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Blockchain-IoT Integrated System for Automated Compliance in Dairy Logistics

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Abstract

Maintaining product quality and regulatory standards in dairy transportation is difficult because dairy products spoil quickly and involve multiple handling stages. Conventional logistics systems are now highly dependent on manual supervision, which can lead to delays, inaccurate records and security issues. This paper presents an integrated Blockchain and IoT-based framework for automated compliance management in dairy logistics. IoT sensors continuously collect environmental data such as temperature, humidity and vehicle location during transportation and storage. The collected information is stored in a secured manner using blockchain technology to prevent any unauthorized modification. Smart contracts are used for automatic verification of compliance conditions and for the generation of alerts when abnormal conditions are detected. Experimental evaluation with simulated logistics data shows that the proposed framework enhances transparency, decreases compliance violations and improves monitoring efficiency compared to traditional monitoring approaches.

Keywords: *Blockchain, IoT, Dairy Supply Chain, Smart Contracts, Compliance Automation.*

1. Introduction

The dairy supply chain is vital to offer safe and nutritious products to consumers. Milk and dairy products are highly perishable, so it is very important to keep the right environmental conditions during transportation and storage. Temperature, humidity and cleanliness among other things directly impact the product freshness and safety. In many of the existing logistics systems, the monitoring is done manually and the records are stored in centralized databases. Such approaches are error-prone, slow and vulnerable to unapproved changes. With recent technological advancements it is possible to use internet of things (IoT) devices for real time monitoring. Vehicle and storage-unit sensors can continuously monitor environmental conditions and immediately transmit data. A further development is the emergence of blockchain technology as a secure and decentralized way of storing digital records. Blockchain data is not easily changed, which increases trust and transparency among all participants in the supply chain. Existing studies focus on improving product traceability, but few

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systems are developed for automatic compliance verification. Most of the solutions in place today monitor environmental conditions, but they do not instantly validate them against pre-determined safety limits, or automatically initiate corrective actions. Hence, there is a requirement for an intelligent monitoring framework to ensure real-time compliance. To address this problem, this paper proposes a Blockchain-IoT integrated compliance monitoring system for dairy logistics. The framework combines IoT based sensing devices with blockchain based secure storage and smart contract automation. The developed solution reduces manual dependency, improves transparency, and supports reliable compliance management throughout the logistics process.

2. Literature Survey

Blockchain technology has gained significant attention in supply chain management because of its capability to provide decentralized, transparent, and tamper-resistant data storage. Earlier studies by Saberi et al. [3] explained the role of blockchain in improving sustainability and trust within supply chains. Tian et al. [1] introduced a blockchain-supported food traceability framework, while Caro et al. [2] demonstrated its practical use in agri-food logistics systems. Casino et al. [14] further discussed the benefits and challenges of blockchain applications, especially issues related to scalability and system performance. In parallel, IoT technologies have become widely used for monitoring environmental conditions in logistics environments. Lin et al. [4] designed an IoT-enabled monitoring framework capable of observing temperature and humidity conditions in cold-chain transportation. Zhang et al. [5] also proposed a smart logistics monitoring approach to reduce spoilage and improve operational efficiency. However, centralized IoT systems are still exposed to cybersecurity risks and data manipulation problems [16]. To improve security and trust, researchers started combining blockchain with IoT systems. Reyna et al. [6] discussed block chain supported secure communication for IoT environments, while Dorri et al. [7] proposed a lightweight blockchain model suitable for low-resource devices. Singh et al. [8] developed a blockchain-IoT architecture for logistics monitoring that enhanced transparency and integrity of collected data. Within dairy and food logistics applications, Khanna et al. [9] proposed a blockchain-supported dairy management platform to improve food safety and traceability. Varriale et al. [11] investigated the integration of RFID, IoT, and blockchain technologies for improving logistics efficiency. Nalini et al. [10] introduced smart contracts for automating monitoring activities and reducing manual effort. More recent research has explored artificial intelligence integration within blockchain-IoT systems. Tahir et al. [13] proposed an AI-enabled blockchain framework for smart agriculture applications, while Manisha et al. [12] combined deep learning with blockchain and IoT for dairy product quality prediction. Even though these methods improve analytical capabilities, they also increase computational complexity and implementation cost. From the existing literature, it is evident that many studies mainly focus on traceability and monitoring rather than automated compliance enforcement. Real-time validation against predefined safety standards and automatic response generation are still insufficiently addressed. Therefore, an integrated framework of IoT sensing, blockchain security and smart contract automation is needed for efficient compliance monitoring for dairy logistics.

3. Methodology

This paper offers an integrated framework for secure monitoring in dairy logistics using IoT devices, blockchain infrastructure and smart contract mechanisms. The methodology focuses on continuous collection of environmental data, automatic validation of compliance conditions and secure storage of transaction records to improve transparency and operational reliability.

