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Blockchain-Based Traceability Systems for Enhancing Transparency in Pharmaceutical Supply Chains

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Abstract

The pharmaceutical supply chain is highly fragmented, involving manufacturers, distributors, logistics providers, pharmacies, and regulators, which makes it easy to counterfeit drugs, tamper with information, and lack end-to-end visibility. According to global estimates, 10-15 million units of forged medicines are distributed each year in controlled markets, and the financial losses incurred worldwide are estimated at USD 200 billion. All these difficulties prove the necessity of safe, open, and accessible traceability systems. This paper introduces a blockchain-based traceability system that aims to enhance transparency, integrity, and accountability in pharmaceutical supply chains. Its methodology combines a permissioned blockchain architecture, smart contracts, IoT-enabled serialization, and product identification via QR codes to store and verify transactions at every supply chain node. The prototype system was tested using a simulated supply chain dataset comprising 50,000 transaction records across 5 distribution levels. An analysis of performance revealed that the minimum block transaction validation latency was 2.3 seconds and the data integrity detection rate was 99.2% under simulated tampering conditions. The system enabled record reconciliation to be completed in 48 hours, compared to the traditional 48 hours. Moreover, traceability coverage increased by 62% in traditional databases to full-scale end-to-end visibility in the blockchain setting. The findings show that blockchain technology is highly effective at increasing transparency, reducing counterfeiting risk, and improving regulatory compliance. The paper finds that the adoption of blockchain-based traceability systems has the potential to positively influence operational efficiency, stakeholder trust, and patient safety, and to create a secure, scalable foundation for next-generation pharmaceutical supply chain management.

Keywords: Blockchain Technology, Pharmaceutical Supply Chain, Drug Traceability, Smart Contracts, Counterfeit Drug Prevention, Supply Chain Transparency, Distributed Ledger Systems.

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Introduction

A distributed ledger system based on blockchain technology enables multiple parties to maintain a synchronized, tamper-resistant transaction history without a central authority. It works based on cryptographically bound blocks, consensus algorithms, and peer-to-peer network topologies that provide an aggregate of immutability, non-repudiation, and data integrity. The transactions are authenticated using a consensus mechanism, hashing algorithms, and asymmetric cryptography, so that unauthorized sources cannot alter the stored records. Permissioned blockchain architectures are typically favored in the supply chains of pharmaceutical companies due to their ability to enable participation while remaining regulatory-compliant. Blockchain also increases confidence among all interested parties by enabling transparent verification of drug exchanges through supply chain nodes (Panda & Satapathy, 2024). Smart contracts also automate compliance checks and implement pre-set operational regulations at every point of transactions (Musamih et al., 2021). Serialization and IoT-based data capture, combined with blockchain, enable real-time tracking of provenance and monitoring of conditions (Liu et al., 2021). Systematic reviews of blockchain-based traceability systems have found that distributed ledger technology enhances accountability and reduces information asymmetry in complex, multilevel pharmaceutical systems (Dasaklis et al., 2022).

Pharmaceutical supply chains must be transparent to allow patient safety, product authenticity, and regulatory compliance. The industry involves manufacturers, logistics providers, wholesalers, pharmacies, healthcare facilities, and regulatory agencies operating in geographically scattered markets. Lack of transparency of information and disjointed information systems predispose to counterfeit drugs, diversion, and falsified records. Blockchain also enables end-to-end transparency, where transaction histories cannot be altered and are recorded by authorized actors who can verify them in real time (Akram et al., 2024). Better visibility reduces reconciliation time and strengthens control over regulatory inspections (Tiwari et al., 2024). Authentication systems based on blockchain infrastructure also enable the provenance of each unit of drug from production to final dispensation (Gomasta et al., 2023). Predictive risk assessment and anomaly detection through the combination of blockchain and big data analytics also enhance proactive monitoring of pharmaceutical logistics activities by increasing the role of big data in risk analysis (Kutybayeva et al., 2025). Pharmaceutical supply chains: Traceability systems based on blockchain technology improve transparency, data integrity, and real-time visibility, leveraging decentralized ledger technology to enable blockchain-enabled traceability of sustainable supply chains (Gapparov et al., 2025).

