

Development of a Blockchain-Based System for Drug Counterfeiting and Traceability in the Pharmaceutical Supply Chain

Asfia Aziz^{1*}, Sunil Suman²

Abstract

Counterfeit drugs present a major risk to public health and pose a substantial threat to the pharmaceutical industry, leading to severe economic losses and risking patient lives. Ensuring the safety and authenticity of the pharmaceutical supply chain is critical to addressing this issue. This study presents a novel approach for enhancing the security and authenticity of the pharmaceutical supply chain through the integration of blockchain technology, decentralized storage, and artificial intelligence (AI)-based predictive analytics. The proposed system establishes an immutable public ledger and records all transactions within the supply chain, ensuring transparency and traceability and making it nearly impossible for counterfeit drugs to infiltrate the system. This study handles the issue of storing huge quantities of data on the blockchain by employing the interplanetary file system (IPFS). In this approach, the hash of the data is maintained on the blockchain, while the actual data is safely stored over the IPFS network. The performance of the proposed system was evaluated using several metrics, demonstrating significant improvements over existing solutions. The execution time for processing 1,000 transactions was reduced to 1,806.7s compared to 2,396.53s in Hyperledger Fabric and 7,533.74s in Ethereum. The throughput of the system was also improved, achieving 0.0015 transactions per second (tps) at 1000 transactions, which is higher than Ethereum's 0.0001 tps. Additionally, the AI-based predictive analytics demonstrated an accuracy of 96.52% in detecting counterfeit drugs, further enhancing the reliability of the pharmaceutical supply chain.

Keywords: Counterfeit drugs, traceability, pharmaceutical supply chain, blockchain, artificial intelligence, interplanetary file system

INTRODUCTION

Counterfeit pharmaceuticals, often known as fake drugs, are intentionally and deceitfully mislabeled in terms of their identity or source [1–4]. These are typically medicinal goods that either include incorrect substances or may have the proper chemicals but in incorrect quantities. Worldwide consumers are facing a significant danger from drug counterfeiting [5]. It not only has a significant impact on human health, but it also causes significant financial losses for the healthcare industry. Consuming these counterfeit drugs may have significant consequences, ranging from minimal health deterioration to quite severe outcomes, including patient fatality. Considering the present circumstances, both the prevalence of diseases and the overall number of patients are steadily rising, leading to a corresponding increase in the use of counterfeit pharmaceuticals [6, 7].

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An important challenge in addressing counterfeit medications is the management of health information, including drug records and transactions, through

throughout the whole supply chain [8]. Healthcare data management has several challenges, notably regarding access control, data exchange, and storage. In the counterfeit pharmaceutical supply chain, the original manufacturing process of the medicines is the primary concern about medication safety. Tracing the origin and movement of correct and effective pharmaceutical components throughout the actual manufacturing process is a time-consuming task. Identifying medications that lack the required active components might potentially result in injury or fatality to the end-consumer patient [9]. Figure 1 illustrates how blockchain technology is used to establish pharmaceutical traceability.

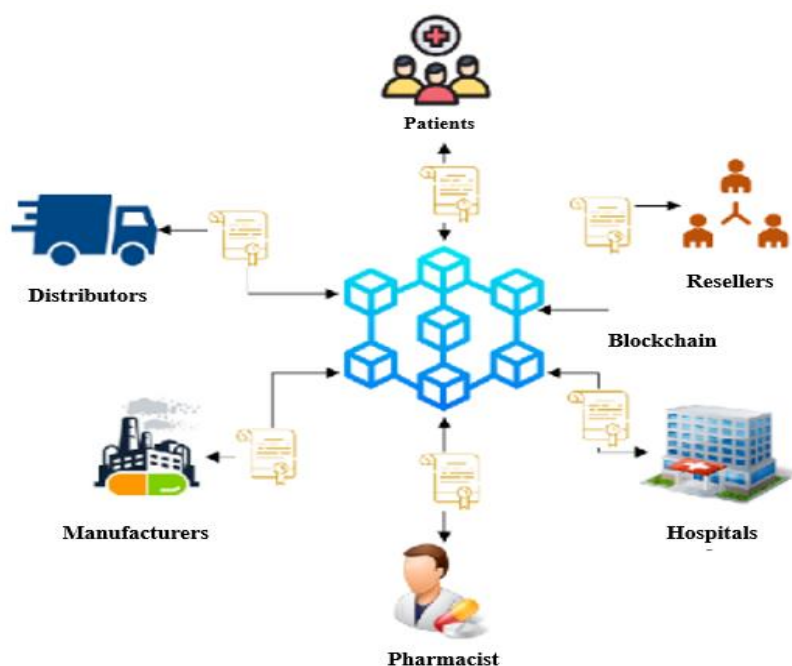


Figure 1. Drug traceability using blockchain [10].

