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The Integration of RFID and Blockchain Technology for the Supply Chain Traceability of Durians

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Abstract

Traceability is an essential practice to ensure transparency, authenticity, and regulatory compliance in modern agricultural supply chains, especially high-value agricultural products. Regarded as the king of fruits in Southeast Asia for its unique taste, texture, and aroma, durian dominates the market of exported fruit commodities. However, recurring issues such as fraudulent GAP numbers, mislabelled origins, premature harvesting, and product tampering undermine consumer trust and export credibility. To address these challenges, this study presents an integrated traceability architecture combining RFID, a MySQL database, an automated Node.js backend, and Ethereum-compatible smart contracts. The developed system enables automated ingestion of physical RFID data, secure on-chain recording via immutable ledger functions, and optional generation of ERC-721 NFTs as digital certificates. Empirical validation includes RFID read-rate testing, blockchain performance measurement, and gas usage analysis. Carton-level tagging, wherein a single RFID tag is attached to a carton rather than each individual fruit, significantly reduces per-durian blockchain cost. The results demonstrate that the proposed architecture is technically robust, flexible, economically scalable, and suitable for SME use in high-value or ultra-premium fresh-produce chains.

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1. Introduction

Durian is a tropical fruit primarily grown in Thailand and Southeast Asia, thriving in hot and humid climates. Thailand is home to many durian varieties, with the most common durian clones being Gob, Chane, Kan Yao, and Monthong. Known for its unique taste and exotic aroma, durian has rapidly gained popularity, especially in China. However, its harvest season occurs only during the summer and lasts for a limited period. Therefore, durian is considered a highly valuable agricultural commodity in Thailand, with strong demand both domestically and internationally. China is the main export destination, and due to its rising popularity, durian prices can reach up to 130 Baht (≈ 4 USD) per kilogram. This growing demand has led to a rapid expansion of durian cultivation in recent years.

In Thailand, durian is cultivated in several regions, with Chanthaburi province being one of the most prominent due to its ideal climate and fertile soil. These conditions contribute to the unique and bold flavour of durians grown in the area, making them highly sought after. As a result, Chanthaburi durians consistently fetch premium prices, and China remains the primary market. In 2024, durian exports from Chanthaburi were valued at 8.38 billion Baht. However, the lucrative nature of this market has led to challenges, such as the illegal smuggling of cheaper durians from neighbouring countries into Thailand. There are several reports that these smuggled durians are falsely claimed to be of Thai origin, often obtaining fraudulent GAP certifications before being re-exported.

Another serious concern is the harvesting of unripe durians. In an effort to meet export demand quickly and increase profits, some farmers and traders harvest durians before they are fully mature. These unripe fruits lack the proper flavour, aroma, and texture, leading to customer dissatisfaction, particularly in key markets like China. This practice not only diminishes consumer trust but also damages the reputation of Thai durians as a premium product. Currently, the government has acknowledged this issue, and numerous measures, e.g., mandatory harvest schedules and rigorous quality inspection programs, have been implemented to eliminate these problems.

More recently, another emerging issue is the yellow dyeing of durians – a fraudulent practice in which sellers apply yellow dye to the skin of unripe or low-quality durians to make them appear ripe and appealing. This deception is aimed at increasing sales, particularly in export markets where consumers expect high-quality produce. This raises serious concerns about food safety, customer confidence, and the overall integrity of Thailand's durian industry.

Given all the issues mentioned above, although these problems are well recognized by the relevant authorities and significant efforts have been invested to address them, an effective and sustainable solution is still required. Consequently, the ability to trace durian provenance is considered as one of the powerful solutions, since it is essential for ensuring product authenticity and safety of products.

Numerous studies have been conducted on agri-food supply chains to practically support the complementary role of blockchain and IoT in implementing efficiency, transparency, and authenticity. Lin et al. (2018) showed how the blockchain technology integrated with an IoT sensors-based system for smart agriculture. In their design, IoT sensors continuously monitored environmental variables like temperature, humidity, and soil pH, while blockchain provided the secure foundation. Smart contracts automated agreements, ensuring transparency in stakeholder interactions. The primary objectives were the creation of transparent and tamper-proof records across the supply chain to ensure food safety and quality.

Salah et al. (2019) designed a traceability system to improve both feasibility and scalability of a soybean supply chain. The Ethereum-based system collected soybean data such as origin, growth progress, and quality. Smart contracts automated and managed key transactions across the chain, from farmer seed purchases to processor sales, shipping, and end-consumer purchases.

Prashar et al. (2020) introduced a decentralized system aimed at improving visibility in India's agricultural chains. The model tackled persistent challenges such as food safety concerns, fraudulent practices, and operational inefficiencies. The important outline was the argument of how blockchain's decentralized, non-editable design could overcome fragmented record-keeping by ensuring that all agricultural transactions and transfers were recorded transparently and securely. As a result, the proposed model enabled all stakeholders, from farmers to consumers, to access reliable data regarding the origin, handling, and food quality.

Yang et al. (2021) presented a hybrid traceability approach for agricultural products, combining both on-chain and off-chain data storage to balance security and efficiency. The smart contract featured two algorithms: uploading information to the blockchain and assigning reputation values. Moreover, sensitive and non-sensitive records were separated to balance privacy and efficiency. Extensively, sensitive data were protected with CBC encryption before being added to the blockchain, while non-sensitive records were kept locally but linked with SHA-256 hashes for verification.