3.1.Architecture Overview

The future architecture consists of IoT sensors, a blockchain layer, a smart contract module, and a user dashboard. Environmental data such as temperature, humidity, and vibration is continuously collected from dairy transportation and storage units. The captured data is transmitted to the blockchain network where smart contracts automatically verify compliance conditions. If the recorded values exceed predefined thresholds, the system generates real-time

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alerts and updates the dashboard As shown in Figure 1 Operational Flow of the Proposed Dairy Logistics Monitoring Model.

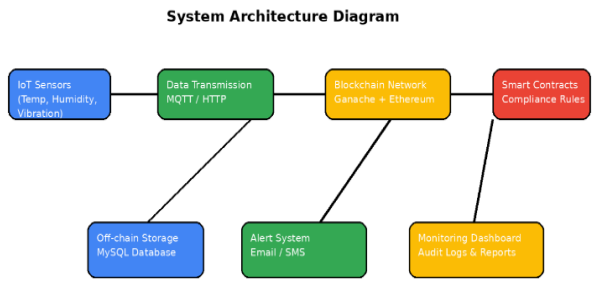

Figure 1 Operational Flow of the Proposed Dairy Logistics Monitoring Model

3.2.Data Acquisition Layer

The data acquisition layer consists of IoT sensors deployed in dairy transportation vehicles and storage environments. The sensors continuously monitor environmental conditions including:

- Temperature
- Humidity
- Vibration
- Shipment Location

The sensor values are represented as:

$$Dt = \{Tt, Ht, Vt, Lt\}$$

The collected data is forwarded to the blockchain processing layer through[14] lightweight communication protocols such as MQTT and HTTP APIs[15].

3.3.Blockchain Integration

A private Ethereum blockchain environment is implemented using Ganache for secure transaction processing and testing[16 – 20]. The blockchain layer stores all validated records as immutable transactions.

The blockchain provides:

- Tamper-proof data storage
- Transparency
- Decentralized verification
- Secure audit tracking

The transaction validation process is represented as:

$$B(Dt) = \text{Validated transaction}$$

3.4.Smart Contract-Based Compliance Validation

Smart contracts are implemented using Solidity to automate compliance verification. The compliance rules are defined based on acceptable environmental thresholds[14].

3.5.Data Storage Mechanism

The proposed system adopts a hybrid storage architecture combining on-chain and off-chain storage as shown in Table 1 Data Storage Components in the Framework[13].

Table 1 Data Storage Components in the Framework

Storage Type	Purpose	Advantages
Blockchain (On-chain)	Immutable transaction storage	Security and transparency
MySQL Database (Off-chain)	Large sensor dataset storage	Scalability and efficiency
Hash Storage	Verification and integrity checking	Tamper detection

3.6.Monitoring And Data Alert

Sensor information from transportation and storage units is monitored continuously throughout the logistics process. Smart contracts automatically verify whether the environmental conditions satisfy predefined compliance thresholds. If any abnormal condition is detected, real-time alerts are generated through the dashboard and notification system. This enables immediate response to potential violations and helps maintain the quality and safety of dairy products throughout the supply chain[21].

3.7.User Interface And Dashboard

The projected system includes a web-based dashboard to allow real-time monitoring of dairy logistics operations. The dashboard provides shipment status, compliance alerts, blockchain

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transaction records and audit logs through a unified interface. It also provides secure user authentication and role-based access control for operators and administrators. Smart contracts can automatically identify compliance violations and show them in real time, enabling quick response and effective monitoring of the supply chain[22].

3.8.Performance Evaluation Metrics

The proposed system work has been analysed based on metrics such as detection accuracy, transaction processing time, alert response time and monitoring efficiency. The system secured transaction storage and low response time and achieved reliable compliance detection by means of blockchain. The IOT and Blockchain integration ensured transparency and reduced manual intervention, enabling efficient real time monitoring in dairy logistics, Table 2 Performance Metrics Considered During System Evaluation[23].

Table 2 Performance Metrics Considered During System Evaluation

Metric	Description
Detection Latency	Time required to identify compliance violations
Throughput	Number of blockchain transactions processed per second
Accuracy	Correct detection rate of compliance conditions
Smart Contract Cost	Gas consumption during validation
Alert Response Time	Time required to trigger alerts

4. Comparison With Existing Work

Current dairy logistics systems are mainly based on centralised databases and manual monitoring methods. These systems have some limitations such as delayed detection, lack of transparency, poor traceability and vulnerability to data tampering. Monitoring systems based on IoT collect temperature and humidity data continuously to improve the tracking of the environment. However, these systems are vulnerable to cyber-attacks and unauthorised modification, and lack secure data storage. Blockchain-based systems improve data security and transparency but mainly focus on traceability rather than automated compliance validation. The proposed system overcomes these limitations by integrating blockchain with IoT and smart contracts to provide automated, secure, and real-time compliance monitoring[24].