The presence of counterfeit drugs in mainstream pharmacies and hospitals is primarily due to the vulnerability of the supply chain. This vulnerability provides ample opportunities for criminal entities to engage in horrific crimes throughout the drug supply chain, either for their own selfish gain or for other malicious purposes [11]. Criminals are often able to successfully carry out this crime because of the inherent intricacy of the pharmaceutical medication supply chain, which involves several stakeholders from various countries worldwide [12, 13].

Therefore, keeping patient data up-to-date becomes critically important in healthcare. Transferring health data between multiple organizations raises two significant issues: data privacy and data integrity [14]. Some of the technology-based solutions suggested to safeguard the drug supply chain from counterfeiting include barcodes [15], radio frequency identification (RFID) [16], data matrices [17], and near field communication (NFC) [18]. While many of these solutions provided some relief from the issue, their lack of security against determined counterfeiters and practical implementation challenges hindered further investigation into their systems. Furthermore, each one relied on a centralized client-server design, which was vulnerable to manipulation and had a single point of failure [19].

Recently, blockchain technology, which is a reliable and distributed digital ledger that became famous through the decentralized cryptocurrency Bitcoin [20], has acquired significant popularity in several industrial sectors, especially in healthcare [21]. Blockchain technology possesses key attributes, including decentralization, cryptographic protection, immutability, transparency, and smart contract execution. These features render blockchain a viable substitute in situations where a final product is associated with significant reputational issues and requires assurance of product integrity

[22]. This accurately characterizes the existing pharmaceutical medication supply chain, which is mostly lacking in trust and integrity [23].

This research presents a novel approach to enhancing the safety and authenticity of the pharmaceutical supply chain through the integration of blockchain technology, decentralized storage, i.e., IPFS, and artificial intelligence (AI)-based predictive analytics. The key contributions of this work include:

- The study utilizes blockchain technology to provide an irrevocable public ledger.
- That records each transaction in the supply chain, from the manufacturer to the end customer. This transparency and traceability make it difficult for fraudulent drugs to enter the system.
- The approach addresses the challenges of storing huge data files directly on the blockchain by using IPFS for decentralized data storage. The hash of the data is kept on the blockchain, whereas the actual information is securely distributed across the IPFS network, ensuring data integrity and availability.
- The research introduces the use of long short-term memory (LSTM) networks to perform predictive analytics on the stored data. This AI-based approach helps identify potential counterfeit risks or anomalies in the supply chain, allowing for proactive intervention.
- The proposed system enables end customers to verify the authenticity of their drugs using a mobile app that scans a QR code linked to the blockchain.

This study is organized in the given sections: Section 1 introduces the critical issue of drug counterfeiting and the need for secure supply chains. Section 2 offers a review of existing studies on enhancing supply chain security. Section 3 presents the research methodology along with the proposed approach to ensure the authenticity and traceability of pharmaceuticals. Section 4 presents the results and discussion, analyzing the performance and comparing it with existing solutions to highlight the efficiency of the suggested method. Section 5 concludes with a summary and suggestions for further study.

LITERATURE OF REVIEW

The pharmaceutical industry faces significant challenges with counterfeit drugs and supply chain transparency, prompting researchers to explore blockchain-based solutions. Nawaz et al. [24] proposed a PHTrack framework using Hyperledger Sawtooth for drug traceability, while Pranitha et al. [25] introduced a blockchain-assisted QR code system (DcB assist QR) for securing drug details. Both studies demonstrated improvements in drug provenance tracking and supply chain efficiency. Similarly, Mega et al. [26] developed a blockchain architecture for Nigeria's drug delivery system, showing high user satisfaction across various performance metrics. Further, Jamil et al. [27] contributed to this body of work by proposing a Hyperledger Fabric-based blockchain system to securely manage records of the drug supply chain. The study includes smart contracts to provide limited access to electronic drug records and uses Hyperledger Caliper to benchmark improvements in throughput, latency, and resource utilization. These studies collectively highlighted the ability of blockchain technology to improve security and transparency in pharmaceutical supply chains.

Building on these foundations, Bapatla et al. [28] presented the PharmaChain model, a distributed ledger technology (DLT)-based system for transparent pharmaceutical supply chains. The research revealed promising results in terms of block times and data source efficiency. Bandhu et al. [29] explored an Ethereum-based solution for healthcare supply chain tracking, emphasizing smart contracts and data immutability. Quzmar et al. [30] proposed a secure blockchain system using Hyperledger Fabric, demonstrating efficient consensus mechanisms. These studies further reinforced the applicability of blockchain in addressing supply chain challenges, showcasing improvements in scalability, reliability, and transaction validation.

