; Misra *et al.*, 2023), IoT sensors in logistic systems to monitor the condition and status of products, RFID tags to track inventories and raw materials (Cocco *et al.*, 2021; Nair and Anbuudayasankar, 2016b), and QR codes for easy access to information. In addition to these technologies, enhancing the framework's efficiency and performance requires that information, such as details about raw materials, products, logistics, etc., recorded in a block adheres to specific standards. Adherence to standards facilitates better adoption and scalability of the platform (Adaryani *et al.*, 2024; Guan *et al.*, 2023; Singh *et al.*, 2023). Existing globally recognized identification codes (AISBL, 2008; Zhang *et al.*, 2020) can be employed for this purpose, and some of the standard identification codes globally used in supply chain management are listed in Table 2.

Table 2 Globally recognized identification codes.

Code	Full Form
UID	Unique Identifier
IFT14	Item Logistics Unit
UPC	Universal Product Code
GTIN	Global Trade Item Number
SSCC	Serial Shipping Container Code
GSRN	Global Service elation Number
GUN	Global Unique Identifier Number
GIAI	Global Individual Asset Identifier
GRAI	Global Returnable Asset Identifier
SGTIN	Serialized Global Trade Item Number
EAN	International/European Article Number
EPCDS	Electronic Product Code Discovery Service
EPCSS	Electronic Product Code Subscription Service
EPCIS	Electronic Product Code Information Services

While the complexity of creating new blocks related to a specific business activity highly depends on the use case scenario, Figure 5 demonstrates a simple sequence wherein the company attempts to order raw materials from a supplier. For the sake of simplifying the demonstration, the diagram does not indicate the public and private blocks mentioned in Figure 4. Initially, the supply chain manager of the company would select the required raw material identified through the production plans at the company from a list provided in the user interface. Next, by choosing a specific supplier, the order with specific details can be placed on the ledger.

The supplier will be automatically notified through the mobile application or developed software about the details of the placed order. Upon agreement for procuring the ordered raw material, a contract will be signed between the two stakeholders, handled by a smart contract. The supplier will be notified to update the ledger with information on the advancement of the material procurement based on the unique order ID at periodic intervals. This would automatically update the company on the other end, allowing for informed decisions and planning.

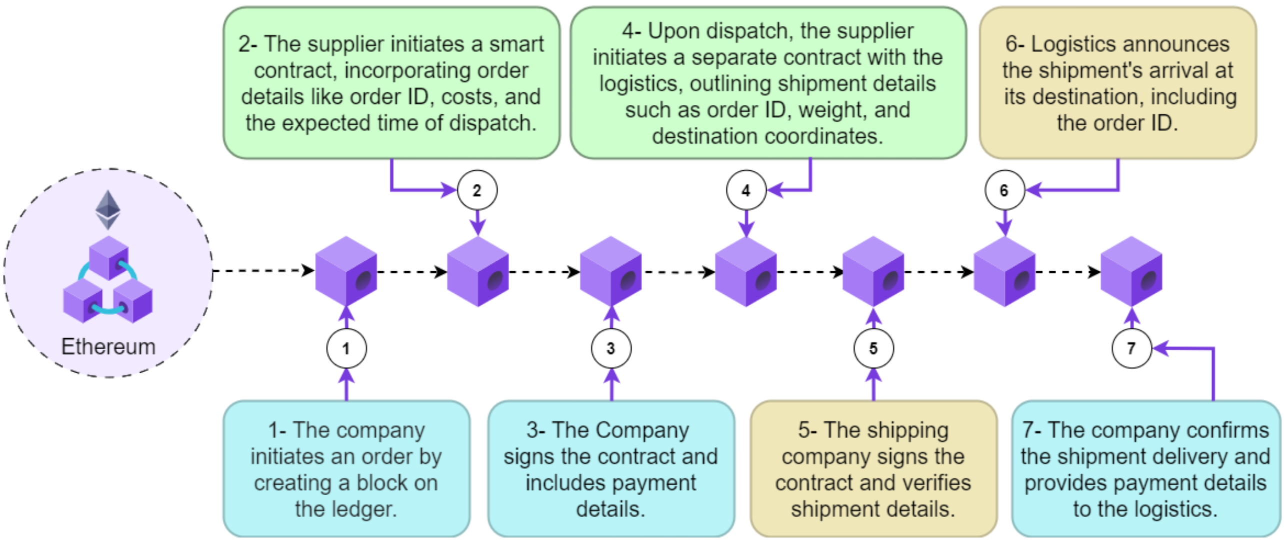

Figure 5 Block creation sequence in a simplified order placement scenario.