Yi et al. (2021) developed a real-time traceability system for monitoring and managing agricultural product transactions, integrated with IoT technology to collect environmental and growth data. The transaction traceability, visible to all stakeholders, was based on a proposed blockchain-based approach, enhancing its credibility and transparency. They organized their model into three tiers: (1) an application layer where producers registered products and sensor data was gathered, (2) a logic layer where blockchain smart contracts validated the records, and (3) a physical layer where sensor devices transmitted real-world product data.

Mane et al. (2022) implemented an agricultural smart contract integrated with IoT technology for the purpose of safeguarding the integrity of agricultural data (humidity, light exposure, soil PH, and temperature), which was collected by sensors. Afterwards, these environmental data were immutably stored in blocks by using the blockchain technology. The Kaleido interface was used as a functional testing platform. This implementation led to the reduction in agricultural pollution and financial loss.

Varavallo et al. (2022) proposed a sustainability-oriented platform applying a green blockchain solution with IoT technology on the dairy supply chain, covering milk production, processing, seasoning, packaging, and consumer application. The transparency, security, and customer confidence across all stages of milk production and distribution were emphasized to enable the integration of environmentally sustainable blockchain technologies. The designed platform not only ensured the record of immutable data but also minimized the environmental footprint commonly associated with traditional blockchain systems.

Wassenaer et al. (2023) reviewed blockchain traceability models and identified the role of blockchain tokens in the agri-food supply chain, focusing on their contribution to the circular economy and sustainability. The study signified that the tokenization had impacts on the circular economy in three aspects, i.e., the traceability enhancement of digital and physical objects, the improvement of credibility and transparency of claims, and the facilitation of business environment with incentives.

Ellahi, Wood, and Bekhit (2023) explored broader blockchain-based frameworks for food traceability. The study indicated how to connect these frameworks to Industry 4.0 and Web 3.0 technologies, e.g., AI, big data, cloud computing, GPS, IoT, QR-code, RFID, smart contracts, and NFC. The goal was the improvement of auditability, efficiency, response times, and sustainability. The gap analysis on the implementation of AI, big data, and Web 3.0 was also performed, and it pointed out the need for more comprehensive and interoperable models to achieve the full potential of applying blockchain technology in the food industry.

Hawashin et al. (2023) showcased the use of composable NFTs to trade and manage high-value packaged food products. In this study, NFTs were based on the ERC-721 standard and implemented on the Ethereum blockchain. The smart contract algorithms included raw material NFT minting, auctioning, and listing; packaged product NFT creation and minting; lot NFT creation and minting; lot NFT auctioning and listing; and redeeming of packaged product NFTs. The traceability, auditability, and product management, were enabled by the proposed system.

Bhadra et al. (2024) introduced AgroBLF, a comprehensive blockchain-based framework specially tailored to address the critical challenges of applying smart agriculture in developing countries. The issues included price volatility, middlemen exploitation, crop spoilage, and weak monitoring mechanisms. Ethereum smart contracts were leveraged and written in Solidity, and the system enhancement was based on product traceability, the integration of cold storage logistics, fair payments assurance, government transparency on subsidy distribution, and parametric insurance for farmers. The performance indices were gas efficiency, CPU utilization, latency, and transaction throughput.

Chiaraluce et al. (2024) examined the adoption of blockchain in high-value European agricultural production with a focus on efficiency, sustainability, and transparency. Targeting the wine and olive sectors, the study addressed food safety, fraud prevention, and the environmental and social dimensions of blockchain implementation to reduce waste and improve supply chain efficiency. An important finding was the specific adoption gap between these two sectors. Another interesting aspect was the capability of blockchain to efficiently drive the social sustainability as well as social awareness.

Ordonez, Gonzales, and Corrales (2024) explored the impact of blockchain technology on strengthening sustainable agriculture in South America from 2018 to 2023 by enhancing traceability, transparency, and trust across supply chain. The key benefits of blockchain technology were data security, fraud prevention, certification by smart contracts and NFTs, and supply chain efficiency. The regional leaders to adopt blockchain in agricultural supply chain were Brazil, Chile, Colombia, and Peru, while the focused products were coffee and wine. On the other hand, the limitations of application were cost-related barriers, scalability, and technical complexity.

Pal et al. (2025) employed the method of smart farming, i.e., cloud, big data, and IoT, combined with blockchain technology to come up with the solution for agricultural stakeholders. These benefits included the improvement of transparency and resilience in the supply chain, including the enhancement of safety, quality, and trust among customers. The study provided practical guidelines for stakeholders to implement blockchain in real-world scenarios.

Wang et al. (2024) presented an innovative case study of implementing blockchain and NFTs to enhance traceability in the supply chain of cotton lint. A digital system, ERC-721 based NFTs, was utilized to uniquely represent seed cotton, lint, and quality inspection certificates – paired with blockchain and InterPlanetary File System (IPFS) for secure, immutable storage of metadata. The target was the dismantlement of traditional information silos, the transparency improvement from harvest to sale, and the fortification of consumer trust in cotton quality.

Li et al. (2024) studied the integration between RFID and blockchain system to trace agricultural products. The focus of this study was the application of SM3 algorithm on RFID reading regarding tag authentication, data integrity, message authentication, and key derivation. The objective was the optimization of this algorithm leading to increase the accuracy of traceability data and reduce the execution time. The theoretical analysis on the RFID technology was also discussed, and the passive RFID sensor was designed to ensure the accurate transmission of traceability data.