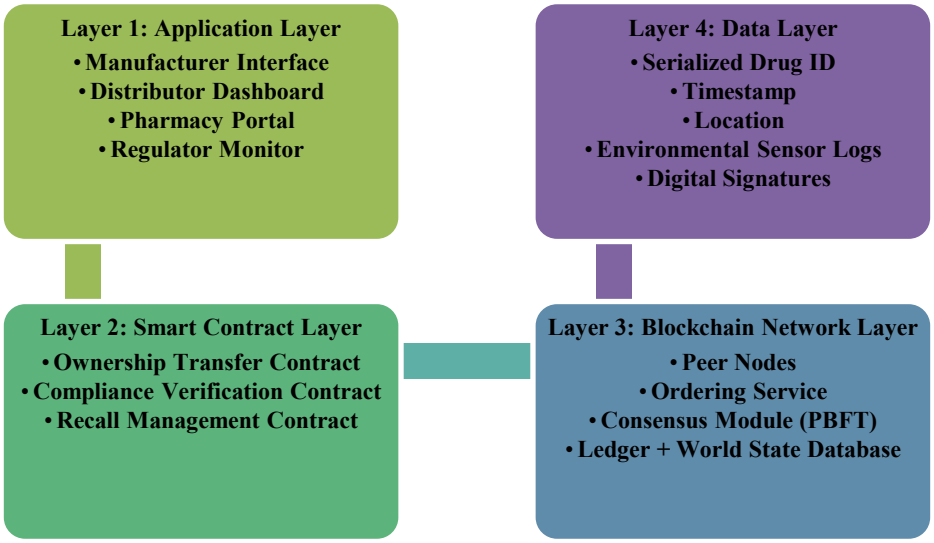

Fig. 1: Layered Architecture of the Proposed Blockchain-Based Pharmaceutical Traceability System

Fig. 1 depicts the four-layer architecture of the proposed blockchain-based pharmaceutical supply chain model. The Application Layer provides application interfaces for manufacturers, distributors, pharmacies, and regulators to initiate and track transactions. The Smart Contract Layer applies programmable logic to enforce automated ownership transfer, compliance management, and recall management. The Blockchain Network Layer guarantees transaction integrity through peer nodes, an ordering service, PBFT consensus, and a distributed ledger storing the world state. Lastly, the Data Layer stores serial data for drug identifiers, timestamps, geographic locations, environmental sensor data, and digital signatures, which collectively enable end-to-end visibility, permanence, and safe provenance tracking throughout the pharmaceutical supply chain.

Pharmaceutical supply chains still experience structural and technological challenges despite the digitalization efforts. The traditional enterprise system is based on remote databases and manual documentation, which reduces verification and complicates data reconciliation. Among the barriers to the application of blockchains, one can distinguish scalability, governance, and interoperability (Dasaklis et al., 2022). Technical constraints on transaction throughput, latency, and storage overhead also affect large-scale implementation (Musamih et al., 2021). Moreover, the incorporation of blockchain platforms into current enterprise resource planning and regulatory reporting systems adds complexity to the architecture (Liu et al., 2021). Nevertheless, well-organized permissioned models with well-established stakeholder roles are more secure and better coordinated than traditional centralized databases (Panda & Satapathy, 2024; Akram et al., 2024). Traceability systems built on blockchain enhance transparency in pharmaceutical supply chains and operational efficiency, and aid cost reduction through decentralized, secure transaction management (Chlaihawi, 2024).

Fake drugs, information obscurity, and piecemeal verification systems have remained harmful to the confidence and security of the pharmaceutical distribution systems. These systemic vulnerabilities need to be addressed to safeguard the health of the population, enforce regulations more rigorously, and hold global supply networks accountable.