When the shipment of raw materials is ready to be dispatched to the orderer, the supplier would contact the logistics to pick up and deliver the shipment. Upon the arrival of the logistics at the supplier location, the supplier would initiate a contract through the provided user interface to record information regarding the details of the shipment, timing, and destination. The logistical entity, in turn, creates the required blocks on the ledger to record information about the loaded shipment, trip initiation time, delivery status, shipping details, and the GPS ID for other stakeholders to track the shipment. IoT sensors would also be installed on the containers to inform the concerned parties regarding the status of the materials in transit. The process does not involve other organizations, such as insurance companies and financial organizations, and only the relevant details are stored on the ledger by the other stakeholders. Additionally, it is assumed that the payment to the supplier is made upfront, and the payment for the logistics is made after delivery, a detail that can vary in each use case based on the agreement between the business partners.

4.3. Addressing the Identified Issues

The proposed system plays a pivotal role in optimizing multiple facets of supply chain operations, particularly in the upstream section, addressing the challenges reported by the company. Decisions influenced by uncertainties, such as the timing and accuracy of produce delivery and the reliability of suppliers, have compelled the company to adopt a cautious approach, leading to prolonged produce storage and increased waste. Planning based on reliable information helps resolve uncertainties regarding the procurement of the raw material and allows them to store the frozen material for a shorter amount of time, hence reducing the waste creation caused by prolonged storage.

The immutability of blockchain facilitates traceability, seamlessly tracking the origin and journey of products (Dhanush *et al.*, 2021). The proposed framework significantly increases the transparency of the information and processes in the supply chain by recording and disseminating the relevant information over the network of stakeholders to address the issue of unclear processes of the upstream supply chain at the company. Transparency, in turn, ensures reliability, providing stakeholders with accurate and up-to-date information.

The framework also enhances planning procedures by offering a transparent and immutable record of every stage, from production to distribution. This record serves as a reliable source of information for informed decision-making and mitigating uncertainties. It facilitates the company with automated procedures and unified data forms, including contracts with stakeholders, record-keeping of supply sources, payments, logistics, and traceability, as well as monitoring the status of materials in transit to substantially reduce the manual paperwork at the company.

Additionally, an automated communication and notification system incorporated in the framework reduces the time spent on order follow-ups and ultimately reduces the cost of subcontracting. The framework unifies information collected from various stakeholders, enhancing data integrity. By identifying and addressing bottlenecks in real-time, it proactively prevents disruptions, fostering a more resilient and responsive supply chain ecosystem (Acero *et al.*, 2022; Narassima *et al.*, 2022). Overall, the framework not only significantly reduces paperwork and time spent on order follow-ups but also enhances the overall efficiency of planning and production procedures at the company.

5. SIMULATION OF SMART CONTRACT FROM THE SCM MODEL

Figure 6 illustrates a data flow related to the smart contract signed between the company and a supplier. The company places an order on the ledger, and the supplier initiates the smart contract containing the necessary information related to the placed order. The company then signs the contract for an official business initiation. Recording contract information on the ledger enhances transparency in the supply chain and facilitates process automation within the system.