According to literature, a clear consensus signifies that the integration between IoT and blockchain technologies holds a substantial promise for strengthening agricultural traceability by enhancing data integrity, transparency, and stakeholder trust. Previous studies demonstrate diverse implementation ranging from IoT-sensor monitoring, hybrid on-chain/off-chain data models, encrypted provenance records, and sustainability-oriented platforms, to tokenization schemes and NFT-based certification, but the research gaps also highlight persistent limitations related to system complexity, interoperability, and high deployment and transaction costs, particularly for SMEs. Many existing frameworks rely heavily on manual data entry, lack seamless integration between the physical identification layer and blockchain, or face bottlenecks due to the high gas consumption of frequent on-chain operations. These challenges are especially highlighted in high-value supply chains, where authentication, anti-fraud protection, and reputation preservation are commercially critical. Building on these research gaps, this study focuses on developing a practical, automated RFID–blockchain architecture that reduces technical overhead and operational cost. Motivated by concerns about blockchain throughput, gas price volatility, and network congestion identified in prior research, this work also incorporates a scalable logistics strategy – specifically, batch-level tagging and selective execution of essential smart-contract functions – to minimize transaction frequency while preserving immutability and provenance integrity. This design directly responds to the barriers identified in the literature and proposes a cost-efficient, small and medium enterprise (SME)-feasible model for improving traceability in the durian supply chain. Furthermore, the research results can also be used as an implementation example for other high-value or ultra-premium fruits.

2. Aims

To address the limitations identified in the literature and support effective traceability in the durian supply chain, it is essential for farmers, buyers, exporters, customers, and related stakeholders to be able to reliably track and verify the authenticity of durian origin. In this study, the focus is on developing a practical and cost-efficient traceability solution by integrating RFID technology with a structured database and a streamlined blockchain architecture capable of automated data synchronization. The system was designed to eliminate manual data entry by employing a Node.js backend that directly ingested RFID scan data and embedded essential metadata on-chain through an immutable ledger function. Rather than relying on multiple high-cost operations, the architecture supports selective activation of blockchain features, such as optional NFT minting, depending on economic feasibility. Therefore, the research objectives include validating the traceability system through RFID read-rate experiments, assessing blockchain performance in terms of confirmation time and gas usage, and proposing scalable logistics strategies, particularly carton-level tagging, to ensure accuracy and scalability in high-volume durian processing environments.

3. Methods

3.1. Radio Frequency Identification (RFID)

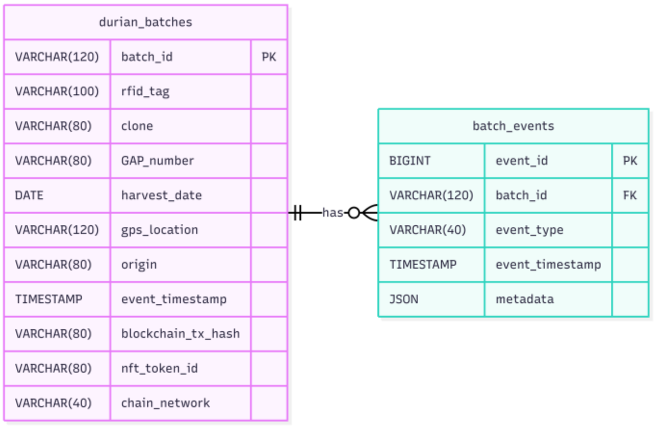
Radio Frequency Identification (RFID) technology is a wireless automatic identification method that utilizes electromagnetic fields to transfer data between a reader and an electronic tag attached to an object. In agricultural supply chains, RFID is employed to track products from farm to consumer by embedding passive or active RFID tags into packaging, containers, or even directly onto the products. Each RFID tag contains a unique RFID key (Unique Identifier or UID), and RFID readers – fixed or handheld – interact with these tags via radio signals, transmitting the collected data to a centralized system in real time. As a result, RFID tags were adopted in this research at the physical layer to capture durian-specific information, which was then linked to blockchain smart contracts deployed on the Ethereum-compatible test network. The chosen RFID tag was equipped with a chip compatible with NXP MIFARE Classic 1K, and it operated in the high frequency band (13.56 MHz). It complied with ISO 14443A. The tag size was 55 mm x18 mm, as shown in Fig. 1(a). The RFID tag was read by using the RFID reader connected to a personal computer (Fig. 1(b)).

(a) (b)

Fig 1. (a) RFID tag; (b) RFID reader

3.2. Database Design

A relational database using two-table schema was implemented using MySQL to provide secure, structured, and scalable storage for RFID-captured traceability data. The database served as the authoritative digital repository linking physical RFID scans with subsequent blockchain transactions. The Entity–Relationship (ER) diagram illustrating the database structure is depicted in Fig. 2. The primary table, durian_batches, stores a single record for each traceability unit, uniquely identified by batch_id and associated with one RFID tag. In this study, the term batch is used as a database abstraction denoting the smallest traceable unit, rather than a production lot. Accordingly, a batch_id may represent an individual durian or a carton containing multiple durians, depending on the tagging configuration employed. The table includes attributes such as clone, GAP number, harvest date, geographic origin, event timestamp, and blockchain-related fields (e.g., transaction hash, NFT token ID, and blockchain network). The secondary table, batch_events, records lifecycle events (e.g., packing, inspection, and transport) and maintains a one-to-many relationship with the primary table via a foreign-key constraint. Referential integrity is enforced at the database level, while a JSON field is used to support flexible and extensible storage of event-specific metadata, enabling scalable traceability across different aggregation levels without requiring structural modification of the schema.