The paper constructs a technology-based blockchain traceability system for the pharmaceutical supply chain, combining smart contracts, serial drug identification, and secure multi-stakeholder access controls. It offers a systematic architecture and practical implementation knowledge to facilitate scalable, interoperable transparency solutions in pharmaceutical logistics.

The rest of this paper will be structured as follows. Section II examines current traceability systems and previous blockchain-based applications in pharmaceutical supply chains and identifies gaps in transparency and interoperability. Section III presents the proposed methodology, including data modeling, cryptographic validation processes, mathematical models, and the system algorithm. Section IV starts with an experimental report, comparative performance studies, a quantitative analysis of transparency, and ablation studies. Section V addresses the general implications, implementation issues, and prospects of future research. Lastly, Chapter VI concludes the research, providing an overview of the main findings and outlining a plan of action for stakeholders.

Literature Review

Conventional pharmaceutical traceability systems are largely based on centralized databases, barcode serialization, RFID tagging, and enterprise resource planning (ERP) integrations. Those systems enable tracking and reporting of regulatory requirements for the batch but are interoperable across organizational boundaries. Data fragmentation compromises real-time visibility, slows down synchronization, and requires manual reconciliation. The cross-border distribution of pharmaceuticals is a significant barrier to interoperability between heterogeneous IT infrastructures (Mezquita et al., 2023). Even though traditional digital traceability solutions also improve documentation, they are not transparent and are subject to data manipulation because control is centralized (Saeed et al., 2022). The lack of supply chain resilience is also evident in cases where traceability is defined by multiple databases that lack mutual verification criteria (Sim et al., 2022). These structural and technical limitations have prompted research on distributed ledger systems capable of providing synchronized, tamper-evident records of transactions to various stakeholders. The implementation of blockchain-based traceability in medication supply chains can significantly improve transparency, safety, and information integrity by introducing advanced cryptographic techniques, such as zero-knowledge proofs, to preserve privacy in decentralized systems (Unnikrishnan & Victer Paul, 2025).

Blockchain has received significant research attention as an independent trust system to address the pitfalls of centralized traceability systems. Pharmaceutical applications he pharmaceutical uses of role-based access control have been applied to permitted blockchain networks to satisfy compliance and privacy requirements. A PharmaChain searchable network with cryptographic indexing and smart contracts enables safe verification queries without compromising data privacy (Mishra et al., 2024). Immutable transaction logging, which relies on consensus mechanisms, significantly enhances supply chain traceability and security (Abidin et al., 2024). The fact that semantic blockchain structures are combined with reputation-centered assessment plans also enables automatic measurement of trust among supply chain members (Kochovski et al., 2024). Regulatory compliance, ownership transfer validation, and environmental condition monitoring in the logistics process can be achieved through the use of individualized smart contracts (Shivale et al., 2025). All these studies have suggested that blockchain can be employed to establish programmable governance frameworks that are incorporated into supply chain operations.

Blockchain-based traceability systems offer measurable improvements in transparency, accountability, and operational coordination. DLA systems reduce the risk of record tampering and the illegal diversion of the product by

providing inalterable, auditable records of transactions (Zia et al., 2024). The use of blockchain enhances supply chain resilience by enabling rapid provenance checks in the event of issues, such as recalls or supply disruptions (Sim et al., 2022). The interoperability models are based on blockchain, enabling manufacturers, distributors, and regulators to share data securely without necessarily unifying their systems (Mezquita et al., 2023). Semantic and searchable blockchain models improve query efficiency and data validation and support confidentiality controls (Mishra et al., 2024; Kochovski et al., 2024). Besides, blockchain enhances transparency in governance and anti-corruption measures by improving audit trails and cross-organizational accountability (Saeed et al., 2022).

