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Seaport logistics of perishable agricultural products: Assessing the effectiveness of a blockchain-based track and trace solution

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Abstract
The increasing global demand for high-quality agricultural products, coupled with significant food wastage in supply chains, highlights the need for efficient and sustainable logistics systems. This study proposes a blockchain-based track and trace solution integrated with Internet of Things (IoT) and Global Positioning System (GPS) technologies to improve transparency, traceability, and quality management in seaport logistics for agricultural exports. The research adopts a conceptual and empirical approach by developing a blockchain architecture and evaluating its effectiveness through an analytical model and a numerical illustration involving the export of spinach from India to Singapore. The results demonstrate that the proposed blockchain-enabled system significantly reduces the risk of product deterioration by ensuring real-time monitoring of critical parameters such as temperature, time, and location. Beyond operational improvements, the study highlights the role of blockchain technology in promoting sustainable entrepreneurship by enabling innovative business models for Agri-logistics startups and enhancing the competitiveness of small and medium enterprises (SMEs) in international markets. The system contributes to sustainable supply chain practices by minimising food waste, improving resource efficiency, and ensuring transparency across stakeholders. The findings align with key Sustainable Development Goals (SDGs), including SDG 2, SDG 9, SDG 12, and SDG 8. The study offers practical implications for policymakers and industry stakeholders to support blockchain adoption in agricultural supply chains, particularly in the Asian context.

Keywords: Blockchain technology, Sustainable entrepreneurship, Agri-logistics supply chain, small and medium enterprises (SMEs), Sustainable supply chain innovation

1. Introduction

The article (IFCO systems, 2020) indicates that the food wasted in the world amounts to 1.3 billion tons, costing the world approximately 1 trillion USD. In June 2017 (IFCO Systems, 2020), a blog (Numadic, 2017) confirmed that $14 billion worth of crops are wasted each year due to poor cold chain facilities and disorganised logistics. Therefore, it is crucial, at the global level, to review food waste along the supply chain to support the expected population of 9 billion by 2050.In the context of Asian agricultural economies, reducing food waste and improving supply chain efficiency is also closely linked with sustainable entrepreneurship, where innovative technologies can enable new business opportunities while addressing environmental and social challenges. The adoption of digital technologies in Agri-export supply chains has the potential to foster entrepreneurial ecosystems, particularly for small and medium enterprises (SMEs) and Agri-logistics startups.Given the supply shortages currently prevailing (in 2022) in many countries, including the United States and Western Europe, seaport logistics for the export supply chain are becoming increasingly important for perishable and non-perishable products. The role of seaport logistics in the agricultural export supply chain is important due to its contribution to the global economy and the perishable nature of the products. Shipments of agricultural products have increased by over double since 1995, reaching $1.5 trillion in 2018.Effective seaport logistics is important for ensuring sustainable agricultural trade, especially in Asia, where most global agricultural exports are generated. Enhancing logistics efficiency not only reduces economic losses but also contributes to environmentally sustainable supply chain practices.Tracking and tracing enable an individual to determine the actual location of perishable goods, regardless of their position in the supply chain. The process enables the user to find the item's location in real time, 365 days a year, 24 hours a day, with just a click. Tracking and tracing the Quality of agricultural products is very important given their perishable nature.The Global Positioning System (GPS) and the Internet of Things (IoT) complement each other well to form a complete technological solution for tracking and tracing. IoT acts as a surveillance system, continuously feeding the user with real-time information and data on the item's key parameters, whereas GPS provides the item's geographical coordinates. The real-time information could be accessed over SMS services or a web browser.Given the volume of container movements worldwide and data asymmetry, it is important to track shipments to ensure smooth global trade and logistics. This can be achieved using blockchain technology coupled with smart containers.Blockchain technology, with its decentralised and tamper-proof architecture, has

emerged as a transformative innovation that can enhance transparency, trust, and coordination among multiple stakeholders in agricultural supply chains. In addition to improving operational efficiency, blockchain adoption can support sustainable entrepreneurship by enabling new digital business models such as traceability platforms, logistics data services, and smart contract-based coordination mechanisms.Research on blockchain applications in seaport logistics is limited, with only a few studies examining how blockchain technology could improve tracking and tracing (Wang et al., 2019). As per Rahmadika et al. (2018), blockchain technology enables track-and-trace functionality that can significantly impact the shipping industry, minimizing the need for intermediation through new, reliable data distribution platforms. As per Tsiulin S (2020), they reviewed a literature review on blockchain's supply chain and logistics-related applications. They found that applications in shipping and port management were limited, and that blockchain integrated with the Internet of Things (IoT) was growing in importance (Wang & Qu, 2019). They also observed a shift across the entire transportation and supply chain toward transparency and traceability to demonstrate the product's quality better. The combined volume of container movements worldwide, along with data manipulation, makes it important to track shipments to ensure smooth global trade and logistics. This can be achieved using blockchain technology coupled with smart containers. Smart containers with IoT sensors are used to monitor prefixed shipping conditions (Hasan et al., 2019). Food traceability is of utmost importance given its short shelf life. Most of the designed mechanisms lack the required accuracy, readability, and scalability, compounded by the complexity of the supply chain. A blockchain machine learning-based food traceability system (BMLFTS) is designed, which incorporates blockchain, Machine Learning technology (ML), and fuzzy logic to improve shelf life in the supply chain (Shahbazi & Byun, 2020). Considering the importance of Logistics and transportation systems for economic development, smart transportation is gaining growing importance. Blockchain with IoT enables an intelligent transportation system to address supply chain gaps (Mamoona, 2020). Considering the complexity of the food supply chain, which involves multiple entities and the perishable nature of the product, it needs innovative ways to gather and transmit data across various levels of the supply chain. A blockchain is designed to help stakeholders upload necessary information, which can then be used to track and trace perishable goods (Rambhia et al., 2021). To ensure quality management and consumer confidence in the products they buy, it is necessary to maintain the required storage conditions throughout the voyage. An edge-cloud blockchain with IoT is designed to reduce delays and enable rapid responses to data collection in the cold supply chain (Yang et al., 2022). Based on the foregoing literature review, there is little research examining the effectiveness of a blockchain-based solution to address perishability.Furthermore, despite the growing body of literature on blockchain in supply chains, limited attention has been given to its role in enabling sustainable supply chain innovation and supporting SME participation in agricultural export logistics, particularly in the Asian context.