Integrating additional technologies, Ouf et al. [31] combined semantic web, IoT, and blockchain to improve medical supply chain transparency and data representation. Musamih et al. [32] focused on drug traceability using Ethereum smart contracts, demonstrating cost efficiency and robust security features. Alam et al. [33] developed a blockchain infrastructure for medicine authentication, optimizing data storage and improving overall reliability. Collectively, these approaches underscore the capability of blockchain technology to revolutionize pharmaceutical supply chains by addressing counterfeit drugs, enhancing traceability, and enhancing overall security and efficiency.

The research indicates that blockchain-based solutions offer promising advancements, though continued development is necessary for widespread adoption in the pharmaceutical industry. Table 1 summarizes the objectives, techniques, and outcomes of the studies presented in the above literature.

Table 1. Summary of review.

Authors	Objective	Technique	Outcome
Nawaz et al. (2024) [24]	Develop a traceability system for drug supply chains.	PHTrack, Hyperledger Sawtooth.	Reliable drug provenance and real-time tracking with minimal resource consumption.
Pranitha et al. (2024) [25]	Enhance drug security and prevent unauthorized access.	DcB assist QR.	21.02 seconds less execution time, 983.7 Kbps throughput.
Mega et al. (2024) [26]	Combat counterfeit drug circulation in Nigeria.	Blockchain-based architecture using Python and Flask.	High user satisfaction: 100% flexibility, 97% data integrity, 95% resilience.
Bapatla et al. (2023) [28]	Analyze scalability and efficiency of the PharmaChain model.	DLT with smart contracts.	5.6 seconds average block time, 285 ms response time for Oracle data, 100% success rate in load tests.
Bandhu et al. (2023) [29]	Track and trace the healthcare supply chain using blockchain.	Ethereum blockchain with solidity smart contracts.	Average gas cost: 18,027.2 for specific functionality, seamless medicine flow without intermediaries.
Quzmar et al. (2022) [30]	Reduce counterfeit drugs in pharmaceutical supply chains.	NodeJS with Hyperledger Fabric.	High performance: $2N*(N-1)$ messages for consensus, efficient transaction validation.
Ouf et al. (2021) [31]	Improve transparency and security in pharmaceutical supply chains.	IoT, Semantic Web, and blockchain integration.	Enhanced transparency, improved patient satisfaction, and prevention of drug counterfeiting.
Musamih et al. (2021) [32]	Enhance drug traceability in pharmaceutical supply chains.	Ethereum blockchain with smart contracts and cryptography.	Cost-efficient gas usage, protection against data integrity, availability, and non-repudiation threats.
Alam et al. (2021) [33]	Develop secure infrastructure for medicine authentication.	Blockchain-based security architecture.	Effective falsified medicine identification, optimized blockchain storage with the removal of expired data.
Jamil et al. (2019) [27]	Manage secure drug supply chain records.	Hyperledger Fabric with Smart Contracts.	Increased performance: higher throughput, minimized latency, efficient resource utilization.

The literature review highlights that although significant progress has been made in applying blockchain technology to pharmaceutical supply chains, there are notable research gaps that need to be addressed. Studies by Alam et al. [33] and Bapatla et al. [28] highlighted ongoing challenges in achieving scalable and secure data storage solutions within blockchain frameworks, particularly when managing large volumes of sensitive information. Ouf et al. [31] underscored the need for integrating advanced AI-based predictive analytics to proactively detect counterfeit drugs, an area that remains underexplored in current implementations. Additionally, while Nawaz et al. [24] addressed traceability, the study does not fully tackle the security implications of decentralized storage or the potential of AI to enhance predictive capabilities. These gaps highlighted the necessity for further research to develop comprehensive solutions that integrate robust security measures, scalable storage

systems, and advanced AI-driven predictive analytics to strengthen pharmaceutical supply chains against emerging threats.

RESEARCH METHODOLOGY

The following section outlines the dataset and techniques of the comprehensive methodology employed in the development of the proposed system.

Data Set Description

The dataset simulates a real-world pharmaceutical supply chain with 50,000 transactions from January 2020 to December 2023, including nodes like manufacturers, wholesalers, pharmacies/hospitals, and patients. This dataset, taken from a primary source, is designed to test the proposed blockchain-based model for detecting and preventing drug counterfeiting. It was synthetically generated to include both legitimate and compromised transactions, with 5% altered to simulate counterfeit drugs. The dataset underwent rigorous validation to ensure it accurately represents real-world conditions, verifying timestamps, drug code uniqueness, and node integrity. This dataset is used to test a blockchain-based model for detecting and preventing drug counterfeiting.

DATA SET OVERVIEW

The synthetic dataset is detailed in Table 2, which includes the total number of entries, the time duration, and the different pharmaceutical supply chain nodes.

Table 2. Overview of the dataset.