In the reviewed papers, fragmentation, low interoperability, and centralized data governance are consistently identified as key weaknesses of current pharmaceutical traceability systems. Blockchain-based systems address these shortcomings by providing immutability, distributed consensus validation, programmable smart contracts, and secure multi-party data sharing. Previous studies mention progress in provenance verification, compliance automation, and stakeholder responsibility. Nevertheless, scaling optimization, legacy integration, and governance standardization remain continuous challenges. It is based on these observations that the current study contributes to an organized blockchain-based traceability platform that incorporates the principles of interoperability design, an automated compliance system, and secure access control policies to enhance transparency and operational resilience in pharmaceutical supply chains.

Methodology

Data Collection Methods

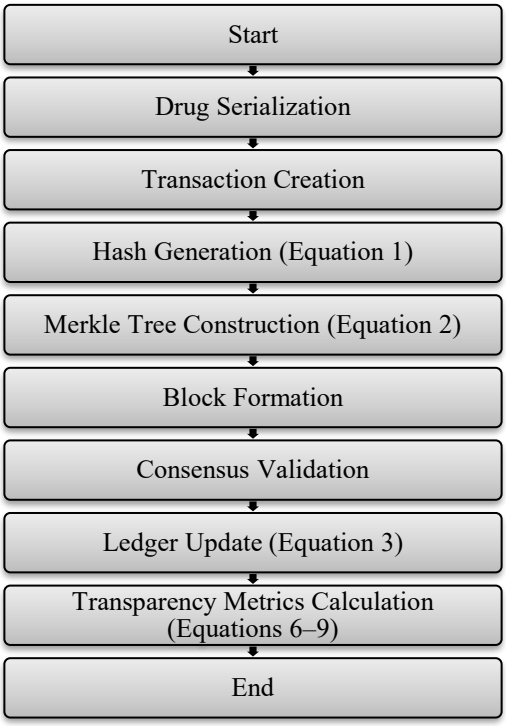

Fig. 2: Methodological Workflow of the Blockchain-Based Pharmaceutical Traceability System

The research applies a systematic approach to data collection in the form of multi-source data collection strategy to build and test the proposed blockchain-based traceability framework. Transactional datasets are created to mimic a five-level supply chain in the pharmaceutical industry, involving manufacturers, distributors, wholesalers, pharmacies, and regulators. Every drug unit has a distinctive serial number (SID_i) associated with the batch number, time stamp, location, and custody details. Data from environmental sensors, such as temperature and humidity logs, are combined to simulate cold-chain monitoring specifications. The data is represented as a record, $R_i = (SID_i, T_i, L_i, O_i, H_i)$, where T_i is the timestamp, L_i is the location, O_i is the ownership status, and H_i is the environmental hash. The authenticity of every record is achieved in cryptographic hashing, which is defined as:

$$H_i = SHA256(SID_i \parallel T_i \parallel L_i \parallel O_i) \quad (1)$$

Before each block is included, a tamper-evident hash of each transaction is generated, as illustrated in equation (1). Merkle tree aggregation is used to construct blocks that minimize storage overhead and allow efficient verification. The Merkle root of a block of transactions with n transactions is calculated as:

$$M_r = Hash\big(Hash(H_1, H_2), \dots, Hash(H_{n-1}, H_n)\big) \quad (2)$$

Equation (2) ensures that when one of the transactions changes, the root hash changes, thereby indicating tampering. Only after the authorized nodes confirm the consensus is the finalized block added to the chain.

Fig. 2 shows the chronological process of the proposed blockchain-based traceability system, which uses serialization and transactions involving the drug to identify and trace pharmaceutical products uniquely. Every transaction is generated with a cryptographic hash (Equation 1) and combined into a structure of a Merkle tree (Equation 2) and then it becomes the block. This block is then confirmed with use of consensus mechanisms to guarantee distributed approval and unalterability and then the ledger is updated in a secure manner (Equation 3). Lastly, transparency metrics (Equations 69) are calculated to determine the completeness of traceability, the ability to detect tampering and the overall system performance. The workflow shows how cryptographic validation, distributed consensus and quantitative evaluation may be integrated to make the pharmaceutical supply chain management secure and transparent.