This paper proposes a blockchain-based solution for tracking and tracing perishable agricultural products, specifically for seaport logistics, and assesses its effectiveness.

The study also contributes to the literature on sustainable entrepreneurship by showing the potential of blockchain-based logistics solutions for increasing transparency, mitigating food waste, and offering new business prospects for SMEs and Agri-logistics startups in Asian agriculture export supply chains. The proposed framework is also aligned with some of the major United Nations Sustainable Development Goals (SDGs), such as SDG 2: Zero Hunger; SDG 9: Industry, Innovation and Infrastructure; SDG 12: Responsible Consumption and Production; and SDG 8: Decent Work and Economic Growth.

The paper's flow is as follows. The subsequent section presents opportunities for using a blockchain solution in seaport logistics for agricultural products. Section 3 outlines the proposed blockchain-based solution. Section 4 explains the method for assessing the effectiveness of the proposed blockchain-based solution. Section 5 describes the application of the blockchain solution through an empirical example, drawing on data from primary sources, secondary sources on the internet, and the authors' subjective observations and estimations. Section 6 presents the results and discussion. Finally, section 7 draws the inference and policy implications.

2. Opportunities for using blockchain-based track and trace solutions in seaport logistics of agricultural products

The seaport logistics process for the export supply chain of agricultural products is shown in Figure 1. Specifically, the seller of the agricultural product is the farmer in the country of origin; the Exporter (buyer) of the agricultural product is an agro-based firm engaged in international trade; and the Importer of the agricultural product is the company in the foreign country purchasing the product for onward sale in the country. The Importer lays down stringent quality specifications for the agricultural product and identifies an exporter that meets them.

The Exporter, in turn, procures the agricultural product from the local farmer, involving negotiation until the maximum bid price by the Exporter exceeds or equals the minimum offer price by the farmer. The farmer dispatches the consignment to the Exporter via inland transportation carriers. The Exporter tests the product at its end before shipping it to importers. After completing all formalities, the exporter ships the consignment through a logistic service provider to be received by the Importer at the destination port. The logistics service provider coordinates the shipment with the shipping line, the port terminal, and the customs broker (Wong & Karia, 2010; Makukha & Gray, 2004). The export of agricultural products requires multimodal transport in a refrigerated container.The complexity in the above process poses problems in terms of information asymmetry and coordination costs for the stakeholders involved in the process. This is an opportunity for the implementation of blockchain technology in the field of agri-logistics for providing a single platform for the stakeholders to coordinate logistics information.From an entrepreneurial perspective, the implementation of blockchain technology in seaport logistics is an opportunity for agri-logistics startups and small and medium enterprises. This is because blockchain technology can be used for providing a platform for traceability as a service, providing real-time monitoring solutions, and providing digital documentation solutions for agricultural logistics.

Moreover, SMEs participating in agricultural export activities can use blockchain technology to increase their reliability and competitiveness in global markets by providing verifiable information about product quality, source, and environmental conditions. This would reduce information asymmetry between export and import companies, helping SMEs meet high-quality requirements set by global markets. Besides economic benefits, blockchain-based track and trace solutions can help promote green and sustainable logistics. Blockchain-based solutions can help minimise wastage, optimise routes, and increase the efficiency of cold chain logistics, thus helping reduce environmental impact.

Thus, the integration of blockchain with IoT and GPS technologies not only improves operational efficiency in seaport logistics but also supports sustainable supply chain innovation and promotes the development of entrepreneurship in the Agri-logistics sector in Asia.

2.1. Gap in tracking and tracing between the Buyer and Seller

Traceability can be divided into two: Upstream & Downstream. In upstream traceability, an item travels from the farm to the production plant; in downstream traceability, it travels from the production plant to the consumer. Normally, an item undergoes many changes even while in transit within the country, and this affects its shelf life, an important measure to determine the richness of the item. Multiple situations in transit can affect shelf life, including changes in environmental conditions such as temperature, ventilation, pressure, and heat. Hence, the buyer (exporter) may find the product's quality different (lower) from the original quality measured by the seller (farmer) during the initial dispatch stage, if the transit conditions are not properly traced and monitored. Thus, the seller and the buyer are subject to the risk of noncompliance with the product specifications, resulting in the rejection of the shipment or the renegotiation of the contract. (Lakkakula et al., 2021) explained the unique features of the blockchain technology in terms of immutability, secure transactions, and a distributed database across the entire supply chain and logistics network.

This gap in the traceability chain between the buyer and seller is not only leading to operational inefficiencies but also hinders the ability of small farmers, SMEs, and Agri-entrepreneurs to participate in high-value export markets. This is due to the unavailability of reliable and transparent data, which often disadvantages small farmers due to a lack of bargaining power and logistics support.

Blockchain technology in track and trace solutions can help to mitigate these challenges by providing a transparent and tamper-proof record of the product's conditions during the entire journey. This will enable all the stakeholders in the supply chain, including farmers and exporters, to have access to this data.

About sustainable entrepreneurship, this would provide scope for start-ups and Agri-tech companies to develop digital platforms of traceability, enabling farmers to connect directly with exporters and global markets. This would promote fair pricing, coordination, and inclusive participation of small farmers in global trade.