durian_batches

VARCHAR(120)	batch_id	PK
VARCHAR(100)	rfid_tag	
VARCHAR(80)	clone	
VARCHAR(80)	GAP_number	
DATE	harvest_date	
VARCHAR(120)	gps_location	
VARCHAR(80)	origin	
TIMESTAMP	event_timestamp	
VARCHAR(80)	blockchain_tx_hash	
VARCHAR(80)	nft_token_id	
VARCHAR(40)	chain_network	

batch_events

BIGINT	event_id	PK
VARCHAR(120)	batch_id	FK
VARCHAR(40)	event_type	
TIMESTAMP	event_timestamp	
JSON	metadata	

Fig 2. Entity-relationship diagram of the database

3.3. Automated Integration Layer

An automated integration layer was implemented using a Node.js backend to enable seamless data flow between the RFID scanning system, the relational database, and the blockchain. As illustrated in Fig. 3, upon each RFID scan, the client application transmits a structured JSON payload to a RESTful API endpoint hosted by the backend service. The backend validates the incoming data and records the scan in a MySQL database (durian_traceability). The system then queries the corresponding batch or carton record to verify traceability information before constructing, signing, and submitting the appropriate blockchain transaction via the ethers.js library. The transaction is executed on an Ethereum-compatible blockchain network to immutably register durian provenance metadata or lifecycle events. Once the transaction is confirmed, the resulting transaction hash and the minted NFT token identifier are written back to the batch_events table in the database. This bidirectional update ensures that the database state remains synchronized with the blockchain ledger, while maintaining consistency between physical RFID events and their immutable digital representations. The proposed integration layer provides end-to-end automation for agricultural traceability, reduces human intervention, and supports scalable multi-stakeholder operations.

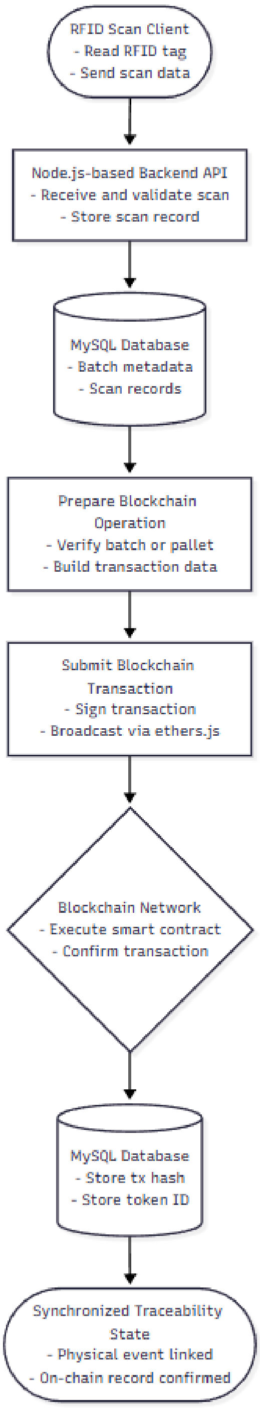


Fig. 3 RFID-to-Blockchain workflow

3.4. Smart Contracts

Ethereum-compatible smart contracts were developed in Solidity to provide the core on-chain functionalities required for provenance recording, data integrity, and digital authentication. In this study, three smart contracts were deployed on the Sepolia network. DurianBroadcast emits structured blockchain events to create an auditable log of RFID scan activities and metadata updates. DurianLedger maintains an immutable registry that maps RFID identifiers to durian batch records, enforcing data integrity by preventing record alteration and duplicate entries. DurianChanNFT is an ERC-721–compliant contract responsible for minting non-fungible tokens that serve as digital certificates of authenticity.

All three contracts are programmatically invoked by the backend integration layer following RFID scan events. The backend directly interacts with the broadcasting and ledger contracts to anchor traceability data on-chain, and it also directly invokes the NFT contract to mint authenticity tokens. NFT metadata are prepared off-chain and stored via IPFS, with the resulting tokenURI supplied to the NFT contract during minting. This architecture ensures tight coupling between physical scan events, off-chain metadata storage, and on-chain verification. Collectively, the smart contract suite provides a secure, tamper-resistant mechanism for recording critical supply-chain information and establishing verifiable ownership and provenance. The system architecture illustrating the backend integration with the Sepolia smart contract suite is shown in Fig. 4.

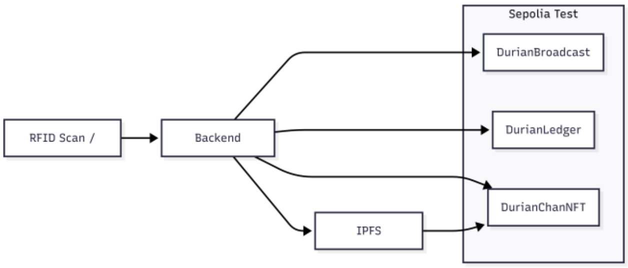


Fig 4. Backend integration with Sepolia smart contracts

Fig. 5 illustrates how these smart contracts are synchronized within a unified backend workflow. The process begins at the backend layer, where RFID UID input and batch-level validation are performed to ensure that incoming scan data conforms to predefined consistency and completeness rules. Batch-level validation refers to the verification of logical traceability unit (individual durian or a carton) depending on the configuration of physical tagging.