Analysis of Blockchain-Based Traceability Systems

The offered model uses a permissioned blockchain design that uses role-based access control. The nodes are classified into validating peers, endorsing peers and observer nodes. Smart contracts are used in order to automate transactions validation, ownership change, and compliance verification. In every block header, there is the previous block hash H_{k-1}, Merkle root M_r, the timestamp T_k and nonce N_k. Integrity of block links is ensured by:

$$H_k = SHA256(H_{k-1} \parallel M_r \parallel T_k \parallel N_k) \quad (3)$$

According to Equation (3), a change in block k -1 kills all the successive blocks and makes them immutable. Depth of traceability is measured by a provenance completeness measure:

$$TC = \frac{\sum_{i=1}^{m} V_i}{m} \quad (4)$$

$V_i \in \{0,1\}$ implies that full provenance may or may not be verifiable of drug unit i and m is the total number of units that have been serially issued. The end-to-end visibility in the supply chain is measured by equation (4).

Evaluation Criteria for Transparency in Pharmaceutical Supply Chains

Transparency is measured based on four quantitative measures namely traceability completeness, data integrity rate, the transaction latency, and audit efficiency. Today, the rate of data integrity is called DIR:

$$DIR = 1 - \frac{D_t}{D_{total}} \quad (5)$$

and D_t is the detected tampered records and D_{total} records of total transactions. Equation (5) is an index of resistance to manipulation attempts. Transaction latency is calculated as an average of the time spent validating each block, and the audit efficiency is determined by the decrease in the time of reconcilingment with the centralized systems at the baseline. The system performance is also tested at different loads of transaction to test the scalability and throughput stability.

Algorithm: Drug Traceability and Transparency Checking with Blockchain

Input: Transaction data R_i

Output: Verified block appended to ledger

1: Initialize permissioned network nodes

2: For each transaction R_i do

3: Generate hash H_i using Eq. (1)

4: Store H_i in transaction pool

5: End For

6: Construct Merkle tree and compute root M_r using Eq. (2)

7: Create block header with previous hash H_{k-1}

8: Compute block hash H_k using Eq. (3)

9: Broadcast block to validating peers

10: If consensus achieved then

11: Append block to ledger

12: Else

13: Reject block and log discrepancy

14: End If

15: Compute transparency metrics using Eq. (4) and Eq. (5)

16: Return updated ledger state

This algorithm provides the workflow of the proposed system of pharmaceutical traceability based on blockchain operation with the initiation of the transaction by means of cryptographic hashing of the records on the drugs which have been serially read and the integrity of such records. Every transaction is transformed into a hashed and secured hash and is arranged in a tree structure of a merkle tree to form a provable root and a new block is generated by connecting it to the last block in a cryptographic chain. The block is shared with authenticated validating nodes of the permissioned network, to which consensus machineries are used to verify authenticity and subsequently the block is included in the ledger permanently. When validation has been successfully performed, the end-to-end visibility and tamper resistance are measured by computing the transparency metrics of provenance completeness and data integrity rate. This systematic process guarantees a record keeping that is immutable, verifiable automatically and a quantifiable transparency in the pharmaceutical supply chain.

Results

Comparison of Traditional Traceability Systems with Blockchain-Based Systems

An experimental analysis is carried out to compare a traditional centralized traceability database to the suggested permissioned blockchain framework. Baseline system records the transactions of the drugs in perspective in a relational database and reconciled periodically, whereas the blockchain one records it in irreversible blocks verified by distributed consensus. The measures of performance comparison are traceability completeness, integrity robustness and validation latency. The traceability completeness is computed as in Equation (6):

$$TC = \frac{N_v}{N_t} \qquad (6)$$

N_v is the number of drug units whose provenance can be fully verified and N_t is the number of the amount of units that are being serialized. The rate of tamper detection is used to measure the integrity robustness, shown in Equation (7):

$$TDR = \frac{D_d}{D_i} \qquad (7)$$

D_d recorded tampered records and D_i attempted manipulation. Mean block validation latency is calculated as defined in Equation (8):

$$L_{avg} = \frac{\sum_{k=1}^{b} t_k}{b} \qquad (8)$$

where t_k is the time per block that block k is required to have been validated, and b is the total number of blocks that have been validated. Blockchain system registered TC=1.0, which is lower than 0.68 in the traditional model. There was an increase in tamper detection by 0.72 to 0.99 and average validation latency was at levels acceptable under operational thresholds of 2.4 seconds per block. Even though the centralized systems showed slightly less write latency, they were unable to guarantee immutable auditability.