Furthermore, enhancing traceability would help ensure sustainability by minimising product rejection, thus reducing wastage, and ensuring efficient use of resources, which would be in line with efforts towards building resilient and sustainable agricultural supply chains in Asia.

2.2. Gap in tracking and tracing during transportation of the agricultural product from the port of exit at the Exporter's end to the port of entry at the Importer's end

In the case of Container transportation, there are several parties involved in the transportation of goods. Each party has its own record and report. The data is updated based on the information provided by other parties with limited visibility and traceability. There are chances of inconsistent data,

data inconsistency, and data location inconsistency (Johnston & Vitale, 1988). The Quality of the agricultural products is something that needs to be tracked and traced. There is no common location where the data is stored and made accessible to all the users at different levels. Also, the data is prone to manipulation and tampering (Vairetti et al., 2019). The absence of data integration and transparency in the transportation of goods internationally creates inefficiency and risks for the SMEs and small-scale exporters who are heavily dependent on third-party logistics providers and have limited control over the transportation conditions. This creates an opportunity for the deterioration of the products and may impact the sustainability of the Agri-export supply chain.

These issues may be addressed through the implementation of blockchain-based track and trace technologies, which may offer a common and shared platform where all the relevant stakeholders may have access to real-time and accurate information regarding the conditions of the shipments, their location, and the processes involved in the handling of the shipments. This may improve the coordination between the logistics service providers, port authorities, and exporters.

From an entrepreneurial perspective, the above gaps may offer opportunities for the development of new logistics startups and technology-driven SMEs that may offer blockchain-based solutions in the logistics sector. These technologies may revolutionise the traditional logistics sector and transform it into a new and digitally enabled ecosystem. In addition, the improved track and trace technologies may offer opportunities for the development of green and sustainable logistics. This may minimise the spoilage of the products during transportation and offer opportunities for the development of environmentally friendly and sustainable logistics. This may support the development of sustainable agriculture exports in the region. The above gaps may be depicted in Figure 1.

2.3 Use of blockchain

The IoT technology with embedded blockchain technology and a smart contract application allows for the monitoring of important parameters such as temperature, time, and location at regular intervals. This will help in taking corrective action and preventing a further decline in the quality of products. If the temperature at a location increases, corrective action will be taken for the rest of the transportation process. The transaction history will help in comparing and identifying the causes. The application will provide a smooth flow of information and will be helpful in planning and providing a transparent environment. The application will provide a platform for exchanging and sharing data parameters through the track and trace facility in various nodes/entities. This will provide coordination and better integration between various nodes/entities. The application will provide instantaneous settlement in case of any violation and will avoid costs incurred in settling such issues.

Besides reducing operational risks in agricultural supply chains, blockchain technology will be extremely beneficial in making such supply chains more sustainable by reducing spoilage and waste in products and efficiently utilizing logistics facilities. The ability to monitor and control environmental conditions in real-time also helps in reducing unnecessary waste and promotes the overall sustainability of agricultural export operations.

Thus, blockchain technology for track and trace innovations not only promotes efficient and effective logistics operations but also supports the promotion of sustainable supply chain innovations and entrepreneurship ecosystems in the Agri-export sector. Recent developments in electronic transportation management systems also demonstrate the role of disruptive innovations in transforming logistics operations in the supply chain (Jović et al., 2020). The seaport logistics process for the agricultural export supply chain under the conventional system is presented in Figure 1.

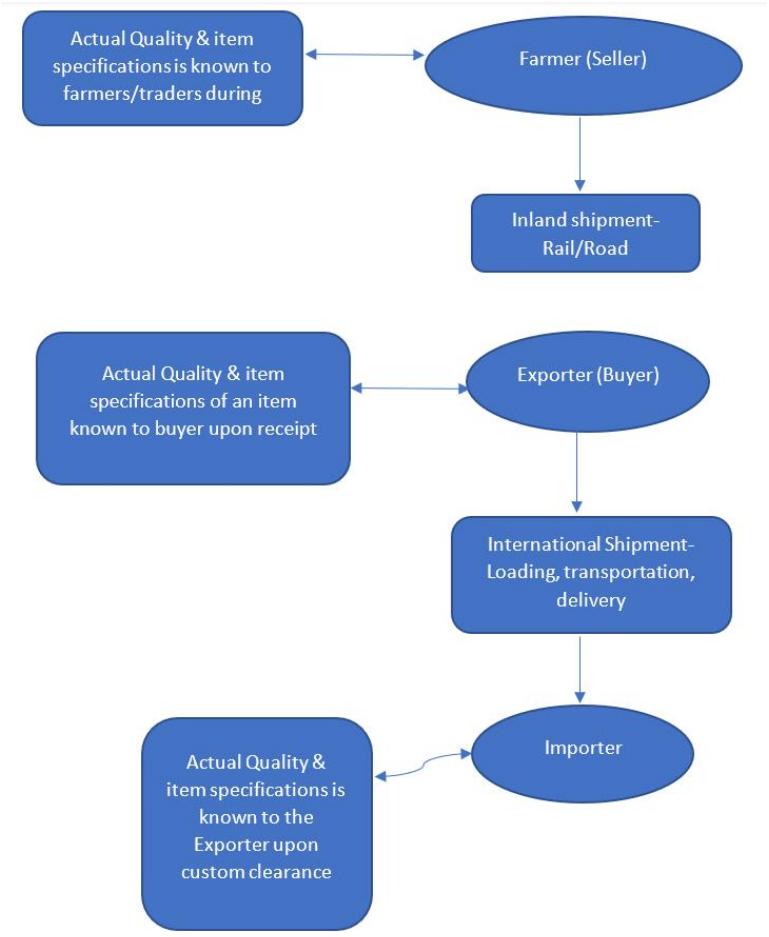

Figure 1: Traditional seaport logistics process for agricultural export supply chain without blockchain-based tracking and tracing

The blockchain-based track and trace system for seaport logistics is shown in Figure 2, highlighting the potential for all parties in the supply chain to benefit from the use of a common digital platform.

