

IoT-Based Smart Contract Framework for Rice Supply Chain Traceability Recall System and Consumer Safety

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Abstract. The rice supply chain has been susceptible to quality deterioration, expiry, and a low level of transparency, which are risks to consumer health and food security. To overcome these challenges, the current research suggests a consortium-based blockchain and IoT-enabled smart contract framework to provide a holistic, traceable, and automated governance model. The framework facilitates a consortium of all key stakeholders in the rice supply chain from farmers to retailers as a blockchain network that is co-controlled and resistant to tampering. At key storage infrastructures, Internet of Things (IoT) sensors are deployed to provide the variable storage conditions (humidity and temperature) in real-time that are important in storing rice. The monitoring variables are sent to smart contracts that generate a two-tiered governance system. Upon data showing that a rice lot reached 90% of its shelf life, the intervening automated process will promulgate notifications. Upon expiration of the rice, monitoring will render a smart contract disables the ability to purchase or distribute in the supply chain. The automated process therefore notifies users of public health risks by preventing the introduction and sale of products deemed unsafe for consumption. The framework ensures the sustainable, validated, and tamper evident functionality for continuous monitoring and rule-based execution of perishable products on a public ledger to facilitate enhanced food governance, to lower food safety risks to consumer health, and to promote consumer trust in the rice supply chain.

Keywords: Rice supply chain, traceability, IoT, smart contracts, automated expiry governance.

1 Introduction

The rice supply chain is an extremely critical segment of world food security that finds itself faced with many multifaceted problems like quality loss, expiry, poor record keeping, and fraud [1]. These systemic inefficiencies make end-to-end traceability difficult and enable distributing expired or low-quality rice to the population with serious health consequences and inflexibility in terms of economic efficiency [2]. It is possible to view the technology of blockchain as a paradigm-shift one as the solution which can be used to introduce transparency and accountability by offering a decentralized, immutable and verifiable registry [3]. Its use in agriculture is useful in avoiding tampering of data, developing trust, and enhancing regulatory compliance [4].

In rice-unspecific applications, it allows strict traceability of rice between planting and sale to maintain authenticity and fair market operations, and overcome adulteration and inventory tracking [5].

However, the blockchain applications that have remained function on public models that have bottlenecks in scaling, high cost of transactions, and lack of privacy of their data that cannot fit in the industry [6]. To handle this, Internet of Things (IoT) technologies are to be incorporated, which would enable the permanent monitoring of the environment with the help of sensors attached to the main parameters, including temperature and humidity, to ensure that rice remains fresh [8]. Smart contracts can be used to provide an intelligent layer of automation when combined with the data provided by IoT. This changes the system to become an active mechanism of governance instead of a passive recorder. As an illustration, contractual processes may raise alarm when batches are 90 percent to their shelf life, and block sale when batches have 100 percent expired inventory, and dangerous products will not be distributed [9]. This proactive governance transcends responsive measures and ensures consumer security and regulatory provisions. The consortium blockchain paradigm is purpose-designed to multi-stakeholder supply chains, e.g. rice, and allows joint governance between vetted entities (e.g. GSNs, NFRNs, distributors, retailers) [10]. Unlike public blockchains, consortium models sacrifice full participation in favor of controlled participation, maximization of scalability, transaction throughput and consensus efficiency [11]. Validations are orchestrated in a manner that rights those whose authority is important, hence enhancing the level of security and agility of operations [12]. It has been proved that recall systems based on blockchain are more responsive [4], that smart contract verification with the help of IPFS is viable [14], and that food safety governance with the help of rule-based automation is a solid basis [13].

Despite these vast technological advances, however, there is one gap in the research that has not been fully addressed so far: the number of studies that combine consortium blockchain, IoT-based environmental monitoring and smart contract-based automated recall into a single end-to-end rice traceability solution is minimal. The models available are inclined to pay more attention to technical feasibility or high-level conceptual designs but are not associated with operationalized frameworks of humidity sensitive storage, multi-level distribution networks, and automated consumer safety interventions on a single architecture. The proposed work is aimed at addressing this gap by introducing a new framework based on the consortium blockchain, IoT, and smart contracts as the means of forming a secure, transparent, and automated rice supply chain ecosystem. The central concept of this design is constant observation of the environmental factors with respect to IoT sensors, which will measure the vital parameters like temperature, humidity and length of storage. Smart contracts absorb this information and enforce two-level governance policies, namely, the activation of proactive warnings when the products are over 90% of shelf life elapsed and deactivation of purchase options when the batches expire more than 100 percent, which allows them to recall products immediately [8], [9].

