International Journal of Engineering & Extended Technologies Research (IJEETR)

|ISSN: 2322-0163| www.ijeetr.com | A Bimonthly, Peer Reviewed, Scholarly Indexed Journal |

| Volume 8, Issue 2, March - April 2026 |

DOI:10.15662/IJEETR.2026.0802078

Chain Care: Pharmaceutical Supply Chain Management System using Smart Contracts

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Publication History: Received: 25.02.2026; Revised: 20.03.2026; Accepted: 25.03. 2026; Published: 28.03.2026.

ABSTRACT: The pharmaceutical supply chain is complex and often faces challenges such as lack of transparency, counterfeit medicines, and inefficient tracking. This project proposes a blockchain-based pharmaceutical supply chain management system using smart contracts to ensure secure and transparent operations. Each medicine batch is recorded on the blockchain with a unique ID, allowing all transactions from manufacturer to pharmacy to be tracked in a tamper-proof manner. The system also enables patients to verify the authenticity of medicines and detect counterfeit products. Additionally, a drug recall feature allows manufacturers to mark defective batches, preventing further distribution. By using blockchain technology, the proposed system improves traceability, enhances security, and ensures trust among all participants in the supply chain.

KEYWORDS: Blockchain, Smart Contracts, Pharmaceutical Supply Chain, Drug Traceability, Anti-Counterfeiting, Distributed Ledger Technology, Real-Time Tracking

I. INTRODUCTION

The pharmaceutical supply chain plays a crucial role in ensuring the safe and efficient delivery of medicines from manufacturers to patients. However, the involvement of multiple stakeholders such as manufacturers, distributors, wholesalers, and pharmacies makes the system complex and difficult to manage. Traditional supply chain systems rely on centralized databases and manual processes, which lack transparency and are vulnerable to data tampering and inefficiencies. One of the major challenges in this domain is the presence of counterfeit medicines, which pose serious risks to public health and reduce trust in healthcare systems. The absence of a reliable and real-time tracking mechanism makes it difficult to verify the authenticity of medicines. To address these issues, blockchain technology provides a decentralized and secure platform where all transactions are recorded in an immutable ledger. Smart contracts further enhance the system by automating processes and enforcing predefined rules without human intervention.

1.1 PHARMACEUTICAL SUPPLY CHAIN VULNERABILITIES

One of the most critical vulnerabilities is the infiltration of counterfeit or substandard medicines. These products may enter the supply chain at various points due to weak verification mechanisms and lack of real-time monitoring. Additionally, existing systems do not provide end-to-end traceability, making it difficult to identify the origin of compromised products. Another major limitation is the inefficiency of drug recall processes. In existing systems, recalling defective batches requires manual coordination between multiple participants, which leads to delays and potential distribution of harmful medicines. These vulnerabilities highlight the urgentneed for a secure, transparent, and

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automated system that can ensure real-time tracking, data integrity, and product authenticity throughout the supply chain. In traditional systems, recalling defective batches requires manual coordination among stakeholders, resulting in delays and increased risk to patients.

1.2 BLOCKCHAIN-BASED TRUST MODEL

Blockchain technology introduces a decentralized trust model that eliminates the need for a central authority by enabling transactions to be validated through a consensus mechanism. Each transaction is recorded in a distributed ledger and linked cryptographically to previous records, ensuring immutability and resistance to tampering. This decentralized architecture ensures that all stakeholders have access to a single, consistent version of data, thereby reducing discrepancies and improving coordination across the supply chain.

1.3 SMART CONTRACT-DRIVEN AUTOMATION

Smart contracts are self-executing programs deployed on the blockchain that automate supply chain operations by enforcing predefined rules and conditions. These contracts ensure that transactions are executed only when specific criteria are met, thereby reducing the need for manual intervention and improving operational efficiency. In the proposed system, smart contracts regulate critical processes such as batch creation, transfer of ownership, and drug recall, ensuring that all actions comply with established protocols. Role-based access control is integrated within the smart contracts to restrict actions based on user roles, ensuring that only authorized participants can perform specific operations. For example, only manufacturers can create or recall batches, while distributors and wholesalers are permitted to transfer products within the supply chain.