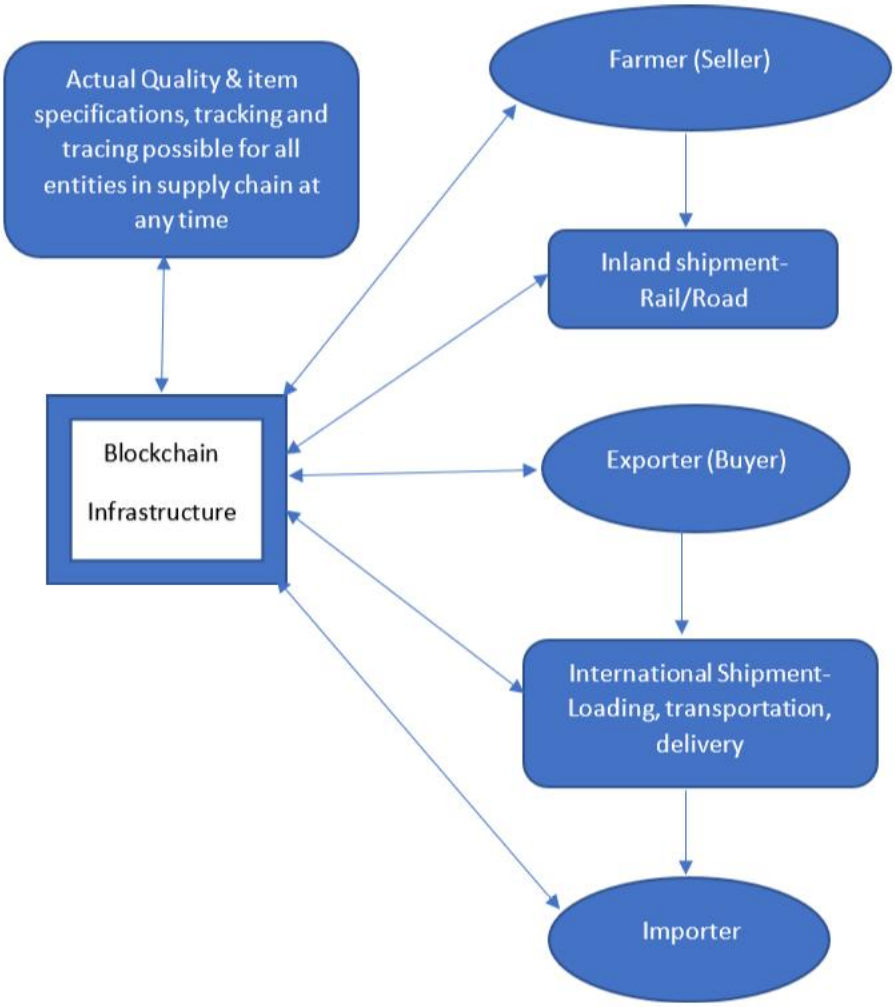

Figure 2: Blockchain-enabled track and trace framework for seaport logistics in the agricultural export supply chain

3. Outline of the proposed blockchain-based track and trace solution

This section outlines the architecture of blockchain technology, using a technical assessment of the requirements identified in the previous section, based on empirical analysis, against available research on blockchain architecture (Irannezhad, 2020; Ko et al., 2015). The proposed blockchain architecture is structured into the back end, sensors, and other data, as outlined in Figure 3.

Apart from its technical capabilities, the proposed blockchain-based architecture may also be used as an enabling tool for developing innovative business models in Agri-logistics. With the integration of digital technologies such as IoT, GPS, and blockchain, it may be used as a foundation for developing innovative business models by startups and SMEs in the development of cost-effective and efficient logistics solutions for perishable agricultural products. The overall architecture of the proposed blockchain-based track and trace system is presented in Figure 3, which comprises three main components: sensors and data, front-end interfaces, and back-end infrastructure.

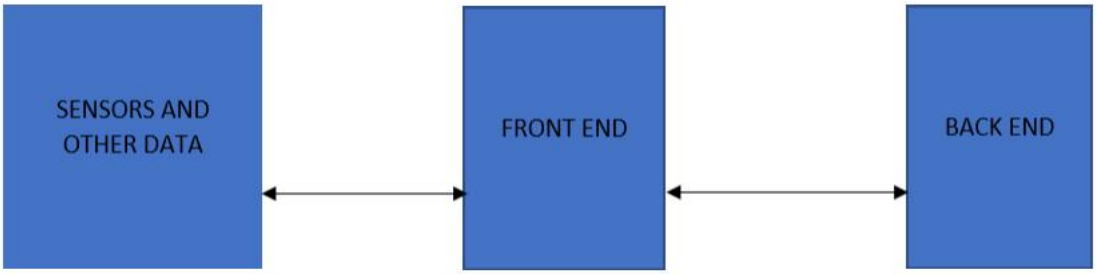

Figure 3: Proposed blockchain architecture for track and trace solutions in seaport logistics

Sensors and other data: A smart cold chain application framework (SCCAF) based on Cloud and IoT (Internet of Things) is proposed, which enables users to develop and apply cold chain management systems with low cost and in a short time and facilitates the use of any IoT devices to measure temperature such as RFID tags, WSN sensor nodes, etc. (Ko et al., 2015). GPS enables tracking the location of the items in transit.
The use of such sensor-based systems also creates opportunities for technology-driven enterprises to offer real-time monitoring services, predictive analytics, and data-driven logistics optimisation, thereby enhancing both operational efficiency and entrepreneurial innovation in the sector.