The remaining portion of this paper is organized in the following way. Section 2 is a literature review concerning blockchain use in supply chain, IoT integration, and smart contract automation. Section 3 gives the proposed system architecture/methodology,

the consortium model and the stakeholder roles. Section 4 describes the specifics of the implementation of the smart contracts and IoT data flow. Finally, Section 5 is the conclusion section that summarizes the main findings and research directions.

2 Related Work

A combination of Blockchain and the Internet of Things (IoT) has been one of the frequently used techniques to resolve the main concerns of trust, transparency, and safety in agricultural supply chains. The current review dwells upon the old and recent literature that has a direct effect on the main elements of our proposed model: blockchain to trace rice, the IoT to monitor the environment, smart contracts to carry out recalls automatically, and the consortium blockchain architecture.

2.1 Traceability of Rice using blockchain applications

Our framework on rice traceability is founded on the available literature that serves as evidence of the relevance of blockchain in our sector. As a case in point, Farooq et al. [1] introduced a consortium blockchain framework that can be compared to ours where smart contracts and QR code are utilized to enhance rice logistics transparency. Furthering on, Yakubu et al. [6] have proposed a prototype called Rice Chain, which proves that blockchain is capable of ensuring the safety of transaction information and increasing the transparency of stakeholders. Relevance: which is the relevance of blockchain in our context? Haque et al. [2] confirmed the applicability of Blockchain to rice traceability in Bangladesh within the South Asian context. Taken together, these studies [1] constitute the justification of taking blockchain into the rice traceability.

2.2 Real-Time Monitoring IoT Implementation

Our model brings continuity of condition monitoring to basic traceability with the help of IoT sensors. Models like the Iftekhar et al. [11] one can show how IoT sensors in combination with smart contracts can generate safety data that is tamper-proof and in real time. Hasan et al. [7], also confirm the use of hybrid IoT-blockchain in agrifood logistic monitoring of environmental conditions. We have chosen the sensors that are used in our scheme humidity and temperature, which is tested and proven through agricultural applications [16], [17], and is technically feasible in rice storage and transportation.

2.3 Recalling and Automation with Smart Contracts

Smart contracts offer the automation core of our framework through the implementation of pre-defined governance regulations. The primordial studies [13] provide the technical and legal basis of automation of smart contracts in the supply chains. One of the automation features of our model is expiry-based recall. Kravenkit and So-In [4] developed a blockchain-enabled automated recall workflow, which serves as a direct point of reference as far as our approach is concerned. A traceability system based on IPFS was suggested by Patro [14], which is proposed as a recall management system, which is compatible with our expiry-based recall system. Combined, these works point out that automated recall is achievable and enhances governance.

2.4 Research Gap

Although the literature supports blockchain in rice [1], IoT in sensing [11], and smart contracts in autonomous recall [3], all the prior studies do not include them as a whole framework. A majority of the current models are applying these technologies individually without a complete end to end solution to rice supply chain. The given gap is addressed in the proposed study that will offer an all-encompassing, operational architecture that integrates consortium blockchain governance [15], real-time IoT monitoring, and expiry-based smart contracts into a single recall-enabled system. The framework does not only advance on the traditional traceability, but also gives a sound theoretical base on how to solve the problems of the halal food supply chain.

3 Methodology and System Framework

This is a Consortium blockchain- IoT Smart contract-based scheme to offer end to end traceability, environmental surveillance and automated recall within the rice supply chain. The methodology integrates an on-premise permissioned blockchain network, IoT Sensor activated data collection and smart contract rule-based automation to ensure transparency, security and consumer protection.

3.1 System Architecture Overview

The suggested system will be a semi-decentralized consortium blockchain network that includes farmers, collectors, rice mills, government storage node (GSN), national food resource node (NFRN), distributors, retailers and consumers, and constructs an irrevocable record of transparency and authenticity of rice supply chain.