Category	Details
Total records	50,000 transactions
Time span	January 2020 to December 2023
Patients	1,000 unique patients
Pharmacies/hospitals	100 outlets
Manufacturers	10 unique entities
Wholesaler	20 primary and 30 secondary wholesalers

FEATURES

Significant fields in the dataset utilized for monitoring and validating pharmaceutical transactions are listed in Table 3. These elements include unique IDs, timestamps, and verification status.

Table 3. Dataset fields and their description.

Field Name	Description
Transaction ID	Unique identifier for each transaction
Patient ID	Unique identifier for the patient
Pharmacy/hospital ID	Identifier for the dispensing outlet
Manufacturer ID	Identifier for the manufacturing entity
Wholesaler ID	Identifier for the distributors
Transaction timestamp	Exact time of transaction recording
Drug QR code	Unique QR code for each drug batch
Verification status	Binary value indicating drug authenticity check at each node

Techniques Used

This subsection would explain the specifics of each technique, providing a comprehensive understanding of their roles within the proposed system for fake drug traceability in the medical supply chain

Blockchain Technology

It is a decentralized system for conducting online data transactions. These transactions may be either public or private, depending on the individuals involved [34, 35]. The technology ensures secure and reliable data storage. Each node participating in a network has its own individual copy of the blockchain, as seen in Figure 2. Transactions in a private blockchain are often only accessible to legal users, while in a public ledger, transactions are available to all participants. This arrangement enhances the privacy of transactions in a private blockchain network [36]. Within a public ledger, the main means of identifying a node are the asymmetrical keys. Unrestricted or publicly accessible blockchains are suitable for anybody to participate in validating blocks or creating new transactions. However, the drawback is that scalability becomes a concern owing to its accessibility to the public [37].

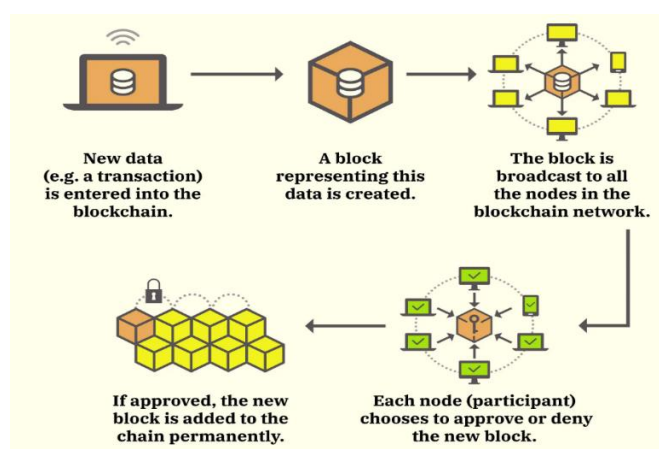


Figure 2. Blockchain process [38].

In this study, the QR code along with other manufacturing details, is hashed using a cryptographic function, such as SHA-256 and stored in the blockchain. The blockchain confirms that the data is immutable and securely linked to the previous transactions in the supply chain, creating a transparent and tamper-proof record that can be accessed by authorized participants. The public ledger in this system provides a verifiable record of each transaction and movement of the drug through the supply chain [39]. The public ledger is updated at every stage, from the wholesaler storing the verified drugs to the transporter loading them for delivery.

IPFS

The storage of large files in a blockchain becomes impractical because each data point must be accessible on every node, resulting in increased storage space requirements [40]. An effective resolution to this problem in blockchain is presented by IPFS, where instead of storing the actual data, a hash value is created using a cryptographic method and inserted into the blockchain transaction. IPFS does not permit the storage of data with specific nodes unless it involves the storage of confidential data. Currently, IPFS uses the list of authorized users to distribute hashed information between specified entities that communicate with each other [41].

In this study, IPFS is used to efficiently store and retrieve large data files in a decentralized manner. IPFS identifies each file by its content address, allowing nodes to retrieve data using a distributed hash table without needing a direct server connection. When a file is uploaded, it is split into smaller 256-kilobyte pieces, each hashed and interconnected for easy storage and retrieval. To overcome the limitation of blockchain in storing large files, only the hash of the data is stored on the blockchain using, while the actual data resides in IPFS [42]. This integration ensures that the system remains scalable and efficient, with the data securely distributed among the nodes.

AI-BASED PREDICTIVE ANALYSIS

AI is used in the medical field to analyze data and gain insights into medical issues with the aim of enhancing healthcare outcomes. It is used in healthcare to achieve several advantages and enhance the accuracy of identifying drugs in the pharmaceutical sector [43]. Machine learning (ML) algorithms play a crucial role in medical discoveries. Many kinds of counterfeit drugs are distributed globally. AI can readily assess whether a drug is counterfeit or not. Counterfeit drugs may be identified based on their distinct patterns, which are found using AI by analysing data collected from various medicines [44]. This approach has the potential to detect counterfeit medications by utilizing the unique characteristics of their medicinal formulation or the specific molecules of the drug, which are pre-established in the system using ML techniques [45]. Therefore, in this study, ML is used to analyze counterfeit pharmaceuticals in supply chain management.