Front end: This comprises end-users registering new shipments and sending records of temperature, prices, and quality specifications to the Back end for tracking.
The front-end interface can be leveraged by SMEs and Agri-logistics startups to provide user-friendly digital platforms that simplify shipment tracking, improve decision-making, and enhance transparency for all stakeholders, including farmers, exporters, and importers.

Back end: The back end comprises the following components:

Blockchain platform: The decentralized public permissioned platform is inevitable. The Ethereum platform is proposed for its popularity in seaport logistics applications and for enabling smart contracts.
Such a blockchain platform can also act as a shared digital infrastructure supporting multiple stakeholders, enabling collaborative and decentralized logistics ecosystems that foster innovation and reduce dependency on centralized intermediaries.

Validation: The proposed blockchain platform uses the computationally light validation algorithm Istanbul Byzantine Fault Tolerance (IBFT), suitable for the public permission Ethereum platform.

Data storage and encryption: Off-chain data storage and encryption are proposed because many transactions are expected to remain forever.

Smart Contract: The buyer (Exporter), Importer, and logistics service provider negotiate and finalise the following terms of shipping:
(1) The quantity, time, and cost of the shipment.
(2) The product temperature is to be maintained during transportation.
(3) The payment terms.
(4) Importer and Exporter ports and probable transit route, considering the perishable nature
The buyer (Exporter) executes a smart contract in accordance with the finalised shipping terms.
Another important feature of smart contracts is that they allow for the automation of the compliance and payment processes. This helps in avoiding delays and disputes and creates trust among the stakeholders. This feature is also important for SMEs because they are often faced with problems such as delayed payments and contractual issues.
The logistics service provider exporter provides a container that is fitted with an IoT device.
The exporter ships the product in a container fitted with the IoT device.
All transactions between the logistics service provider and the transporters and shipping lines are executed offline.
Overall, the proposed system contributes to sustainability by ensuring optimal environmental conditions during transit, reducing food waste, and improving resource efficiency. By enhancing transparency and accountability, it supports the development of sustainable and responsible supply chains in agricultural exports. Furthermore, it enables the emergence of innovative, technology-driven business models in Agri-logistics, thereby promoting sustainable entrepreneurship in Asia.

4.0 Assessing the effectiveness of the proposed blockchain-based track and trace solution

4.1. Determinants and metrics for seaport logistics about the export supply chain of agricultural products

The export chain of agricultural products crosses international boundaries, and final consumers expect consistent quality and safety over time and are prepared to pay a premium price for Quality (Salin, 2003). Problems associated with perishable products, such as longer transit times, have increased, thereby influencing product quality (Cheaitou & Cariou., 2012; Arduino et al., 2015). Products are handled multiple times during ocean transportation that involves many ports (Salin, 2003). Liner shipping companies provide maritime transportation services after consultation with shippers and coordination with port operators (Dulebenets, 2017). The vessel's sailing speeds are adjusted according to weather and sea conditions (Wang & Meng, 2012). Therefore, the decay rate of perishable assets, such as agricultural products, must be accounted for in vessel scheduling. The Quality of products in transit deteriorates due to transportation time and adverse environmental conditions encountered, such as temperature (Dulebenets, 2017; Haass et al., 2015; Aung, M., &

Chang, Y., 2014). The agricultural product to be received by the customer before its shelf life expires (Jedermann et al., 2014; Dulebenets, 2017) imposes a time constraint on the value chain. A suitable temperature is maintained in refrigerated container boxes (called "reefers") that are used for the transportation of perishable products (Haass et al., 2015). This affects the nature of perishable product decay (Dulebenets, 2017). According to Filina-Dawidowicz and Gajewska (2018), perishable cargoes require adequate care during seaports' handling and storage processes. This situation is compounded by demand-related uncertainties regarding such shipments, which compel liner shipping companies to optimise their planning strategies (Wang & Meng, 2012).

In addition to traditional operational determinants, it is important to incorporate sustainability-oriented metrics while assessing seaport logistics performance. These include a reduction in food wastage, improvement in cold chain efficiency, energy utilisation in refrigerated transportation, and minimisation of environmental impact associated with delays and spoilage. Such metrics provide a more holistic evaluation of logistics systems in line with sustainable supply chain management practices.

The integration of blockchain-based track and trace systems enables the measurement and monitoring of these sustainability indicators in real time. By offering correct and unalterable information about temperature, transit time, and handling conditions, blockchain technology ensures better control over product quality and minimises uncertainties in logistics operations.

From an entrepreneurial viewpoint, such metrics for performance open opportunities for SMEs and Agri-logistics startups to innovate in data-driven logistics operations and performance monitoring, and analytics tools that may have positive implications for decision-making and sustainable business practices in agricultural exports.

Moreover, by incorporating sustainability metrics into this system, it becomes aligned with sustainable development principles by reducing resource wastage and supply chain vulnerabilities and promoting sustainable international trade practices, especially in the context of Asian agricultural export markets that are in a high-growth trajectory.

The key determinants and corresponding metrics used to assess product quality in seaport logistics for agricultural exports are summarized in Table 1, distinguishing between direct and indirect evidence of quality.