3.2 IoT Perception Layer

The IoT sensors (temperature and humidity modules) at the rice mills, GSNs, and NFRNs monitor the environmental conditions used to conserve the quality of the rice. The Sensor readings the information sent through the secure MQTT connections to the gateway (ESP32), hashed, time stamped and uploaded in the blockchain. Real time monitoring averts the data tampering and gives a confirmation of the environmental conditions to offer compliance during processing, storage and transportation.

3.3 Blockchain Governance Layer

Governance layer consists of the permissioned ledger of Hyperledger Fabric where only authorized identities can authorize or write down the transactions. RAFT consensus is charged with the responsibility of: (i) quickly validating blocks, (ii) fault tolerance and (iii) Reducing the use of energy. Individual blocks are accompanied by the relevant metadata (i.e. certain batch identifier, storage data, timestamps, and information about the origin of the batch) in order to guarantee a verifiable integrity of the data between farmer and consumer.

3.4 Smart Contract Automation Layer

Smart contracts allow automated governance, through the application of the environmental data due to the IoT to the records on the blockchain which include: Early Warning Contract - Dispatches notifications to remind customers when a product has 90 days to its shelf-life. Auto-Recall Contract - Automatically seals the transaction

of the container when it is 100% expired. Quality Assurance Contract - Alarm at a batch in case the temperature or humidity is out of range. These rules can be automated to remove human participation, they remove risk and will remove unsafe rice out of the market as soon as it occurs.

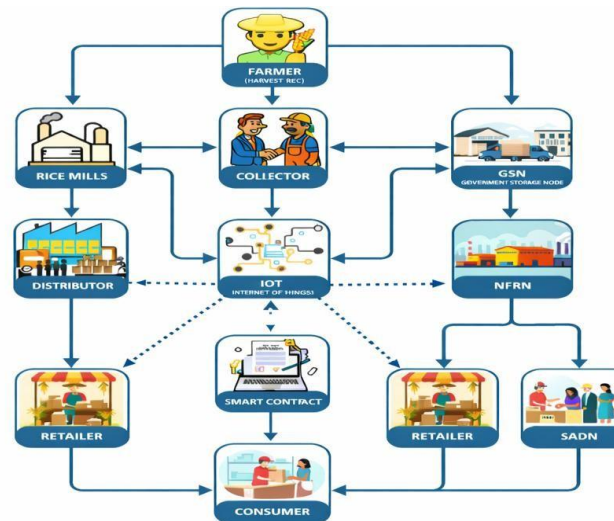


Fig. 1. Architecture of Rice traceability System.

3.5 Collector and Rice Mill Stage

After harvesting, the rice steps to the collector and rice mill. IoT sensors track the drying process, milling temperature, and coldness level. Smart contracts continuously check the environmental readings. If the coldness or temperature exceeds the safe limit, an alert is automatically triggered to ensure product safety before packaging. In this way, it provides data quality assurance, and ensures low quality rice does not proceed to the next phase.

3.6 Government and National Storage (GNS)

At GSN and NFRN, the stored rice is exhibited in real-time through IoT devices. Smart agreements are used to enforce the provider's food safety management policies: At 90% of the shelf life, an expiry warning is automatically sent. When At 100% expiration the product. Then, the smart agreement locks the batch of products, prohibiting further sale or transfer is closed the system.

3.7 Distributor and Logistics Monitoring

During transit, IoT sensors and GPS track routes, duration, and storage conditions inside the transit containers. In case the system identifies out-of-limit situations (e.g., excessive humidity or temperature), the blockchain network identifies the shipment and smart contracts alert stakeholders to take necessary action. It guarantees that only quality rice reaches the distribution and casual phases.

3.8 Retailer and Sale Stage

At the retailer level, each rice batch is confirmed through the blockchain using its unique ID. Smart agreements automatically check expiry status before allowing the sale. Expired batches are immediately deactivated, and information is sent to distributors and storage units. This ensures that consumers only receive safe and verified rice.

3.9 Consumer Transparency

Consumers can identify a QR code on the rice package to see the complete product history from farmer to retailer along with temperature and coldness logs, harvest date, and departure status. This open visibility increments consumer conviction and develops reliance on food quality.

System Components

3.10 The framework is made of three basic components:

Consortium Blockchain: Ensures the decentralized but qualified participation into trusted organizations, observing clearness and data integrity.

IoT Sensors: Collect data real-time processing environmental data (coldness, temperature, and storage time) at the different factors of the supply chain.