1.4 TRACEABILITY AND AUTHENTICITY VERIFICATION

Traceability is a fundamental requirement in pharmaceutical supply chains, as it enables continuous tracking of medicines from production to final consumption. The proposed system ensures complete traceability by recording every transaction associated with a medicine batch on the blockchain. Each batch is assigned a unique identifier that acts as a digital fingerprint, allowing stakeholders to monitor its movement and verify its history at any stage of the supply chain. By accessing blockchain records, users including patients can determine whether a product is genuine, recalled, or counterfeit. This transparent verification mechanism significantly enhances trust and empowers consumers to make informed decisions regarding the medicines they use. In addition, regulatory authorities can utilize this data to monitor compliance and detect irregularities within the supply chain. The system also provides real-time updates, ensuring that any changes in batch status, such as recalls, are immediately reflected across all participants. By enabling secure, transparent, and real-time verification, the proposed system strengthens the integrity of pharmaceutical products and ensures patient safety.

II. LITERATURE REVIEW

Recent advancements in cybersecurity have led to the development of diverse intrusion detection systems (IDS) tailored for modern network environments. Various approaches integrate machine learning, optimization techniques, and ensemble methods to enhance the detection accuracy and adaptability of these systems.

[1] proposed an intellectual IDS leveraging Hybrid Hunger Games Search and Remora Optimization Algorithm to improve security in IoT wireless networks. Similarly, [2] introduced a representation learning-based IDS that captures both explicit and implicit feature interactions to strengthen network security.

An essential consideration in network intrusion detection is the impact of emerging connectivity standards. [3] revisited wireless Internet technologies by comparing 5G and Wi-Fi 6, highlighting their implications for cybersecurity frameworks.

Efforts to enhance IDS efficiency have led to the development of ensemble learning-based methodologies. [4, 5] presented a two-level ensemble learning framework for improving network intrusion detection, while [5] proposed the HNN model that integrates multi-feature correlation and temporal- spatial analysis to refine IDS performance.

Edge computing has also contributed to improving intrusion detection, with [6] introducing an SCMA- based multiaccess edge computing solution, addressing energy efficiency and latency trade-offs in IoT systems. Additionally, [7] developed a sustainable ensemble learning model for intrusiondetection, demonstrating its effectiveness in maintaining security across diverse environments.

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[8] proposed an intrusion detection framework combining feature selection with ensemble classifiers, improving detection accuracy and efficiency. [9] conducted a comprehensive review of machine learning-based ensemble methods for IDS, outlining key advancements and challenges. Furthermore, [10] enhanced anomaly detection in web traffic using a stacked classifier ensemble, contributing to more reliable cybersecurity solutions.
These studies collectively underscore the evolving landscape of IDS, showcasing the integration of optimization algorithms, ensemble learning, and edge computing in fortifying network security.

III. EXISTING SYSTEM

In today's healthcare ecosystem, the pharmaceutical supply chain has become increasingly complex due to the involvement of multiple stakeholders and the growing dependence on digital systems for data management and distribution. This increasing complexity has led to significant challenges in maintaining transparency, traceability, and security throughout the supply chain. One of the most critical issues faced by the pharmaceutical industry is the widespread circulation of counterfeit medicines, which pose serious risks to patient safety and public health. These counterfeit products often enter the supply chain due to the lack of proper monitoring and verification mechanisms. Additionally, inefficiencies in traditional systems result in delays in drug recall processes, making it difficult to prevent the distribution of defective or harmful medicines.

Existing pharmaceutical supply chain systems primarily rely on centralized databases and manual record-keeping, which are highly vulnerable to data manipulation, unauthorized access, and lack of real- time visibility. The absence of a unified and secure platform makes it difficult for stakeholders to verify the authenticity of medicines and track their movement across different stages. Furthermore, these systems do not provide an effective mechanism for patients to independently validate the legitimacy of pharmaceutical products. Although some digital solutions have been introduced to improve tracking and management, they often lack scalability, transparency, and automation, limiting their effectiveness in real-world scenarios.