Determinant	Literature	Metrics
Direct evidence of Quality		
Final consumer preference and pricing are based on consistent quality over time.	Salin & Nayga, (2003); Kleinhenz & Bumarne	-
Perishable product with a low shelf life	Jederman et al. (2004)	Rate of deterioration of the product
Indirect evidence of Quality		
Vessel sailing time and handling time at the ports	Arduino et al., (2015); Aung & Chang, (2014); Haas, 2015; Dulebnets & Ozguven, (2017); Salin & Nayga, (2003); Filina-Dawidowicz & Gajewska (2018); Cheaitou & Cariou, (2012)	Transportation time
Temperature during transportation	Haass et al., (2015); Dulebenets & Ozguven, (2017); Jedermann et al., (2014); Aung & Chang, (2014);	Temperature

Table 1: Determinants and metrics for assessing quality in seaport logistics of agricultural export supply chains

4.2. Calculation of the remaining shelf life

(Aung, M. & Chang, Y., 2014) Moreover, (Jedermann et al., 2014) discussed the relationships among decreased product quality, shelf life, transportation time, and transportation temperature. The remaining shelf life of the product and the rate of deterioration of the product is used as the measures of product quality governed by the perishable nature of the product as specified in Table 1. (Jedermann et al., 2014) argued that when time and temperature data are captured from the point of harvest or production, logistics systems and managers can adjust the remaining transport time for products, matching products with a shorter shelf life to shorter routes and holding products with a longer shelf life in inventory or sending them on longer transport routes. Therefore, the remaining shelf life is calculated as the difference between the

shelf life of the freshly harvested product and the total transportation time. as follows:

1. The temperature coefficient corresponding to the temperature increase is obtained from the temperature curves for the product.
2. The calculated temperature coefficient is multiplied by the respective number of hours of the time interval obtained from the temperature-time curves for the product, and the sum of the products is calculated.
3. The fraction that this sum is of the constant K of that product will indicate exactly how far the deterioration of the lot in question has proceeded.

Apart from this, the calculation of the product's shelf life may also be used as an important aspect in the assessment of the overall sustainability of the agricultural supply chain. This is because the precise estimation of the product's shelf life may help in planning the logistics routes in an efficient manner, thus reducing any delay in the transportation process and avoiding any wastage of the product.

From the entrepreneurial perspective as well, this may help in providing opportunities for the development of innovative entrepreneurship in the Agri-logistics sector. This is because the use of data-driven approaches may help in the efficient calculation of the product's shelf life through the implementation of blockchain technology and IoT devices. This may also help in the efficient execution of sustainable business operations in the agricultural sector.

Thus, the calculation of the product's shelf life may not only be used as an important aspect in the efficient assessment of product quality but may also play an important role in enabling sustainable supply chain operations and entrepreneurship in the Agri-export sector.

4.3 Data collection and analysis

The extent of product deterioration (spinach) is calculated for the base-case and blockchain scenarios. The data-collection methods for the empirical analysis are presented in Table 2.

Sr. No.	Particulars of data	Source of data
1.	Transportation time	Logistics Service Providers
2.	Product temperature during transportation	Logistics Service Providers
3.	Temperature coefficient, Constant 'K' for the product	Platenius (1939)
4.	Voyage route mapping	Shipping Line & LSP

Table 2: Data inputs and corresponding sources used for empirical illustration of the blockchain-based track and trace model

5. Empirical Illustration

The following numerical example considers the export of one container load of the Spinach product from India (Nhava Sheva port) to Singapore (Singapore port). The recommended storage temperature of the product is 32°F.

The shipment is direct from Nhava Sheva to Singapore. It is assumed that the product is fresh at the start of transportation. The Exporter has entered a contract with a logistics service provider to transport the product in a refrigerated container within 11 days of the date of export at a temperature of 32°F. The Importer claims the product on receipt at the Singapore port.

This empirical illustration is also relevant from the perspective of sustainable entrepreneurship and SME participation in agricultural exports. This blockchain-based model may be implemented by exporters not only from large-scale export houses but also by small and medium-sized exporters and Agri-logistics startups that seek to leverage this model for enhanced traceability and quality assurance in international markets.

For small and medium-sized exporters, this blockchain-based model may be leveraged to reduce information asymmetry with international buyers by providing a clear and accurate picture of shipment conditions during transit. This may be instrumental in developing trust between exporters and international buyers.

Furthermore, Agri-logistics startups may leverage this model to offer novel and innovative services such as real-time cold chain monitoring and traceability as a service to exporters engaged in perishable agricultural products.

From a sustainability perspective, this model may be instrumental in reducing food spoilage and promoting sustainable and responsible resource utilisation in international markets. Thus, this proposed blockchain-based solution not only enhances the efficiency and effectiveness of international agricultural export operations but also contributes to sustainability in international markets.

5.1 Base case

In the base case, it is mentioned that the overall transportation time and temperature are included in the contract. However, it is not mentioned what methods are adopted for maintaining the temperature of the products during transportation. Thus, it can be said that the base case scenario includes an average temperature of 65 °F for 4 days and a normal temperature for the remaining days.

The above-mentioned scenario is an example of the problems that are encountered during traditional logistics, where there is a lack of real-time control and monitoring. This is a major issue for SMEs and small exporters, as they cannot afford advanced technology for maintaining the temperature of the products during transportation.

From a sustainable perspective, it can be said that the lack of control and monitoring of temperature conditions results in the deterioration of products, leading to a high level of food waste. This is a major issue for the environment, as there is a lack of proper environmental conditions during transportation.

Further, the base case scenario illustrates the limitations of conventional logistics practices in facilitating sustainable supply chain activities and entrepreneurial growth. Specifically, there is a lack of transparency and traceability, which affects trust levels, creating a limited scope for Agri-logistics startups/SMEs to offer value-added services.

5.2 Blockchain scenario

The exporter and logistics service provider collaborate in the development and agreement of the product's temperature profile over time during transportation. Blockchain technology with Internet of Things technology is used in this scenario. The product is transported in a container equipped with Internet of Things technology sensors to monitor the product's temperature during transportation. The blockchain technology scenario assumes that the product's temperature is consistent with normal throughout the entire transportation period. The GPS tracking mechanism is based on the actual route traversed compared to the agreed sailing route.