Smart Contracts: Automatically execute governance laws alerts, blocks expired products and shows the system expired product records, and validates transactions automatically.

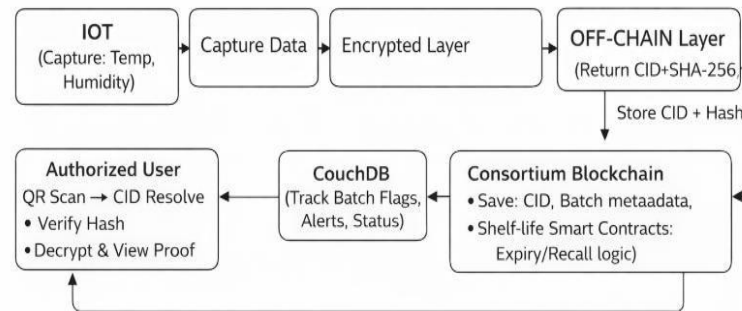


Fig. 2. Interaction with the storage systems.

3.11 Government and Access Control

Access Control Policy (ACP) outlines the read/write access of all the stakeholders. Attempts to access or make alterations unauthorized are automatically blocked. It can be verified, tamperproof and audited throughout the whole workflow- harvest through consumers. This holistic system is a combination of the IoT-based sensing, consortium blockchain governance, and automated smart contract logic to deliver a robust, scalable, and transparent system of rice supply chains. It avoids the delivery of expired products to the consumers, maintains data integrity, and instills trust in the populace by real-time monitoring and self-sustained decision-making.

4 Implementation Framework

The Consortium Blockchain-IoT Smart Contract system proposed is executed by an architecture that comprises IoT sensing, blockchain-based governance and automatic execution of smart contract. The system is based on a hybrid model of on-chain/offchain

storage which guarantees scalability, data integrity, and a smooth process of interaction among parties in the rice supply chain.

4.1 System setup

The prototype runs on a private and permissioned consortium blockchain implemented on Hyperledger Fabric v2.5 because it has modularity, identity-based access control, and scalability. Individual nodes are assigned to each of the participants, which include farmers, collectors, rice mills, distributors, GSN, NFRN, retailers and consumers with unique cryptography identities delivered by Membership Service Provider (MSP). The network is given secure and low-latency block finality by eight validating peers and two ordering nodes that have a RAFT-based consensus mechanism.

4.2 IoT Integration

DHT22 and BME280 IoT sensors are used to monitor the environment in real-time, which is placed on storage silos and transport containers to monitor temperature and humidity levels. The sensor values are sampled with an ESP32 microcontroller and transmitted to an API gateway with the MQTT protocol. SHA-256 is used to hash the data before it is added to the blockchain ensuring immutability and resistance to tampering. The sensor logs of large size are moved to IPFS and only Content Identifier (CID) generated is anchored on the blockchain ledger.

4.3 Smart Contract Deployment

Table 1: Smart Contract Automation Policies and Triggers

Smart Contract	Monitored Parameter	Trigger Condition	Automated Action / Response
Expiry Alert Contract (EAC)	Shelf-life duration	Reaches 90% of total shelf-life	Triggers proactive warning notification to stakeholders
Auto Recall Contract (ARC)	Shelf-life duration	Reaches 100% (Fully expired)	Freezes transaction, locks batch, prevents sale automatically
Quality Assurance Contract (QAC)	Temperature & Humidity	Temp > 28°C OR Humidity > 70%	Issues red flags, marks batch as compromised

Smart contracts were implemented (tested on Hyperledger Caliper) to enforce automatically the policies of governance:

Expiry Alert Contract (EAC): It gives alerts when a batch is 90 percent of its shelf life.

Auto Recall Contract (ARC): This is a permission on each transaction that has been frozen when a batch has expired by 100 percent.

Quality Assurance Contract (QAC): Approves environmental readings and issues red flags whenever there is violation beyond the threshold levels.

4.4 Data Flow and User Interface

React.js and Node.js are applied in the development of a web interface showing the real-time storage status, expiry status, and batch traceability. Using the secure RESTful APIs, retailers and regulators can simultaneously access the full ledger record, and verified product information is available to the consumers via QR-code scanning to maintain transparency and consumer trust.