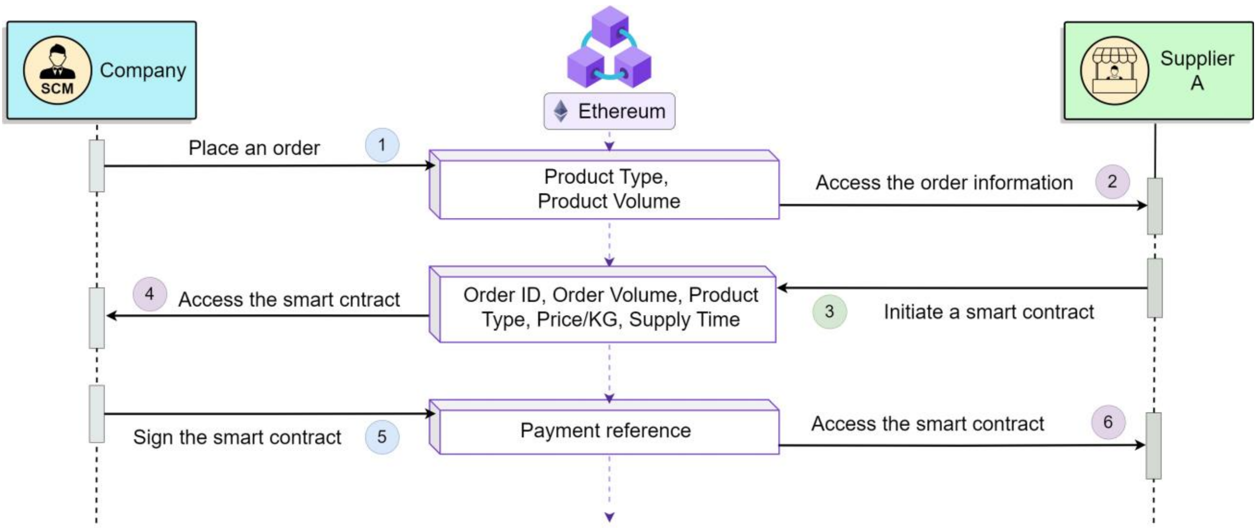

Figure 6 Data flow between the company and a supplier.

The following smart contract is written in Solidity programming language which is specifically coded for the Ethereum blockchain network. It is developed based on the above-mentioned business process between the company and the supplier. The supplier is required to provide necessary information related to the order, such as the order ID, volume of the ordered item in kilograms, the product name, its price per kilogram in dollars, the estimated time required to supply the product, and the digital wallet address of the company that placed the order. The cost related to the placed order will be calculated by the smart contract after being deployed by the supplier. The company is then expected to provide the payment reference number, and delivery address coordination, and sign the contract after checking the information recorded on the smart contract.

```
// SPDX-License-Identifier: MIT pragma
solidity ^0.8.24;

contract SupplyCompanyContract
{

address public supplier;
address public companyAdd;
string public orderId;
string public deliveryCoordinates;
string public productType;
uint256 public priceKG;
uint256 public totalCost;
string public paymentReferenceCode;
bool public supplierSigned;
bool public companySigned;
uint256 public volume;
uint256 public supplyTime;

event ContractInitiated(string orderId,
uint256 volume, string productType, uint256
priceKG, uint256 totalCost, uint256
supplyTime, string paymentReferenceCode,
string deliveryCoordinates, address indexed
supplier, address indexed companyAdd );

modifier onlySupplier() {require(msg.sender
== supplier, "Only for supplier!"); _;}
modifier onlyCompany() {require(msg.sender
== companyAdd, "Only for company!"); _;}

constructor( string memory _orderId, uint256
_volume, string memory _productType, uint256
_priceKG, uint256 _supplyTime, address
_companyAdd) {
supplier = msg.sender;
orderId = _orderId;
volume = _volume;
productType = _productType;
priceKG = _priceKG;
totalCost = _volume * _priceKG;
supplyTime = _supplyTime;
companyAdd = _companyAdd;

emit ContractInitiated ( orderId, volume,
productType, priceKG, totalCost, supplyTime,
"", "", supplier,companyAdd ); }

function provideDetailsByCompany(string memory
_paymentReferenceCode, string memory
_deliveryCoordinates) external onlyCompany {

require(!companySigned, "Details already
provided!");
paymentReferenceCode = _paymentReferenceCode;
deliveryCoordinates = _deliveryCoordinates;
companySigned = true;
emit ContractInitiated( orderId, volume,
productType, priceKG, totalCost, supplyTime,
paymentReferenceCode, deliveryCoordinates,
supplier, companyAdd ); }

}
```