This scenario highlights the benefits of using blockchain technology in logistics to monitor and control the shipment conditions in real-time. The use of Internet of Things technology in conjunction with blockchain technology ensures that stakeholders have accurate information about the product's temperature and route during transportation.

From the entrepreneurial perspective, this model points out important opportunities for agri-logistics start-ups and SMEs in the development and use of blockchain technology monitoring systems, smart container technology, and digital logistics systems, which are important tools for small players to compete in the international market with reliable technology-based logistics services.

For SME exporters, the use of these systems increases the credibility and trust of international buyers about the compliance of the products with the established quality standards, which are important tools in preventing the risk of shipment rejection in international markets.

Regarding the sustainability of the Agri-logistics systems, the maintenance of the optimal conditions in terms of temperature during the transport process minimises the deterioration of the products, which is important in the development of efficient resource use in the Agri-logistics sector, contributing to the development of environmentally friendly Agri-trade practices.

Thus, the blockchain scenario not only improves operational performance but also promotes sustainable supply chain innovation and fosters entrepreneurship in Agri-logistics, particularly within the context of emerging Asian economies.

6. Results and discussion

The results for the extent of product deterioration under the base case and blockchain scenarios are reproduced in Table 3.

Scenario	Temperature profile during transportation		Temperature coefficient	Sum product of I and II	The extent of deterioration of the product* (%)
	Average temperature (°F)	Transportation time (Hours) I	II		
Base case	32	168	1	888	5.7
	65	96	7.5		
Blockchain	32	264	1	264	Nil

Table 3: Results in terms of the extent of deterioration of the product for the base case scenario and blockchain scenario

*K for spinach=840

Comparing the base-case and blockchain scenarios shows that blockchain significantly mitigates the risk of deterioration of perishable products during transportation. The nonexistence of a tracking and tracing mechanism in the base case is explained as follows:

The seller is aware of the product's quality at the time of sale. It is unknown to the logistics service provider, the buyer, and the Importer until it reaches the destination. Upon the consignment's arrival at the destination, the direct evidence of deterioration in the product's quality is known only to the Importer. The cause of deterioration in the product's quality, as indicated by indirect evidence of a temperature increase, is known only to the logistics service provider. For instance, Table 3 shows that increasing product temperature from 32 °F to 65 °F results in approximately 5.7% product deterioration. Such an increase in temperature could be due to various factors within the purview of the logistics service provider, such as a breakdown of the refrigeration equipment or deliberate switching off the refrigeration to reduce energy costs. The logistics service provider may manipulate the actual log of temperature readings during transportation without the other parties involved in the export transaction knowing.

Moreover, the seller may dispatch a substandard product, making it impossible to trace the defect back to the original product quality. The Importer in the base case is therefore exposed to risks. In the event of any deterioration in the product's quality, there is no means to investigate the root causes due to the non-availability of a common platform to evaluate data parameters, such as the product's temperature profile over time during transportation. Therefore, the Importer can either salvage the product and sell the same in the market at a discount, if possible, or dispose of the spoiled product as waste.

The change in the voyage path traversed can be easily traced through the GPS tracking mechanism, ensuring adequate remaining shelf life as per the agreed contract. In the event of any change to the vessel's route, the GPS tracker sends an alert to all concerned parties to either correct the route or explore alternative options, such as adjusting environmental conditions inside the containers or changing the vessel's speed, to prevent deterioration of perishable products.

The results have shown that the proposed blockchain-based scenario avoids product deterioration under a set of specific conditions, which proves its potential in terms of efficiency and quality in supply chain management. In this context, it is worth mentioning that from a sustainability point of view, such a reduction in deterioration is significant in terms of food waste reduction and optimisation in general.In addition, it is worth noting that based on the results obtained from the study, there is a potential role that blockchain-based track and trace technologies play in supporting the development of sustainable innovation in the supply chain. From an entrepreneurial perspective, the results indicate that there is a huge opportunity for agri-logistics startups and SMEs to develop and offer blockchain-based logistics services. This will help in the development of new value propositions and create new streams of revenue while improving the efficiency of the supply chain. In the case of SME exporters, the results indicate that the adoption of blockchain technology will improve the competitiveness of the exporters. This is because the technology will help in the reduction of risks related to product rejection and improve the compliance of the exporters with international quality standards. This will support the integration of the exporters into the global value chain and promote inclusive economic development.

In conclusion, the results indicate that blockchain technology not only improves the efficiency of the supply chain but also plays a critical role in the development of a sustainable, transparent, and innovation-driven supply chain in the agricultural export sector, particularly in the Asian region.

6.1 Mitigation of risk caused by the nonexistence of a tracking and tracing mechanism by using blockchain technology

The IoT embedded blockchain technology, combined with a smart contract application, enables tracking of critical variables such as temperature, time, and location at predefined intervals, which helps take timely corrective actions and prevent further deterioration in product quality. For instance, if the temperature at a location increases, corrective steps can be taken for the remainder of the transportation. The history of transactions will enable comparison, tracing, and identification of root causes. The application enables a seamless flow of updated, continuous information across nodes/entities, facilitating planning and creating a transparent environment. The application facilitates the exchange and sharing of data parameters via the track-and-trace function across various nodes/entities, enabling coordination and enhanced integration. The application enables instantaneous settlement in the event of any violation and eliminates the cost of settling disputes.

In addition to mitigating operational risks, the use of blockchain technology significantly enhances the sustainability of agricultural supply chains by reducing product spoilage, minimising waste, and ensuring efficient utilisation of logistics resources.

The ability to monitor and control shipment conditions in real time contributes to environmentally responsible logistics practices and supports sustainable trade.

From an entrepreneurial perspective, such blockchain-enabled systems create opportunities for Agri-logistics startups and SMEs to offer innovative services, including real-time monitoring, automated compliance verification, and dispute resolution platforms. These services can improve efficiency while reducing transaction costs and enhancing trust among stakeholders.