These limitations highlight the need for a secure, transparent, and automated system that can ensure end-to-end traceability, prevent counterfeit drugs, and improve overall efficiency in pharmaceutical supply chain management.

IV. PROPOSED SYSTEM

The proposed system utilizes blockchain technology and smart contracts to enable secure and transparent management of the pharmaceutical supply chain. At its core, the system consists of decentralized data storage and automated smart contract execution that ensures every transaction is recorded in an immutable and tamper-proof ledger.

Each participant in the supply chain, including manufacturers, distributors, wholesalers, and pharmacies, interacts with the blockchain through authorized access. Unlike traditional systems that rely on centralized control, the proposed approach ensures that all transactions are verified and validated through predefined smart contract rules, eliminating the risk of data manipulation and unauthorized activities.

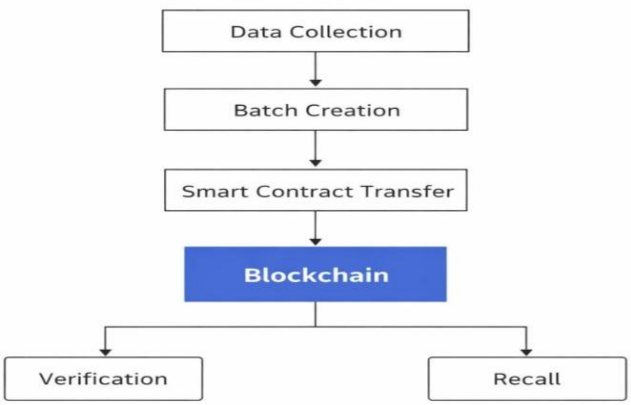

Figure 1 System Flow Diagram

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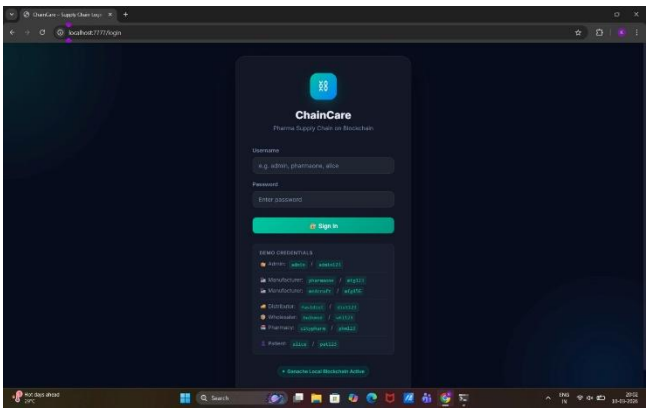

A. Data Collection and Registration Module

The Data Collection and Registration Module is responsible for gathering and managing all relevant information related to pharmaceutical products and supply chain participants. This module collects detailed data such as medicine name, batch number, manufacturing date, expiry date, composition, and regulatory details. In addition, it registers all stakeholders—including manufacturers, distributors, wholesalers, and pharmacies—by assigning them unique blockchain addresses and roles within the system. The collected data is verified before being recorded on the blockchain to ensure accuracy and authenticity. This module also ensures that only authorized participants can enter or modify data, thereby preventing unauthorized access. The structured data is then stored in a decentralized manner, making it accessible to all stakeholders while maintaining data integrity. By establishing a reliable and secure data foundation, this module plays a crucial role in enabling seamless tracking and transparency throughout the pharmaceutical supply chain.

B. Batch Creation Module

The Batch Creation Module allows manufacturers to generate new medicine batches and record them on the blockchain. Each batch is assigned a unique batch ID that acts as a digital identity for the product throughout its lifecycle. The manufacturer inputs essential details such as product information, quantity, production date, and expiry date, which are then validated using smart contracts before being permanently stored. This module ensures that only registered and verified manufacturers can create batches, thereby preventing unauthorized production of medicines. Once the batch is created, it becomes part of the blockchain ledger, ensuring immutability and traceability. This module forms the starting point of the supply chain process and ensures that every product entering the system is genuine and can be tracked from its origin.