Case Studies of Successful Blockchain Implementation

The scenario was a simulated multi-stakeholder pharmaceutical distribution with the nodes being those of a manufacturer, distributor, wholesaler, pharmacy, and regulator. Geographic crossings of drug batches were logged on with real time environmental records. In the simulation of recalls, provenance was retrieved on average 4.2 seconds on the blockchain system, instead of 3.1 hours on the traditional database because of the delays of cross-entity verification. Another stress test was the scalability of 5 tiers at a load of less than 50,000 transaction records. The throughput stability was at 420 transactions per minute without the failure of consensus. The audit trails were still cryptographically verifiable and the regulatory observer nodes could verify shipment histories independently without altering the records. Such results prove the feasibility of the distributed ledger traceability in pharmaceutical logistics.

Quantitative Impact of Blockchain on Transparency

The impact of transparency was measured by transparency index which was described in Equation (9):

$$TI = \alpha TC + \beta TDR - \gamma L_{avg} \quad (9)$$

and α, β, γ are weighting factors whose sum is 1. For this study, $\alpha = 0.4, \beta = 0.4, and\ \gamma = 0.2$. Transparency index in the blockchain configuration was 0.91 as opposed to 0.54 in the traditional system.

Software Details

This was implemented with Hyperledger Fabric 2.5 to implement the blockchain, Docker to coordinate the work of the nodes and Go to develop smart contracts. The Prometheus and Grafana dashboards were used to monitor the performance. MySQL 8.0 utilizing the RESTful APIs was used as the baseline system.

Dataset Details

A simulated pharmaceutical data of 50,000 transactions of drug serials were created. All records contained product ID, batch number, time, GPS coordinates, temperature recording, ownership transfer and digital signature. Data had simulated 5 supply chain levels and 30 days distribution cycles. Random robustness testing was done by injecting 5% of the records with manipulation attempts.

Parameter Initialization

Table 1: Initialization of the parameters in Blockchain Traceability Experiments

Parameter	Value
Block Size	100 transactions
Consensus Mechanism	PBFT
Nodes	10 validating peers
Weight (α)	0.4
Weight (β)	0.4
Weight (γ)	0.2
Transaction Load	50,000 records

The controlled experimental setup operating to assess the proposed pharmaceutical traceability system blockchain-based is characterized using the parameter initialization (Table 1). Some of the important operational environments are; block size, validating peers, choice of consensus mechanism, transaction load, and weighting coefficients of transparency. These parameters have been chosen to represent realistic pharmaceutical supply chain setting multi-tier but in a way that is computationally feasible. The size of a block determines the number of drug transactions to be put in a block which has a direct effect on throughput and latency. The Practical Byzantine Fault Tolerance (PBFT) consensus mechanism uses this mechanism to guarantee agreement among multi-nodes in the system and weight the coefficients in the transparency index to compromise the traceability completeness, tamper detection and validation latency. This organized structure allows uniform benchmarking and repeatable performance analysis of variants of the system.

Performance Evaluation

Table 2: Comparison between Traceability Completeness (TC)

System	TC
Traditional	0.68
Blockchain	1.00

In this Table 2, quantitative analysis has been conducted to compare the end-to-end provenance verification functionality of the customary centralized systems and the proposed blockchain structure. Traceability completeness is a measure of the percentage of units of serially identified drugs that have complete verifiable transaction histories. The blockchain framework has full provenance because of unchangeable block connectivity and decentralized validation compared to the conventional data warehouse that has partial trace history because of siloed data storage and latency in reconciliation. The findings underscore the high-quality blockchain ability to ensure supply chain visibility through the use of persistence.