For SMEs and small exporters, the adoption of blockchain technology reduces dependency on intermediaries, lowers operational risks, and improves access to international markets by ensuring transparency and compliance with global quality standards. This promotes inclusive participation and strengthens the role of SMEs in global agricultural value chains.

Overall, blockchain-based risk mitigation mechanisms not only improve supply chain reliability but also contribute to the development of sustainable, transparent, and innovation-driven logistics ecosystems, particularly in emerging Asian economies.

7.0 Inference and policy implications

This research developed blockchain technology embedded with IoT functionality for tracking and tracing in seaport logistics for the agricultural export supply chain. The opportunities for blockchain technology were identified, and the nonexistence of a tracking and tracing mechanism in seaport logistics for the agricultural export supply chain was confirmed. The architectural requirements of the blockchain, including the blockchain platform, client nodes, validation algorithm, cryptography, data storage, and smart contracts, were outlined based on the export process and architectural design requirements for blockchain systems, to demonstrate the suitability of blockchain technology for seaport logistics. The determinants and metrics for seaport logistics about the export supply chain of agricultural products were developed. An analytical model based on relevant literature was used to carry out an empirical analysis for a numerical example with data from primary sources such as logistics service providers based in India, secondary sources from relevant literature, and the authors' estimates. The analysis was carried out for two scenarios: the base case and the blockchain scenario. The numerical example considered exporting one refrigerated container load of the Spinach product from India (Nhava Sheva port) to Singapore. The results showed that blockchain significantly mitigates the risk of deterioration of perishable agricultural products during transportation. The study confirmed the nonexistence of a tracking and tracing mechanism by using direct and indirect evidence of product quality. It also presented the potential of blockchain embedded with IoT, GPS, and smart contracts to enable timely actions to prevent a decrease in product quality, with optimal monitoring of data parameters through tracking and tracing of essential variables such as temperature, time, and location. The system allows for instantaneous settlement in case of any violation and eliminates the cost of settling disputes. The entire transaction history, node details, and timestamp help in complying with the requirements.

From a sustainability perspective, the research finding indicates that the blockchain technology-based logistics system can help in reducing food wastage and increase the overall efficiency and sustainability in the agricultural sector. The proposed system ensures optimal storage and transportation conditions for the products, thus contributing to sustainable Agri-export.

The research highlights the opportunity costs of not using the blockchain application, including wasted inputs and capacity that must be paid for, fewer sellable products to bear the fixed costs, and lower profits due to declining sales.

From an entrepreneurial perspective, the study also underscores the opportunities for innovation in Agri-logistics, which can be created using blockchain technology, for example, traceability platforms, real-time monitoring, and smart contracts for logistics. These can, in turn, create opportunities for new entrepreneurial ventures, particularly for SMEs, to effectively participate in global agricultural value chains.

The study also has policy implications for seaport logistics stakeholders, exporters, and importers, particularly in raising awareness and appreciating the benefits of using blockchain technology, particularly for tracking and tracing. Blockchain technology can also be a solution for global problems, for example, ending world hunger by feeding an ever-increasing world population, as well as the millions of tons of avoidable waste in the food chain.

Therefore, it is recommended that policymakers in Asian economies foster the use of blockchain technology in agricultural supply chains by developing digital infrastructure and providing financial and technical support to SMEs and Agri-logistics startups. It is recommended that policymakers in Asian economies create a favourable environment for the development and use of blockchain technology in agricultural supply chains. This will foster innovation and competitiveness in agricultural exports.

Moreover, it is recommended that policymakers in Asian economies and industry stakeholders foster the use and development of blockchain technology

in conjunction with other digital technologies such as IoT and data analytics to foster sustainable supply chain innovation.

The adoption and use of blockchain technology in logistics are in line with some of the Sustainable Development Goals (SDGs), such as SDG 2 - Zero Hunger, SDG 9 - Industry, Innovation and Infrastructure, SDG 12 - Responsible Consumption and Production, and SDG 8 - Decent Work and Economic Growth.

Further research is recommended to study the application of blockchain technology in different supply chains. For example, the potential of blockchain technology in lowering transactional costs in seaport logistics. This model has been developed for a single echelon supply chain. Future research may extend this model for a multi-echelon supply chain.

Future research may also focus on the potential of blockchain technology for enabling inclusive entrepreneurship and supporting small-scale producers' access to global markets and the sustainability of agri-food systems in different contexts.

8. Conclusion

This study demonstrates the potential of blockchain technology, integrated with IoT and GPS, to enhance tracking and tracing in seaport logistics for agricultural export supply chains. By addressing key gaps related to information asymmetry, lack of transparency, and inadequate monitoring of shipment conditions, the proposed blockchain-based solution significantly improves product quality management and reduces the risk of deterioration during transportation. The empirical illustration confirms that maintaining optimal environmental conditions through real-time monitoring can eliminate product spoilage and enhance overall logistics efficiency. Beyond operational benefits, the study highlights the broader implications of blockchain adoption for sustainable entrepreneurship. The proposed system enables the development of innovative business models such as traceability platforms, real-time monitoring services, and smart contract-based logistics coordination, creating new opportunities for Agri-logistics startups and small and medium enterprises (SMEs). This enhances their ability to compete in global markets by improving trust, compliance, and transparency. From a sustainability perspective, the solution contributes to reducing food waste, optimising resource utilisation, and promoting environmentally responsible logistics practices. These outcomes align with key Sustainable Development Goals, including zero hunger, responsible consumption and production, and industry innovation. Overall, the study underscores the role of blockchain as a transformative enabler of sustainable, transparent, and innovation-driven supply chains, particularly in the context of agricultural exports in Asia.

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