ML algorithms may be employed to build diverse models for recognizing molecules and characteristics of physical substances in medicines [46]. The pharmaceutical business deals with supply chain management to produce and distribute complex pharmaceuticals that are identifiable. The present study used an LSTM model to analyze counterfeit drugs. LSTM networks have internal memory cells that may be utilized by forget and input gate networks, as seen in Figure 3.

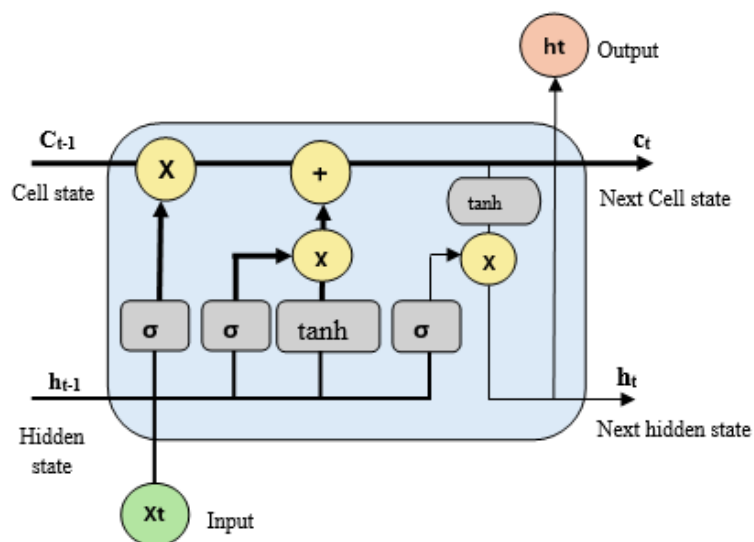


Figure 3. Functional architecture of LSTM [47].

The forget gate in an LSTM layer controls the rate at which memory is transferred to the next time step, while the input gate regulates the quantity of receiving input that is being sent to the memory cells. The LSTM model has the capability to understand and represent both short- or long-term connections in sequential information, depending on the present state of each of the gates [48]. This makes it highly effective in examining and identifying counterfeit medications.

Proposed Approach

The detailed explanation of the proposed approach to maintaining security and authenticity using blockchain is explained in this section. The process begins with hospitals/pharmacists placing an order for drugs. This order is then forwarded to the wholesaler, who processes the order and sends the necessary information and drugs to the manufacturer. The manufacturer is responsible for packaging the drugs, assigning a unique QR code to each package, and monitoring environmental conditions using IoT devices. These steps ensure that the drugs are securely packaged and accurately tracked. The manufacturer then records the relevant data on the blockchain, storing the data hash in the blockchain itself and the actual data in a decentralized storage system, i.e., IPFS.

Once the data is securely stored, AI-based predictive Analytics is performed using LSTM for potential counterfeit risks and anomalies. Based on the results of this analysis, if the model evaluates potential risks, it will send an alert to all the stakeholders else verified, and genuine drugs are passed to the transporter, who then loads these verified drugs for transportation to the warehouse. The warehouse physically stores the verified drugs until they are ready for distribution to the end customer, as shown in Figure 4.

When the drugs reach the end customer, they can authenticate the originality of the drugs by scanning the QR code using a mobile app. This app accesses the public ledger, tracing the drug's entire journey through the supply chain to confirm that it is genuine and has not been tampered with. At each stage of the process, the public ledger is updated, ensuring that all actions are transparent and can be audited by stakeholders. This process ensures a secure, transparent, and reliable pharmaceutical supply chain, leveraging blockchain, decentralized storage, and AI technologies to combat drug counterfeiting.

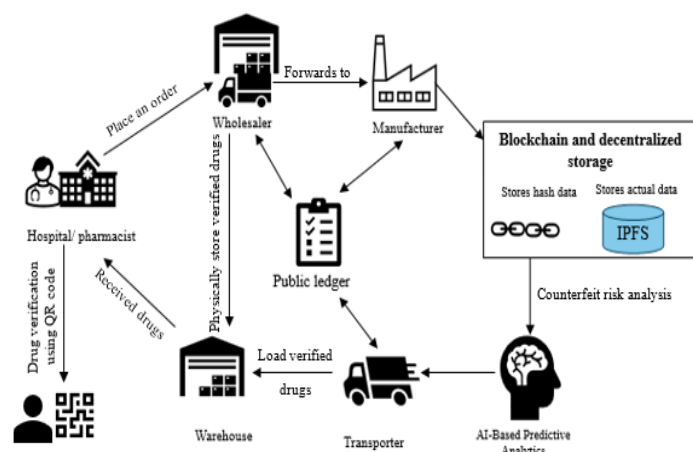


Figure 4. Proposed architecture.