5 Results and Discussion

The theoretical analysis of the suggested framework shows that it is possible to allow real-time traceability, predict expiry gaps before they can occur, and allow transparency of product verification.

5.1 Expected Performance Evaluation

Depending on the architectural design, it is expected that the time needed to authenticate a transaction in RAFT-based consortium blockchain is considerably less, and the throughput rate is much faster in a RAFT-based consortium blockchain than in a traditional public network. In comparison to traditional Ethereum-based public blockchains, the consortium system is aimed to reach a significant decrease in latency and a smaller energy consumption because of the negligible role of heavy mining operations and the attempt to use authorized validating nodes. Moreover, the incorporation of the subsystem of IoT based on the MQTT protocol is organized in a manner that will ensure high integrity of the information exchange involving a stable synchronization of the blockchain registry, which reduces the loss of information.

5.2 Operational Logic Validation

The conceptual map stipulates that the three automation policies are all implementable in the smart contracts. Expiry warnings will be set to be issued before the shelf-life expiry date; those batches found to have exceeded the environmental limits (e.g. $>28^{\circ}\text{C}$ or >70 humidity) will be programmed to be automatically labelled as such; and the batches that are out of expiry will be automatically locked so that they will not be sold to the food supply chain to enable us to control the product safety.

5.3 Comparative Analysis

Table 2: Comparison of the Proposed Framework with Existing Systems

Features	Traditional Traceability	Types of Blockchain	Proposed Framework (CBIoT-RSCT)
Network Type	Centralized	Open / Public	Consortium
Consensus Mechanism	N/A	Proof-of-Work (PoW)	RAFT (Crash Fault Tolerance)
Energy Consumption	Low	Very High)	Minimal (Efficient)
Product Recall	Manual & Slow	Passive Tracking	Automated
Storage Architecture	Centralized DB	Fully On-chain	Hybrid (IPFS + On-chain)
Data Privacy	Vulnerable	Public (Low Privacy)	Access Control via MSP

Unlike previous models of agriculture- applications based on blockchain [4], our framework includes a typical multi-layer automation and consortium-type governance, with some advanced features integrated into it. The new scheme employs a RAFT consensus mechanism to use less energy and rather turn to trusted parties as opposed to an open network (like Ethereum) that employs the use of proof-of-work. It also includes with the implementation of smart contracts and the use of IoT-based data monitoring, the evidence of prediction safety guarantee that is more effective than more traditionally old-style passive traceability systems that are still in existence today [20],[21].

5.4 Security and Transparency

The ability of blockchain to provide a resilient storage solution ensured tamper-proof records and the data was cryptographically hashed, which ensured that one could not tamper with the information. The authorized model limited the exposure risk, which established a balance between the transparency and privacy. The access control policy of all the stakeholders or participants ensured data sovereignty and allowed the regulators and consumers to gain an end-to-end visibility of the products or services. Overall, the architectural discussion reveals that the proposed consortium blockchain and IoT architecture is theoretically valid to achieve real-time traceability and automated expiry management. RAFT consensus and smart contracts are highly beneficial to the governance of food safety and transparency of data in extensive agricultural surveillance.

6 Conclusion and Future Work

In their research work, a Consortium Blockchain and Internet of Things-enabled Smart Contract system for ensuring end-traceability, automatic management of expiry dates, and proactive handling for the rice supply chain was proposed. The system showcased its efficiency in implementing intelligent automation for safe food monitoring by integrating Internet of Things information with the governance capabilities of the Blockchain system. The results also demonstrated its capabilities in terms of transaction speed, integrity, and real-time monitoring capabilities. Implementation of Artificial Intelligence (AI) for predictive analytics – for example, storage degradation prediction, optimal storage life estimation, quality control, etc.). Securing Layer-2 scalability opportunities like Polygon to provide lower transaction latency and lower network congestion. Implementing systems for anomaly detection using machine learning for proactive risk assessment with the trend in sensor values [18], [19]. The creation of interoperability modules for connecting the consortium blockchain to other agri-food systems in the international standards. Halal and Ethics compliance module implementation for certification trackability in sensitive markets. By connecting transparency on the blockchain, precision in IoT technology, automation in the smart contract, it enables a self-sustaining digital structure for next generation food systems with respect to agricultural governance in a scalable, secure, intelligent manner.

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