After the validation, the backend prepares a structured metadata payload representing the current traceability state of the corresponding batch. Depending on system configuration and the traceability stage, the prepared metadata may be optionally uploaded to IPFS, yielding a content identifier (CID) that serves as a compact reference to off-chain metadata. The backend then selectively invokes one or more blockchain smart contracts based on the intended operation. For event-level traceability, the DurianBroadcast contract is called via the broadcastDurian function to emit scan-related events, enabling lightweight and scalable logging of supply-chain activities. For authoritative record keeping, the DurianLedger contract is invoked through addDurian function to store immutable batch records directly on-chain. In cases where a digital certificate of authenticity is required, an ERC-721–based NFT is minted by calling the mintNFT function, using the corresponding tokenURI that may reference the IPFS CID.

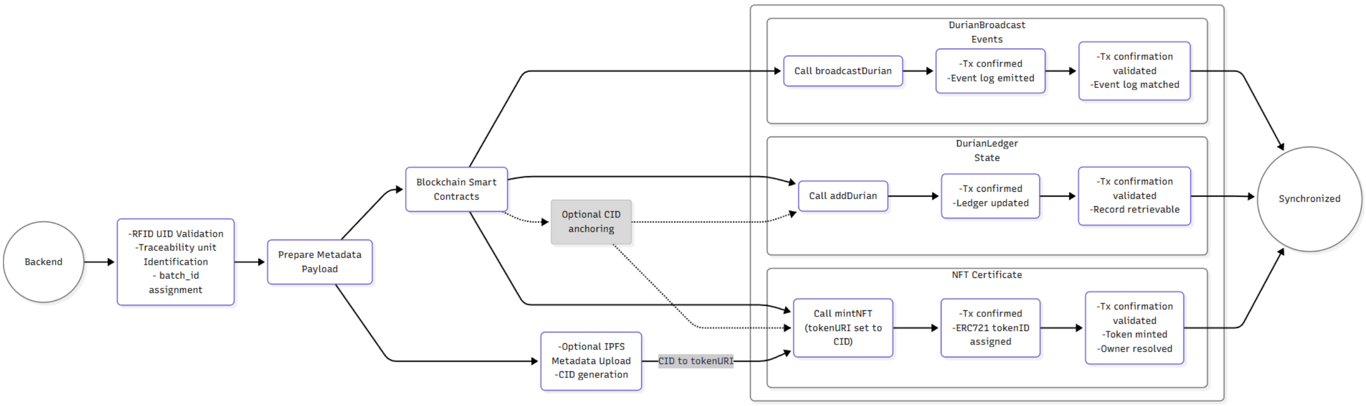


Fig 5. Smart-contract–level traceability workflows

Each contract invocation is executed as a blockchain transaction and independently validated according to its functional role. Event-based operations are validated through transaction confirmation and event log inspection, ledger operations are validated by retrieving stored records using the RFID UID, and NFT issuance is validated through token existence, ownership resolution, and tokenURI consistency checks. Together, these coordinated workflows enable flexible traceability execution while maintaining clear separation between high-frequency event logging, persistent state storage, and optional certification. This design allows the system to balance cost efficiency, scalability, and data integrity across different stages of the durian supply chain.

3.5. Gas Usage

Gas is the measurement unit for computational work on Ethereum and the Ethereum Virtual Machine (EVM) compatible network. It quantifies the computational effort required to perform specific activities, e.g., the execution of a function, data written to the blockchain, smart contract deployment, and Ethereum (ETH) or tokens transfer.

-Execution Gas Used: Execution gas used is the amount of actual gas consumed by the EVM to perform transaction logics including storage operations, arithmetic and logic, event emission, and contract function execution.

-Transaction Cost: Transaction cost is the total gas paid by the sender for the transaction, including execution and intrinsic as shown in equation (1).

$$\textit{Transaction Cost} = \textit{Execution Gas} + \textit{Intrinsic Gas} \tag{1}$$

The overhead cost is the minimum gas required before any code execution starts.

-Cost in ETH and USD: To find the final price, the total gas units are multiplied by the Effective Gas Price (Base Fee + Priority Fee) by following (2) and (3), consecutively.

$$\begin{aligned}\textit{Cost (ETH)} &= \textit{Transaction Cost (Gas)}\\ &\times \textit{Effective Gas Price (ETH)}\end{aligned} \tag{2}$$

$$\textit{Cost (USD)} = \textit{Cost (ETH)} \times \textit{ETH price (USD)} \tag{3}$$

where the unit of Gas Price is gwei (10^{-9} ETH).

4. Results

4.1. RFID Implementation

In this pilot study, harvested durians from an orchard in Chanthaburi Province were registered into the traceability system using RFID tagging. Durians with two types of tags, hang tag and label tag, containing RFID, are depicted in Fig. 6 and 7. A durian with RFID hang tag is presented in Fig. 6, and Fig. 7 demonstrates a durian with RFID label tag. Each durian was assigned a unique RFID tag, while an alternative carton-level tagging approach – where a single tag was placed on a carton of multiple fruits – was also evaluated to reduce scanning workload and associated blockchain transaction costs. When an RFID tag was scanned, the UID and relevant batch metadata – including harvest date, clone, GAP number, GPS coordinates, and origin – were automatically captured by the Node.js backend and stored in the MySQL database, eliminating the need for manual entry by farmers or middlemen.