PROPOSED ALGORITHM

Phase 1. Order Placement and Initiation

Order Placement (Hospital/Pharmacist)

Let O be the order containing the drug details D

$O = \{D, H, P, T\}$, where:

D is drug ID, H is hospital ID, P is pharmacist ID and T is timestamp

Order Forwarding (Wholesaler)

The order O is forwarded to the wholesaler W . The wholesaler processes O and forwards it to the manufacturer M .

Phase 2. Manufacturing and Packaging

Manufacturing Process (Manufacturer)

For each drug D in O , execute the manufacturing procedure $M(D)$.

Blister Packing

Pack the drug D into blister packs, denoted by $BP(D)$.

QR Code Assignment

Generate a unique QR code $QR(D)$ for each package:

$QR(D) = \text{Hash}(D \parallel H \parallel P \parallel T \parallel M(D) \parallel BP(D))$

Store QR(D) in the blockchain and decentralized storage.

Phase 3. Data Storage and Security

Data Hashing in Blockchain

Compute the hash of the manufacturing data H(D):

$$H(D) = \text{Hash}(M(D) \parallel BP(D) \parallel QR(D))$$

Store H(D) in the blockchain to ensure immutability.

Data Storage in IPFS

Store the actual manufacturing and environmental data E(D) in IPFS:

$$E(D) = \{M(D), BP(D), QR(D), Env(D)\}$$

Store E(D) in the IPFS network, and record the corresponding IPFS hash in the blockchain:

$$\text{IPFS_Hash}(E(D)) = \text{Hash}(\text{IPFS}(E(D)))$$

Link IPFS_Hash(E(D)) to H(D) in the blockchain.

Phase 4. AI-Based Predictive Analytics

AI-Based Analysis

Apply AI algorithms to analyze E(D) from IPFS:

$$\text{AI_analysis} = \text{AI_model}(E(D))$$

The AI model evaluates potential risks:

If risk (AI_analysis) > Threshold, then trigger alert in the blockchain and notify stakeholders.

Phase 5. Distribution and Transport

Drug Verification and Loading (Transporter)

The transporter verifies the drug data against the blockchain:

Verify QR(D) with H(D) in the blockchain.

Upon successful verification, load the verified drugs for distribution.

Storage in Warehouse

The warehouse receives the drugs and stores them, updating the public ledger with the transaction.

Phase 6. Public Ledger and Verification

Public Ledger Updates

For every movement and transaction, update the public ledger L:

$$L = \{\text{Transaction_ID}, \text{timestamp}, \text{entity}, QR(D), H(D)\}$$

Each update is recorded as a new block in the blockchain.

End Consumer Verification

The consumer scans the QR code QR(D) on the drug package. Retrieve and verify the drug's journey from the public ledger and IPFS. Validate QR(D) against the blockchain entry H(D). Display the entire drug journey to the consumer, ensuring authenticity.

Performance Evaluation Metrics

The performance of the suggested approach is evaluated using various metrics. Below is a brief explanation of these metrics

Execution Time

This metric represents the total time (in seconds) taken by the system to execute and confirm all transactions (t) in the dataset. The execution time is calculated as the sum of the time differences between the start and end times of all transactions, as given:

$$\text{Execution Time} = \sum_{i=1}^n (t_2 - t_1) \quad (1)$$

Average Latency

It is the mean latency for all transactions in a dataset, and it is given as:

$$\text{Latency} = t_2 - t_1, \text{ for Each transaction} \quad (2)$$

Average

$$\text{Latency} = \frac{\sum_{i=1}^n (t_2 - t_1)}{n} \quad (3)$$

Average Throughput

It is calculated as the mean of the throughput over the execution time. Throughput is defined as the total committed transactions per second, as given

$$\text{Throughput} = \frac{n}{\sum_{i=1}^n (t_2 - t_1)} \quad (4)$$

Average

$$\text{Throughput} = \frac{\text{Throughput}}{n} \quad (5)$$

Data Retrieval Time

The time required to retrieve data from IPFS or decentralized storage. Faster retrieval times indicate better performance.

Accuracy

The percentage of correctly identified counterfeit risks or anomalies by the AI model. High accuracy is crucial for effective risk detection.

Result and Discussion

The outcomes of the proposed system designed to detect counterfeit drugs in the medical supply chain are presented in this section. The results are analyzed to assess the system's performance using various performance metrics. The proposed system was implemented on the system with the following specifications given in Table 4, ensuring that the hardware and software environment is suitable for running the necessary computations and algorithms.

Table 4. System configuration.