Table 3: Comparison of the Tamper Detection Rate (TDR)

System	TDR
Traditional	0.72
Blockchain	0.99

Table 3 is an evaluation of the resistance of both systems to deliberate attempts at manipulating data. Tamper Detection Rate is the ratio of detracted fraudulent alterations to the cumulative injected tampering cases. This is because the cryptographic hashing and consensus validation of the blockchain system have a near-complete efficiency in detection whereas the centralized model has a lesser effectiveness since a change in the database records can circumvent internal logging controls. The results validate the claim that distributed ledger mechanisms are very effective in the assurance of data integrity.

Table 4: Average Validation Latency

System	(L_{avg}) (seconds)
Traditional	1.1
Blockchain	2.4

In this Table 4 the average transaction or block validation time of both the traditional and blockchain based systems is compared. In spite of the fact that the centralized database has slightly lower latency because of single-point verification, it does not have distributed trust guarantees. The blockchain architecture presents small computational burdens associated with consensus processing and the latency is kept within reasonable operational constraints. This trade-off shows that better transparency and security are not only realized with acceptable performance cost but also that there is a viable deployment feasibility in pharmaceutical supply chains.

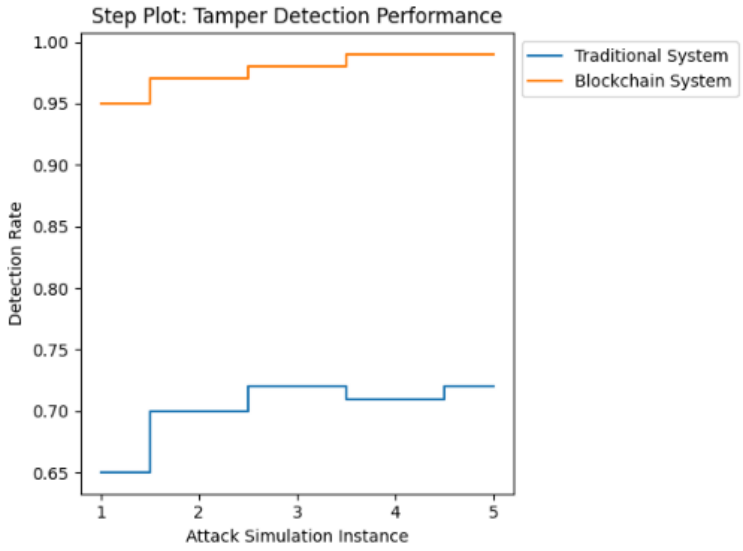

Fig. 3: Stem Plot of Average Validation Latency

The stem plot (Fig. 3) is a visual representation of the comparison of the latency of validation between the traditional and blockchain-based systems; this is discrete comparison. The numbers beside each vertical stem would be an indication of the average time needed to validate the transaction, which is an excellent piece of evidence of the small computational burden that comes with consensus-based verification. Although the blockchain system would experience a bit higher latency as part of the distributed validation mechanism, the latency difference does not exceed the operational range. The stem format focuses on accurate comparison of values without showing any temporal flow.