4.2. RFID Read-Performance Results

Read performance was strongly influenced by both surface geometry and the distance between reader and RFID tag. When a passive tag was affixed to a flat mounting surface – such as a printed label – the planar alignment improved inductive coupling efficiency, resulting in highly stable read behaviour. Therefore, adhesive RFID tags were applied on flat-surface hang or label tags for the best read-performance results. Upon 30 readings, the system achieved the success rate of 100% at the distances of 0-3 cm. The test was conducted with a 0° alignment angle between the tag and the reader. To validate the application under practical operating conditions, the test was extended to evaluate different tag orientations (the alignment angle between RFID tag and the reader antenna), since operators tend to scan tags at varying angles. The chosen orientations were 45° and 60°, and the results indicated a 100% reading success at a distance within 1.5 cm for both orientations. However, the tag could not be successfully read at either orientation when the reading distance exceeded 2 cm. The corresponding results regarding distances and orientations are shown in Table 1.

Fig 6. Durian with RFID hang tag

Fig 7. Durian with RFID label tag

Table 1. RFID reading success rate at 45° and 60° orientations

Distance	**1 cm**		**1.5 cm**		**2 cm**	
Angle	**45°**	**60°**	**45°**	**60°**	**45°**	**60°**
Success rate	100%	100%	100%	100%	0%	0%

4.3. Smart Contract Implementation

To assess the implementation of smart contracts, 30 repeated executions were included in the experimental dataset. According to the results, the broadcastDurian function achieved the average transaction confirmation latency of 15.4 s (minimum = 11.21 s, maximum = 36.95 s, standard deviation = 6.42 s), and it confirmed fast and stable execution under test-network conditions. Moreover, the implementation of this function also reflected lightweight and event-only design. The immutable ledger insertion (addDurian) and ERC-721 minting (mintNFT) functions exhibited computational demands, consistent with their additional storage writes, validation logic, and ownership mapping operations. The addDurian function handled on-chain storage operations and duplicate-entry validation, and the latency was as follows: average = 14.67 s, minimum = 11.18 s, maximum = 37.06 s, and standard deviation = 6.43 s. Similarly, the following parameters, average = 14.23 s, minimum = 11.19 s, maximum = 32.7 s, and standard deviation = 6.09 s, indicated the latency of mintNFT function, since it needed the higher execution complexity of ERC-721 token minting, including ownership mapping and metadata registration. The results indicated that all observed latencies remained within acceptable bounds and showed no abnormal outliers, indicating stable and predictable execution behaviour suitable for batch-level blockchain-based traceability systems. The latency results are summarized in Table 2, while the latency distribution histograms for each transaction function are shown in Figs. 8, 9, and 10.

Table 2. Latency of each function

Function	**Avg. Latency (s)**	**Min. Latency (s)**	**Max. Latency (s)**
broadcastDurian	15.40	11.21	36.95
addDurian	14.67	11.18	37.06
mintNFT	14.23	11.19	32.70

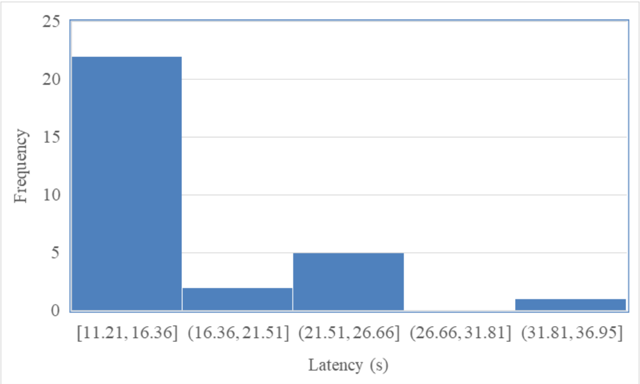


Fig 8. Latency distribution of broadcastDurian transactions

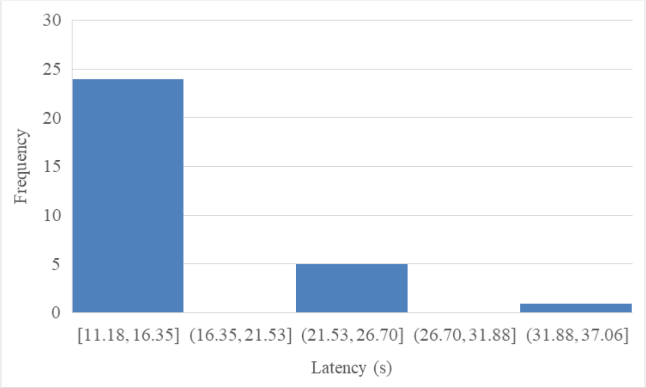


Fig 9. Latency distribution of addDurian transactions

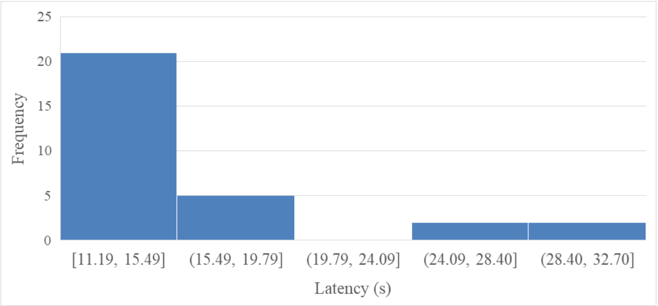


Fig 10. Latency distribution of mintNFT transactions

It is noteworthy that although NFT minting in the proposed workflow was preceded by metadata publication to IPFS, the upload process was entirely off-chain and does not contribute to Ethereum gas consumption nor affect transaction confirmation latency. Experimental results confirmed that gas usage and block inclusion times were invariant with respect to IPFS interaction, with observed variations attributable primarily to network-level factors rather than on-chain storage behaviour, indicating that confirmation time is largely governed by Ethereum network conditions.