5.1. *Simulation Setup*

An Ethereum smart contract is written in the Solidity high-level language and necessitates a Compiler for interpretation into machine language. The compiler produces Bytecode, which is then processed by a Virtual Machine (VM). This VM sits atop Ethereum's hardware and node network layer, executing the contract's intended function. The specified smart contract is simulated and validated using the Remix online Integrated Development Environment (IDE), a widely used tool for Ethereum smart contract simulation. Accessible at *https://remix.ethereum.org* (last accessed on 27 Sep 2024), the IDE provides essential tools for deploying, debugging, and testing smart contracts, including different Solidity compiler versions and various Virtual Machines. This simulation is configured to run on Solidity Compiler version 0.8.24 and Remix VM. For deployment and execution on the network, each smart contract requires a valid wallet address, along with payment for its execution fee. In the Remix IDE, 15 Ethereum test wallet addresses are available, each credited with 100 ether, representing various entities during smart contract simulations. Additionally, 15 test chains, including virtual machines, are provided for users to run their smart contract code.

5.2. *Simulation Result*

Figure 7 illustrates the outcome of the smart contract simulation conducted on the Remix online IDE, following the mentioned setup. The smart contract is crafted in the coding area located at the top-right section of the figure, labeled 'SupplyCompanyContract.' To initiate the contract, one of the wallet addresses is selected to represent the supplier, facilitating deployment. In the figure, green check marks signify the successful compilation and deployment of the contract. The wallet address is altered when actions are taken by the company. It's important to note that, for the sake of space efficiency, only one simulated smart contract is included in this article.

Figure 8 portrays the identical smart contract as simulated in Figure 7, utilizing the same setup. In this scenario, an unauthorized entity, represented by a wallet address different from the one specified by the supplier during contract deployment, attempts to access the smart contract. For simulation purposes, an incorrect wallet address was chosen in the Remix IDE to represent the unauthorized entity. In response, the contract throws an error, showcasing the implemented security measures designed to protect against unauthorized manipulation. The smart contract can only be endorsed by the company whose wallet address was provided by the supplier during the contract's deployment on the blockchain network.

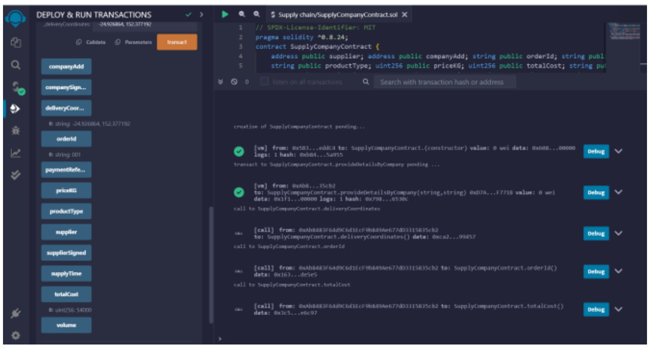

Figure 7 Simulated smart contract on Remix IDE.

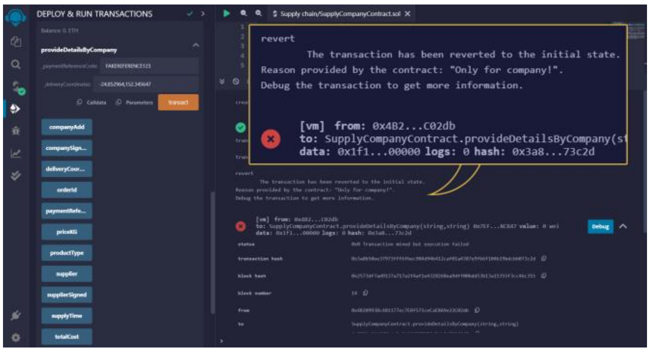

Figure 8 Prevention of unauthorized access to the contract.

5.3. Limitations of the Study

Similar to other studies, this research also has some limitations. The first limitation is the study's reliance on investigating only the reported issues already identified by the company's supply chain management department. This approach may result in an incomplete understanding of the problematic situation, as the issues could have been identified by the research team for a more rigorous investigation and a deeper understanding of the entire procedures at the company. Secondly, the authors opted for a qualitative methodology, focusing solely on the supply chain management department staff, due to constraints related to the availability of staff at the company and funding. Future studies should take a mixed-method approach adding a quantitative survey research design to generate causal inferences to identify specific indicators and to generalize the findings. Thirdly, the research team was unable to conduct interviews with all suppliers and logistics companies to align the proposed solution with their perspectives on the issues. Finally, the proposed design was not implemented due to the phased funding arrangement, the next phase of the study will involve the implementation of the proposed framework and an examination of the effectiveness of using blockchain technology to resolve the identified issues.