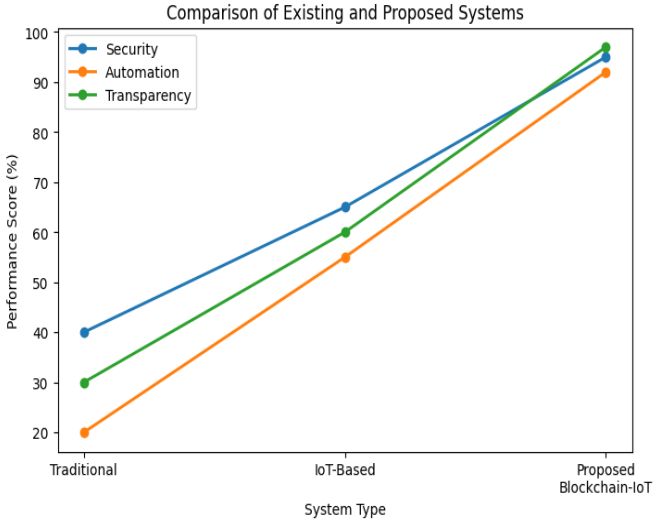

Figure 2 Functional Comparison Between Traditional and Smart Dairy Logistics

5. Results And Discussion

The performance of the developed framework was tested using simulated dairy transportation data generated through IoT sensors under varying environmental conditions. The implementation utilized Ganache for blockchain simulation, Solidity smart contracts for compliance verification, and a web-based interface for monitoring system activity During testing, the sensors continuously recorded parameters such as humidity, vibration, and temperature. The collected information was forwarded to the blockchain layer, where compliance rules were verified automatically using smart contracts. Whenever abnormal environmental values

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were detected, alert notifications were generated immediately through the monitoring dashboard[25].

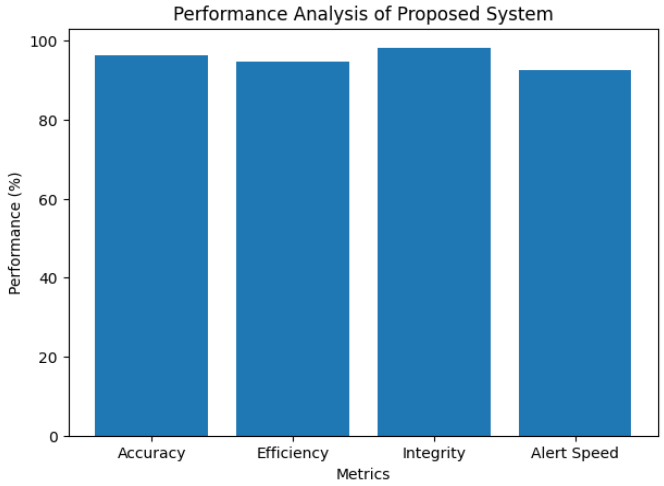

Figure 3 Evaluation Results of Compliance Monitoring Framework

The obtained results indicate that the proposed framework improves operational transparency and reduces dependency on manual supervision. Blockchain-based storage also strengthened data integrity by preventing unauthorized modification of logistics records. Performance analysis showed satisfactory monitoring accuracy with acceptable transaction processing delay for real-time dairy logistics applications.

6. Future Work

Although the proposed Blockchain-IoT integrated system provides the secure and automated compliance monitoring for dairy logistics, few improvements can be made in the future work to improve the scalability, intelligence, and real-world applicability. Future enhancements can be the deployment of the system in real-time dairy transportation environments using advanced IoT devices and cloud-based blockchain infrastructure. Machine learning and artificial intelligence techniques can be used to further improve predictive analytics by predicting possible compliance violations before they occur. Moreover, integration of advanced anomaly detection models can be employed to enhance monitoring accuracy and reduce false alerts. the current implementation uses a private blockchain network for simulation and testing purposes. Future work can explore the use of scalable public or consortium blockchain networks to support large-scale logistics operations involving multiple stakeholders. Optimization techniques can also be applied to reduce blockchain transaction latency and smart contract execution cost. furthermore, integrating GPS-based vehicle tracking, RFID technology, and mobile application support can improve real-time shipment visibility and operational efficiency. Future research may also focus on interoperability between different supply chain systems and regulatory platforms to enable seamless data sharing across organizations. Global, these enhancements can improve the scalability, intelligence, and practical adoption of Blockchain-IoT systems in modern dairy logistics and supply chain management.

Conclusion

This research introduced a Blockchain-IoT based framework for automated compliance monitoring in dairy logistics systems. The proposed model combines IoT sensors, blockchain storage, and smart contract automation to support secure and real-time monitoring of environmental conditions during dairy transportation and storage. IoT devices continuously captured important parameters such as temperature and humidity, while blockchain technology ensured that all logistics records remained secure, transparent, and resistant to unauthorized modification. Smart contracts automatically verified compliance conditions and generated alerts whenever abnormal situations were identified. Experimental analysis demonstrated that the developed system achieved reliable monitoring accuracy with low response delay and improved operational transparency. The dashboard interface also simplified tracking of shipment status, compliance conditions, and blockchain transactions. Total, the proposed framework offers a secure, scalable, and efficient solution for improving traceability, transparency, and automated compliance management in dairy supply chain operations.

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