Besides the latency analysis, a further study was performed to show the reliability and robustness of the whole system. As a result, the end-to-end transaction reliability was assessed to ensure the successful transaction from the start to final steps as follows, RFID scan, Database insert, Blockchain transaction, confirmation and Database update. The performance index used was end-to-end success rate, defined as 100*(successful end-to-end runs/total attempts). With the total of 59 traceability runs and 58 successful end-to-end executions, the end-to-end success rate was 98.31% (58 out of 59 runs). The single failure was due to unexpected system shutdown, so the proposed system and its integration were robust and exhibited the expected level of reliability.

5. Gas Usage and Transaction Cost Analysis

Gas consumption was evaluated across all core smart contract functions to assess the operational cost and computational complexity of the blockchain layer. Measurements were obtained from 30 repeated executions of each function on the Sepolia network. Event broadcasting via broadcastDurian exhibited the lowest gas consumption, averaging 32,138 gas, as the function primarily emitted structured event logs without performing persistent state updates. Immutable ledger insertion through addDurian required substantially higher gas usage, averaging 148,477 gas, due to on-chain storage writes and duplicate-entry validation necessary to preserve data integrity. As expected, ERC-721 token minting via mintNFT was the most gas-intensive operation, consuming an average of 152,572 gas as a result of ownership mapping updates, token indexing, metadata linkage, and standard transfer event emissions. When evaluated in monetary terms (baseline: gas price = 0.1 gwei; ETH = USD 2,266, as of February 4, 2026), the per-operation cost ranged from approximately USD 0.0073 for event broadcasting to USD 0.0336 for immutable ledger and USD 0.0346 for NFT minting. The gas consumption and transaction costs of each function are listed in Table 3. Since the gas price and ETH/USD exchange rate were subject to volatility, USD-equivalent costs are reported for the baseline scenario together with ± 5% variation to offset short-term price uncertainty.

Although blockchain gas costs were potentially prohibitive for individual-level transactions involving low-value durians, this limitation could be mitigated through a carton-level trade-off, whereby costs are amortized across multiple units within a single transaction. Individual-level blockchain operations were therefore economically justifiable only in high-value contexts, such as premium durians sold through auction channels (e.g., Musang King or Kan Yao), whereas batch-level tagging offered a more scalable and cost-efficient solution for general commercial distribution. Overall, these findings demonstrated that the proposed architecture delivered a flexible, predictable, and economically viable blockchain operating model, making it well suited for real-world agricultural traceability deployments.

Table 3. Gas used and transaction costs on Sepolia network

Function	**Gas used**	**Cost**		
		-5%	**Baseline**	**+5%**
broadcastDurian	32,138	0.0069	0.0073	0.0076
addDurian	148,477	0.0320	0.0336	0.0353
mintNFT	152,572	0.0328	0.0346	0.0363

6. Comparison With Existing Traceability Systems

The proposed RFID–blockchain architecture extends beyond existing research by combining validated RFID performance, blockchain performance, operational cost analysis, targeted product domain, and cost saving, resulting in a more comprehensive and deployment-ready traceability system. The comparison between the existing and proposed system is detailed in Table 4.

7. Scalable Logistics Implementation

Based on the study results, the costs of smart contract transactions can be high and fluctuate significantly due to variations in the ETH price. Another critical factor is the volume of data that the traceability system must process, which can become substantial when a large number of RFID scans are generated daily. Furthermore, the market price of durian plays an important role in determining economic feasibility. The use of a dedicated RFID tag and associated smart contract for each individual durian may be viable when the fruit commands a high market price; however, this approach becomes difficult to justify when durian prices are heavily discounted.

For the gas usage analysis, the cumulative gas consumption for the three on-chain actions was 333,187 gas. When applied at the individual-durian level with three actions executed together, the resulting cost reached approximately USD 0.0755 per durian under baseline conditions, making large-scale deployment economically unattractive. To address these challenges, the concept of scalable logistics was adopted to efficiently manage increased data volumes without compromising cost efficiency.

Table 4. Comparison between existing and proposed research

Comparison Criteria	Existing Research	Proposed System
1. RFID validation	-RFID is widely utilized as the IoT input technology (Bhat et al., 2022). - The communication range of different RFID tags are reported by Ruiz-Garcia and Lunadei, 2011. -The RFID communication range as a function of operating frequency is documented by Tasic and Cano, 2024.	-RFID read performance is empirically validated to cover both reading distances (0-3 cm) and orientations (0°, 45°, and 60°).
2. Blockchain performance	-Average processing time and distribution of frequent blockchain transactions are reported by Pincheira, Vecchio, and Giaffreda, 2022. -Transaction processing time is discussed theoretically by Panwar et al., 2023.	-Blockchain confirmation latency is empirically measured and statistically analyzed with the following parameters, average, minimum, maximum, and standard deviation. -Latency distributions are also visualized using histograms.
3. Operational cost analysis	-ETH price is based on multi-year monthly average price for cost estimation (Pincheira, Vecchio, and Giaffreda, 2022). -One-month average cryptocurrency price for operational cost calculation is adopted by Chacko et al., 2023.	- ETH price sensitivity of ± 5% is applied to account for the price volatility over a short-term price fluctuations.
4. Targeted product domain	-Prior studies mainly focus on low- to medium-value agricultural commodities, e.g., grains (Salah et al., 2019), dairy (Varavallo et al., 2022), or packaged goods (Hawashin et al., 2023).	-The system targets high-value fresh durians in Thailand's export sector. -The proposed framework could be extended to other high-value agricultural products traded at the auction markets.
5. Cost saving	- Although blockchain enhances traceability and transparency in food supply chains, its adoption is often constrained by high transaction and data acquisition costs, particularly for smallholder farms, as collecting, validating, and uploading reliable on-chain data can be expensive and may disproportionately favor larger producers (Xiong et al., 2020)	-To address the high transaction and data acquisition costs reported in existing blockchain-based food traceability studies, this work introduces a carton-level, batch-preserving traceability approach that reduces the frequency of blockchain transactions and significantly lowers overall traceability costs.