Component	Specifications
CPU	Intel Core i5-3517U 1.90 GHz
Operating system	Ubuntu 20.04 LTS
Physical memory	16 GB

The following subsections would detail the findings from these experiments, providing insights into the strengths and potential areas for improvement of the proposed system.

Performance Evaluation

The performance evaluation of the proposed system reveals a clear relationship between the number of transactions processed and various performance metrics, including execution time, average latency, average throughput, and data retrieval time. As the number of transactions increases from 100 to 1,000, the execution time rises significantly, from 118.9 seconds to 1,806.7 seconds. This increase in execution time is followed by a corresponding rise in average latency, which grows from 1.23 seconds to 3.74 seconds. The average throughput, however, shows a decreasing trend, dropping from 0.0065 transactions per second (tps) at 100 transactions to 0.0015 tps at 1000 transactions, indicating that the system becomes less efficient as the load increases, as shown in Table 5.

Table 5. Performance metrics of the proposed method.

No. Transactions	Execution Time (s)	Average Latency (s)	Average Throughput (tps)	Data Retrieval Time (s)
100	118.9	1.23	0.0065	0.15
200	321.61	1.56	0.0048	0.20
300	508.83	1.89	0.0037	0.25
400	704.88	2.15	0.0029	0.30
500	934.95	2.48	0.0025	0.35
600	1163.68	2.79	0.0022	0.40
700	1291.23	3.02	0.0021	0.45
800	1419.09	3.28	0.0019	0.50
900	1647.41	3.52	0.0017	0.55
1000	1806.7	3.74	0.0015	0.60

Additionally, the data retrieval time also increases with the number of transactions, from 0.15 seconds at 100 transactions to 0.60 seconds at 1,000 transactions. These results suggest that while the system can handle a high volume of transactions, there is a trade-off in terms of increased latency, reduced throughput, and longer data retrieval times as the transaction load grows. This performance evaluation provides valuable insights into the scalability and efficiency of the proposed system under varying transaction loads.

Accuracy

The accuracy outcomes reveal that as the number of transactions increases, both the training and testing accuracy of the proposed LSTM system for counterfeit drug detection improve progressively. Starting with a training accuracy of 94.85% and testing accuracy of 94.50% at 100 transactions, the system's performance steadily enhances, reaching a training accuracy of 96.87% and testing accuracy of 96.52% at 1000 transactions, as shown in Table 6. This indicates that the system maintains high accuracy levels even as the transaction volume increases, reflecting its robustness and reliability in handling larger datasets.

Table 6. Accuracy of the proposed model for detecting Counterfeit drugs.

No. of Transactions	Training Accuracy	Testing Accuracy
100	94.85	94.50
200	95.23	94.88
300	95.65	95.22
400	95.90	95.50
500	96.12	95.73
600	96.30	95.85
700	96.45	96.05
800	96.58	96.25
900	96.73	96.40
1000	96.87	96.52

Comparative Analysis

The comparative analysis of execution time and throughput between Hyperledger Fabric [38], Ethereum [38], and the proposed approach reveals significant differences in performance. When examining execution time, the proposed approach consistently outperforms both Hyperledger Fabric and Ethereum. For instance, at 100 transactions, the proposed approach completes the task in just 118.9 seconds, which is approximately 50% faster than Hyperledger Fabric (238.84 seconds) and more than ten times faster than Ethereum (1507.03 seconds) as shown in Figure 5.

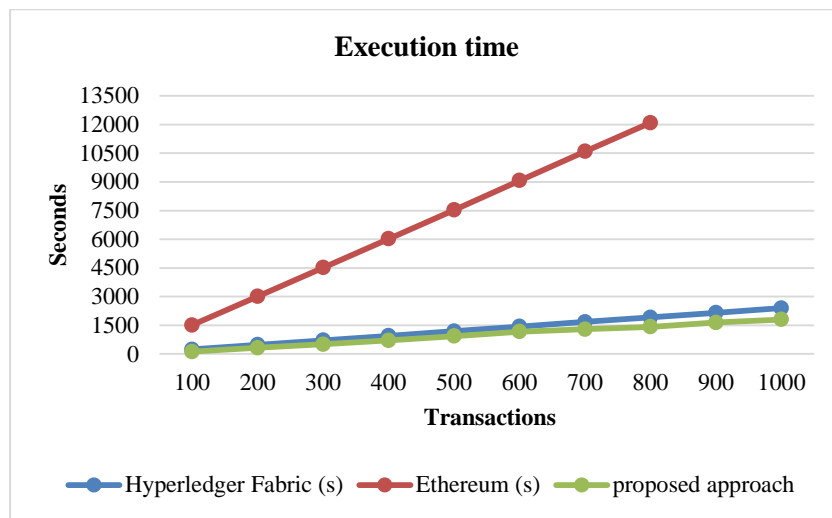


Figure 5. Comparison with existing methods based on execution time.