C. Smart Contract-Based Transfer Module

The Smart Contract-Based Transfer Module manages the secure transfer of pharmaceutical products between stakeholders in the supply chain. Each transfer is governed by predefined rules encoded in smart contracts, ensuring that only authorized participants can initiate and complete transactions. For instance, a manufacturer can transfer products only to a distributor, and a distributor can transfer them only to a wholesaler. The smart contract verifies the identity of the sender and receiver, checks the validity of the transaction, and updates the ownership details on the blockchain. Every transaction is recorded with a timestamp, ensuring complete traceability. This module eliminates the need for intermediaries and reduces the risk of fraud, data manipulation, and unauthorized transactions. By automating the transfer process, it enhances efficiency, security, and transparency in the supply chain.

D. Verification and Counterfeit Detection Module

The Verification and Counterfeit Detection Module enables stakeholders and patients to verify the authenticity of pharmaceutical products using the batch ID. When a batch ID is entered into the system, it retrieves the complete history of the product from the blockchain, including its origin and transfer records. If the batch ID is not found in the blockchain, the system identifies the product as counterfeit. Additionally, if the batch is marked as recalled, the system generates a warning indicating that the product is unsafe for use. This module plays a critical role in preventing the circulation of fake medicines and ensuring patient safety. By providing a simple and reliable verification mechanism, it increases consumer trust and promotes transparency in the pharmaceutical supply chain.

E. Drug Recall and Monitoring Module

The Drug Recall and Monitoring Module is designed to handle the efficient recall of defective or unsafe pharmaceutical

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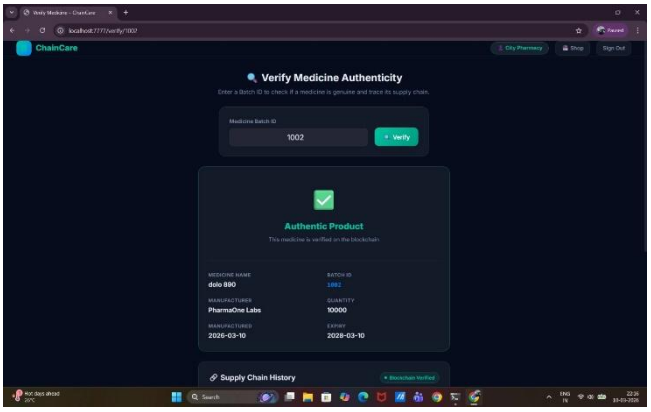
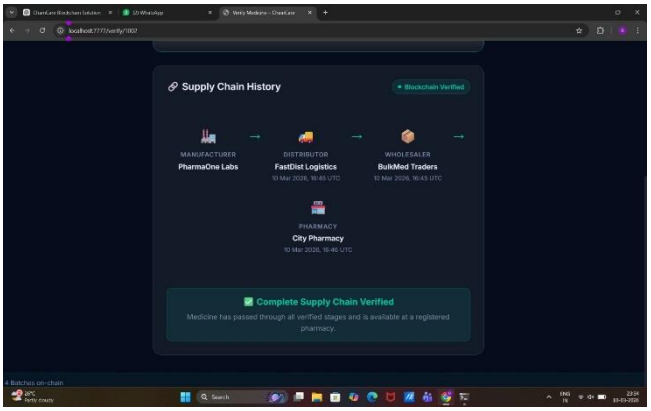
products. When a manufacturer identifies an issue with a particular batch, a recall request is initiated through the smart contract. The system updates the status of the batch to "recalled" on the blockchain, making this information visible to all stakeholders. Once recalled, the batch cannot be transferred further, and its distribution is immediately halted. This module continuously monitors the movement of products across the supply chain and ensures that recalled medicines are not delivered to pharmacies or patients. It also enables real-time alerts and notifications to relevant stakeholders, allowing quick response to potential risks. By automating the recall process and ensuring immediate action, this module significantly enhances the safety and reliability of the pharmaceutical supply chain.