The proposed solution therefore adopts a carton-level, batch-preserving traceability approach, in which each production lot (e.g., a single packing lot, harvest lot, or grade/clone) is consolidated into a single carton and treated as unified traceability unit (identified by a single RFID tag), rather than tagging individual durians. In the carton-level implementation, each production lot is mapped to a single batch record in the database, thereby preserving lot integrity while substantially reducing blockchain transaction costs. Under this approach, the system performs only one on-chain operation per carton (and per lot), regardless of the number of durians it contains. A carton may include multiple durians belonging to the same lot. For example, when a carton contains four durians from a single lot, the blockchain cost for that carton is effectively amortized across all durians, reducing the per-durian on-chain cost to approximately one-quarter of a carton-level transaction. Another solution is the selective minting only for traceability event requiring on-chain certification. As a result, mint-NFT is performed when certain conditions are met, e.g., premium grade classification, auction sales, or regulatory certification. Otherwise, an RFID scan triggered only a light blockchain operation, e.g., event broadcasting.

8. Conclusions and Discussions

Traceability remains a fundamental requirement for ensuring the reliability and transparency of the durian supply chain, especially for premium varieties exported from Thailand. This study demonstrates an integrated digital traceability framework that combines IoT technology – specifically RFID tagging – with blockchain-based data management to enhance the accuracy, security, and credibility of supply chain information. By capturing essential attributes such as batch number, durian clone, GAP certification number, harvesting date, and the geolocation of an orchard in Chanthaburi Province, the system ensures comprehensive and verifiable product provenance.

A key component of the system is the implementation of Ethereum-based blockchain technology. The experimental results proved that blockchain significantly strengthened data integrity and prevented tampering through message broadcasting, immutable ledger creation, and NFT issuance. Smart contracts written in Solidity were used to automate data recording and asset transfer processes, with all on-chain interactions executed by the backend following RFID scan. The DurianChanNFT, minted upon the completion of each transaction, acts as a digital certificate of authenticity, supporting marketing, export compliance, and consumer trust.

However, a major challenge examined in this study was the substantial and volatile gas cost associated with blockchain transactions, which was further influenced by fluctuations in the price of ETH. When durian market prices decline, the relative cost of blockchain transactions becomes disproportionately high, thereby complicating practical implementation. An exception may be ultra-premium durians (such as Kan Yao and Musang King sold through auction) where the high product value justifies the additional transaction costs, making blockchain adoption economically viable. To address this issue, the research introduced a carton-level scalable logistics strategy that distributed transaction execution costs across multiple durians. This approach substantially reduces gas consumption per unit. This finding supports the idea of implementing blockchain-based traceability systems that have been made economically successful through design optimization, batching strategies, and scalable data structures. These enhancements allow small- and medium-sized producers to implement traceability solutions without prohibitive costs and lead to more inclusive digital transformation in the agricultural sector.

Moreover, the NFT component in this study can be used as a digital certificate of authenticity and provenance rather than a speculative asset. The primary recipients of the NFTs are downstream supply chain actors and end stakeholders, including exporters, wholesalers, retailers, regulators, and premium-market buyers. Each NFT represents a specific durian batch or carton and contains a persistent token URI linking to off-chain metadata (e.g., origin, harvest date, certifications, and inspection history) stored on IPFS. Therefore, supply chain actors can interact with NFTs through standard blockchain tools or simple web interfaces to verify provenance, ownership, and integrity without requiring access to the underlying database or relying on a centralized platform.

Beyond its application to durian, the RFID-enabled blockchain traceability framework developed in this study is ready to be applied to ultra-premium fruits whose market value depends heavily on verified provenance and auction-grade quality, such as Crown Melon, Yubari King Melon, Taiyo no Tamago Mango, and Ruby Roman Grapes. For these commodities, authenticity, cultivation origin, and individual fruit characteristics directly influence auction pricing, making tamper-proof data recording essential. By tailoring metadata fields – such as farming method, sugar content, ripeness assessment or grower certification – the system can immutably document fruit attributes and ownership transfers from orchard to auction house. This level of trusted traceability mitigates fraud, prevents mislabelling, and preserves brand prestige in high-value gift and specialty markets. Ultimately, deploying scalable RFID- and blockchain-based transparency mechanisms not only reinforces buyer confidence in auction environments but also enhances regulatory compliance, strengthens producer reputation, and secures premium price realization in global luxury fruit markets.

In conclusion, this study contributes both a practical and scalable blueprint for cost-efficient agricultural traceability. By integrating batch-level smart contract optimization with robust IoT–blockchain architecture, the system moves beyond traditional one-item-per-transaction models, offering a more feasible pathway for large-scale adoption. Future work should explore additional gas-saving mechanisms, hybrid data architectures (e.g., off-chain storage), interoperability with national traceability standards, and field deployment across diverse agricultural sectors. Through these advancements, digital traceability can become a practical and sustainable tool for ensuring product integrity and strengthening Thailand's position in global agri-food supply chains.

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