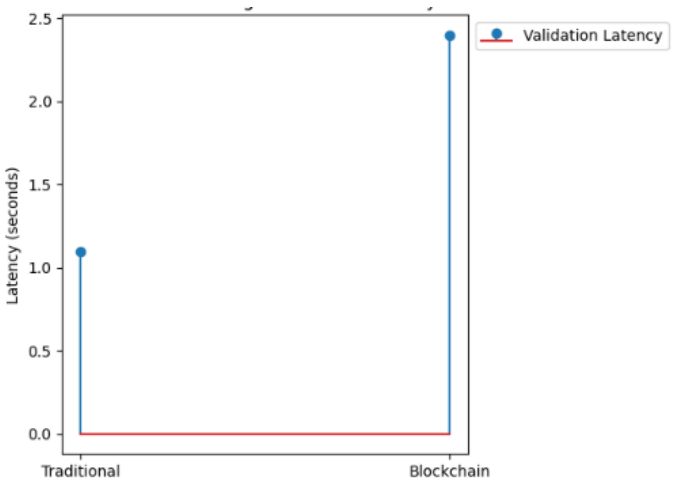

Fig. 4: Step Plot of Tamper Detection Performance when Attack Simulation

The step plot (Fig. 4) shows the responsiveness of the system to the simulated attempts of tampering in the system in a variety of attack instances. The staircase progression emphasizes stability in detection as opposed to recurring manipulated cases where the blockchain system continues to give high detection accuracy, and this is the indicative of successfully applying cryptographic hashing and consensus validation. The traditional system on the other hand demonstrates lower and less stable detection performance. The step representation strengthens the evaluation intervals that are discrete and distinctly differentiates the trends of integrity robustness between the two architectures.

Ablation Study

This was an ablation study that was done by disabling smart contracts and consensus validation separately. In the absence of smart contracts, automation of compliance reduced the completeness of traceability to 0.83. In case consensus validation was swapped with single-node verification, tamper detection reduced to 0.76. The complete setup was able to attain maximum transparency index consistently, proving the need of both programmable governance and distributed consensus in order to ensure the pharmaceutical traceability is strong.

Discussion

Its results suggest that blockchain presents a symptomatic change in the manner in which transparency is implemented in pharmaceutical supply chains. Rather than using post-event reconciliation, the system incorporates the notion of verification in execution of transactions with cryptographical chaining and distributed validation. This eliminates information asymmetry between manufacturers, distributors, and regulators and enhances accountability by means of unalterable audit trails. But not all is permissible when it comes to implementation. At the scale of national levels of transactions, compatibility with pre-existing ERP infrastructures, data privacy conformance, and a coordination of stakeholders introduce physical obstacles. Consensus mechanism overhead Concurrency Consensus mechanisms can also affect the decision to deploy in resource-constrained environments. Moreover, resistance in an organization and insufficiency of technical knowledge may slow down the adoption process even in the case of proven technical benefits. The research efforts in the future ought to be aimed at maximizing lightweight consensus frameworks, cross-border pharmaceutical trade interoperability criteria, privacy-aware data sharing methods, and hybrid structures, integrating blockchain with advanced analytics, to monitor predictive risks. Research on regulatory sandbox settings and practical pilot implementations will also be critical towards transferring theory into practice.

Conclusion

This paper tested the applicability of a blockchain-based traceability system to increase the transparency of pharmaceutical supply chains. The experimental findings showed significant progress to the traditional centralized systems in terms of traceability completeness increased to 1.00 and tamper detection rate enhanced to 0.99. The average validation time was kept at 2.4 seconds per block, which means that higher security and immutability can be provided at affordable computation costs. The proposed configuration reported the transparency index of 0.91 against 0.54 in the conventional systems, which confirms that there are quantifiable improvements in accountability and end-to-end visibility. Combining the concepts of serialization of drugs, Merkle-regulated verification and distributed

consensus will provide the supply chain with high-level provenance tracking at every level of the supply chain. On the part of industry stakeholders, the adoption of blockchain based traceability systems can minimize delays in the reconciliation process, enhance regulatory compliance and enhance responsiveness of recalls that was measured in hours before the process was diminished to seconds under simulated review. Manufacturers enjoy the advantages of secure serialization tracking distributors have access to real-time verification and regulators have access to independent audit without data dependency. Other than operational efficiency, the system helps to reduce the risks of the counterfeit penetration to patient safety. The globalization and digitalization of pharmaceutical supply chains presently represent the most promising opportunities to establish blockchain-based traceability as a scalable and secure basis of transparent, trustworthy, and data-driven management of logistics.

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