As the number of transactions increases, this trend continues, with the proposed approach maintaining the lowest execution times across all tested levels. This indicates that the proposed approach is not only faster but also more scalable and efficient in handling large volumes of transactions.

In terms of throughput, which measures the number of successful transactions processed per second (tps), the proposed approach again shows superior performance. At 100 transactions, the proposed system achieves a throughput of 0.0065 tps, significantly higher than Hyperledger Fabric (0.0042 tps) and Ethereum (0.0007 tps) as shown in Figure 6. This higher throughput is maintained across all transaction levels, highlighting the efficiency of the proposed approach in processing a larger volume of transactions within a shorter time frame. In contrast, Ethereum consistently demonstrates the lowest throughput, making it less suitable for applications that require high processing speeds.

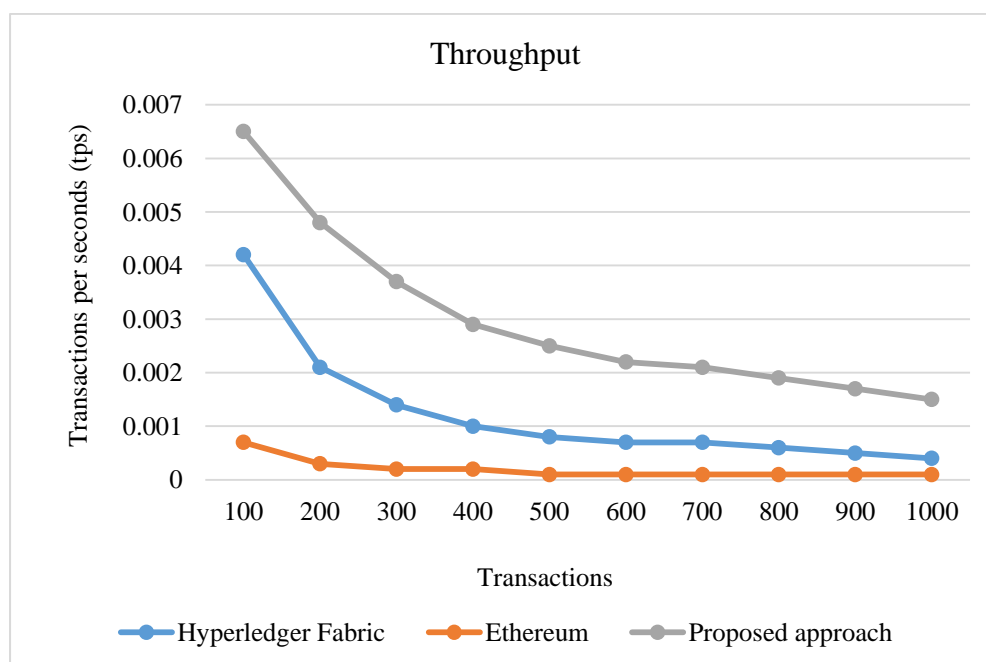


Figure 6. Comparison with existing methods based on throughput.

Overall, the proposed approach's superior execution time and throughput make it an ideal solution for real-time and large-scale applications, particularly in secure supply chains where performance and efficiency are critical.

CONCLUSION AND FUTURE SCOPE

The primary objective of this research was to address the increasing problem of counterfeit drugs in the pharmaceutical supply chain, which poses serious threats to public health and leads to economic losses for the industry. The proposed solution integrates blockchain technology to create an immutable public ledger that records every transaction from the manufacturer to the end consumer, ensuring transparency, traceability, and security throughout the supply chain, thereby preventing counterfeit drugs from infiltrating the system. The study employs IPFS to address the challenge of handling huge data files on the blockchain, where only the data's hash is stored on the blockchain while the actual data is securely distributed across the IPFS network, ensuring data integrity and availability without overburdening the blockchain's storage capacity. Furthermore, AI-based predictive analytics using LSTM networks were integrated to enhance the system's ability to detect counterfeit drugs, achieving a high accuracy of 96.52% in identifying potential risks or anomalies. The system's performance was evaluated using metrics, such as execution time, average latency, average throughput, and data retrieval time, revealing significant improvements over existing solutions like Hyperledger Fabric and Ethereum. Specifically, the proposed system achieved faster execution times and higher throughput, demonstrating its efficiency and scalability for real-time applications, with the execution time for processing 1,000 transactions is 1806.7s. These results highlight the effectiveness of the proposed method in addressing the critical issue of counterfeit drugs and enhancing the overall safety of pharmaceutical products.

Future studies could discover the application of this system in other critical supply chains, such as food or medical devices, and further enhance the predictive analytics component by integrating more advanced AI models to detect emerging threats and anomalies. Additionally, exploring the use of edge in high-volume environments could provide valuable advancements.

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