These limitations prompt readers to approach the proposed solution cautiously. Future research endeavors could benefit from a more in-depth investigation of the procedures at the company under study; incorporation of a mixed- method research design to achieve a richer dataset and a more holistic perspective; collect information from all stake- holders for a deeper understanding of the problematic areas. Despite the identified limitations, the study sheds valuable insights on the benefits of utilizing blockchain technology for improving the resilience and performance of supply chain management systems. The framework proposed in the study shows significant promise as a solution.

6. CONCLUSION

This study examined the supply chain management system of an Australian food processing company, to identify the challenges faced by it, and proposed a blockchain-based framework to enhance of its resilience for transparency and reliability. It makes a significant contribution in identifying the pathway to incorporate the attributes of blockchain technology in improving the resilience, traceability, transparency, and automation of the supply chain management systems in companies with manual procedures specifically in their upstream supply chain management section. To answer the first research question, the study shed light on five cases of challenges faced by the company in its supply chain management section namely a lack of reliable information for informed decision-making, excessive bureaucracy, lack of automated procedures, unknown status of the material in transit, and various formats of information provided by other stakeholders.

To provide an answer to the second research question, a blockchain-based framework is proposed which takes a more holistic approach and offers a solution for the whole supply chain, rather than a piecemeal one. Upon implementation, the framework has the potential to track products through the supply chain in real time using data received from GPS tracking devices, IoT monitoring devices installed on vehicles transporting raw food materials and perishable supplies, and updated status at each checkpoint through- out the proposed supply chain design. This would enable rapid identification of faults and bottlenecks where expected progress is not observed on the developed mobile/web applications, leading to faster and more cost-efficient delivery of products, ensuring freshness, reducing waste, enhancing traceability and coordination between stakeholders, and promoting total quality by correcting the conventional supply chain management system.

The framework can be easily customized to specific domains depending on the nature of the business process as well as the territory of operations. The framework can also be modified to include domestic, national, and international trade norms in order to facilitate transparency and reliability at every stage of the supply chain. Furthermore, the smart contract between the company and a supplier suggested in the proposed SCM model has been developed, simulated, and validated using the Remix online IDE.

Finally, the framework recognizes and incorporates pro- visions for the United Nations Sustainable Development Goals (UNSDGs) (Nations, 2015) by ensuring that the up- graded supply chain management in the company directly contributes to four UN SDGs. It facilitates the achievement of SDG2 by supporting a more sustainable food production system (2.4) and proper functioning of the food commodity market (2.C). Additionally, it aligns with SDG8 by promoting resource efficiency in production (8.4), and with SDG9 by increasing access to ICT and communication technologies (9.C), upgrading infrastructure with sustainable technologies (9.4), and enhancing technological capabilities (9.5).

Furthermore, the framework supports SDG12 by promoting the efficient use of natural resources (12.2), reducing food loss along production (12.3), and preventing waste generation (12.5).

Despite the numerous benefits of blockchain technology, it also poses certain limitations that must be addressed when applied in a specific field. While challenges like storage concerns, power consumption, technology adoption, transaction charges, scalability, and confidentiality can be mitigated during the design phase, others, such as legislative issues and oracle challenges involving data input into the ledger, require close cooperation among governments, private entities, and academia to resolve. Government policies that provide a clear legal framework for blockchain applications and encourage innovation, coupled with support from the private sector through investments in research and development, can play a pivotal role in overcoming these challenges and fostering the widespread adoption of blockchain technology. An avenue to explore in future research would be to evaluate and simulate the proposed framework and implement the solution within the actual operations of the food processing company studied.

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AUTHOR CONTRIBUTIONS

Enayati: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.
Gudimetla: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Project administration.
Arlikatti: Writing - Review & Editing.

DATA AVAILABILITY

The data used in this study are available upon request and following the execution of a Commercial Non-Disclosure Agreement (NDA) due to the presence of commercially sensitive information within the raw data.

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