V. RESULT ANALYSIS

The implementation of a blockchain-based pharmaceutical supply chain management system introduces several potential risks that must be carefully analyzed and mitigated to ensure system reliability and effectiveness. One of the primary risks is related to the scalability of blockchain networks. As the number of transactions increases with multiple stakeholders participating in the supply chain, the system may experience delays in transaction processing and increased latency. This can affect real-time tracking and verification, especially in large-scale deployments involving high volumes of pharmaceutical products. Another significant risk involves the security of smart contracts. Although smart contracts are designed to automate processes securely, vulnerabilities in the contract code may lead to unintended behavior or exploitation by malicious entities. Any flaw in the implementation could compromise critical operations such as batch creation, transfer validation, or drug recall.



Therefore, rigorous testing, auditing, and validation of smart contracts are essential before deployment. Data privacy is also a key concern in blockchain- based systems. While blockchain ensures transparency, storing sensitive pharmaceutical data on a public or shared ledger may expose confidential information to unauthorized users. Proper encryption techniques and access control mechanisms must be implemented to ensure that only authorized participants can view specific data, thereby maintaining confidentiality while preserving transparency.



Many pharmaceutical organizations currently rely on legacy systems for inventory management and logistics. Integrating blockchain solutions with these existing infrastructures may require significant modifications, leading to increased implementation complexity and cost. Additionally, resistance to adopting new technologies among

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stakeholders can slow down system deployment and limit its effectiveness. Regulatory compliance is another critical factor that introduces risk. The pharmaceutical industry is governed by strict regulations, and any technological solution must adhere to legal and compliance standards. Differences in regulations across regions can further complicate the implementation of a unified blockchain-based system. Ensuring compliance while maintaining system efficiency requires careful design and continuous monitoring. Finally, operational risks such as network failures, system downtime, or incorrect data entry can impact the performance of the system. Since blockchain data is immutable, any incorrect data entered cannot be easily modified, which may lead to inaccuracies in the supply chain records. To address this, validation mechanisms and error-handling procedures must be implemented to ensure data accuracy at the point of entry.

VI. CONCLUSION

Finally, the proposed blockchain-based pharmaceutical supply chain management system offers a significant improvement in ensuring transparency, security, and traceability across the entire supply chain. By leveraging decentralized blockchain technology and smart contracts, the system effectively overcomes the limitations of traditional centralized approaches, which often suffer from data manipulation, lack of visibility, and inefficient tracking mechanisms. The proposed system enables secure recording of all transactions, ensuring immutability and preventing unauthorized modifications. The integration of features such as real-time product tracking, counterfeit detection, and automated drug recall significantly enhances the reliability and safety of pharmaceutical distribution. Experimental observations demonstrate that the system is capable of accurately verifying medicine authenticity and maintaining complete traceability from manufacturer to patient. Furthermore, the use of smart contracts automates critical operations, reducing manual intervention and improving overall efficiency.

Overall, the proposed system addresses the limitations of traditional supply chain methods by improving transparency, reducing the risk of counterfeit drugs, and ensuring efficient management of pharmaceutical products. Hence, it can be considered a reliable and effective approach for modern pharmaceutical supply chain management.

VII. FUTURE WORK

Future research will focus on enhancing the scalability, efficiency, and adaptability of the proposed blockchain-based pharmaceutical supply chain management system to support large-scale real-world deployments. One potential direction is the integration of advanced technologies such as the Internet of Things (IoT), which can enable real-time monitoring of pharmaceutical products through sensors that track temperature, storage conditions, and transportation status. This integration would improve the accuracy and reliability of supply chain data. Additionally, the system can be extended to operate on hybrid blockchain architectures, combining both public and private networks to balance transparency and data privacy. Improving interoperability with existing legacy systems is also essential to facilitate seamless adoption across pharmaceutical organizations. Another important area of enhancement is the incorporation of artificial intelligence techniques for predictive analysis, which can help identify potential risks such as supply chain disruptions or abnormal transaction patterns. Additionally, the current system can be extended to operate on a public blockchain network instead of a local environment, enabling large-scale deployment across multiple pharmaceutical companies and healthcare organizations. This will improve interoperability and trust among different stakeholders.

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| Volume 8, Issue 2, March - April 2026 |

DOI:10.15662/IJEETR.2026.0802078

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