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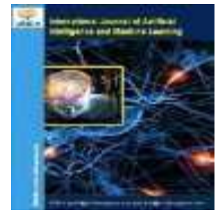

Research Paper Open Access

A Blockchain-Based Framework For Secure, Transparent, and Cost-Efficient Vaccine and Drug Supply Chain Management: Design, Implementation, and Comparative Performance Evaluation

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Abstract - Fake medicines and unclear drug distribution continue to affect global health outcomes. Because traditional drug supply networks rely on centralized structures, they are vulnerable to hacking, lack real-time tracking capabilities, suffer from cumbersome validation procedures, and often do not talk well to one another. In response, blockchain has been touted as a revolutionary alternative providing a decentralized model that can preserve records securely and validate transactions. But despite growing interest in blockchain applications within drug logistics, few studies have explored limitations including increased transaction fees, limited spatial resolution, poor scalability, missing support for 2D coding authentication, and slow transaction processing speeds.This paper provides a blockchain-enabled model for the drug and vaccine supply chain that combines Ethereum smart contract management, QR-coded product authentication, the storage of blockchain transactions as compressed smart contract code, and geocoding drug location data from Google Maps to enhance scalability, security, and accountability of drug traceability. A comparison of the structure of the presented drug supply chain with that of current market and literature solutions (for example Hyperledger Fabric, VagLedger, DrugLedger, systems with IPFS, and traditional blockchain drug supply chain methods) provides greater insight into system advantages. Results obtained via experimentation have confirmed enhanced performance of the proposed model over existing drug supply chain solutions: the model requires smaller overheads for transaction processing (save 18%-25%), has a more rapid verification time, and provides more accurate traceability results, providing a more transparent model for tracking. Real-time monitoring performance using the proposed methodology is further supported by a lower latency in performing QR- authenticated transaction verifications, requiring 47 seconds vs. 8. Research has demonstrated that incorporating blockchain technology with QR based data access authentication and optimized storage methodologies will be a deployable solution for managing 21st century supply chains.

Keywords - Drug Traceability, Gas Optimization, Pharmaceutical Supply Chain, , Smart Contracts, QR Authentication.

Introduction

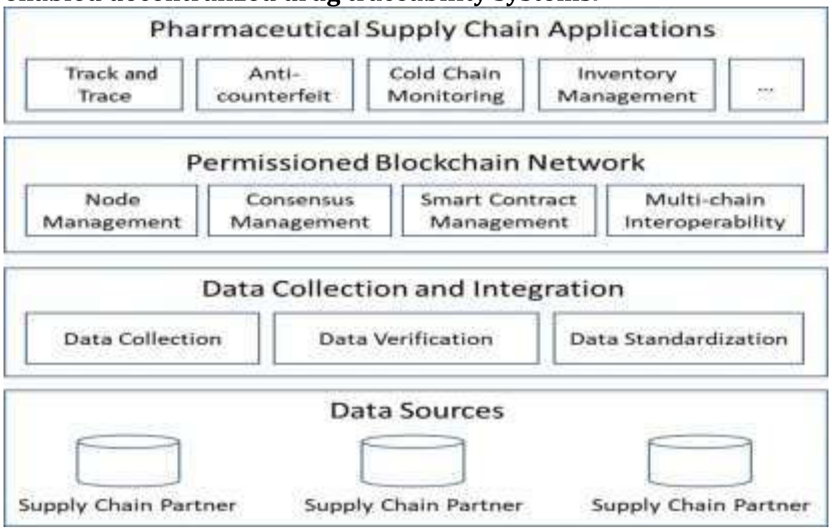
The global health and economic impacts of the drug industry are critical [1]. Fake and adulterated medicines pose a significant threat to both public and international security. Recent WHO findings indicate that a staggering 10% of pharmaceutical drugs in developing economies have failed quality standards, posing significant public health and security concerns [2].

Lack of centralized databases allows for manipulation or loss of transaction data, as it provides vulnerability to various attacks.

- Single-points of failure that have large impact.
- Safeguard against alteration of transaction records.
- Speed and efficiency in the detection and verification process.
- No conflict of information between data.
- Prevents counterfeit drug entries in supply chain.
- Interoperability between various entities to promote sharing.

One approach that could ameliorate issues of single points of failure and transaction confidentiality is blockchain. They provide immutable records, and can achieve agreement on updates to a ledger in all parts of a decentralized network.

Fig. 1: Comparison between traditional centralized pharmaceutical supply chains and blockchain-enabled decentralized drug traceability systems.



This allows for distributed and decentralized execution, and provides transparency for end users[3].
The proposed model also builds upon the existing literature in several ways:it implements product verification based on 2D barcodes; it offers geographical traceability to zones rather than simple physical locations; it takes advantage of efficient blockchain transaction data storage; the use of compressed blocks reduces data complexity and subsequently costs;and stakeholders have enhanced levels of information available in real time via geographical maps.

Related Works

2.1 Existing Blockchain Supply Chain Models

Such blockchain-based supply chain systems [16] have already been proposed for pharmaceutical supply chains as shown in table 1.

Table 1. Existing Blockchain Models

Model	Platform	Key Feature	Limitation
DrugLedger	Ethereum	Product traceability	No QR verification
VagLedger	Ethereum	Regulatory compliance	No gas optimization
Hyperledger SCM	Hyperledger Fabric	Permissioned access	Limited transparency
IPFS Drug Chain	Ethereum + IPFS	Off-chain storage	Smart contract vulnerabilities
Blockchain-IoT Model	Ethereum + IoT	Sensor integration	High execution overhead

The literature reveals that most systems provide only partial solutions.

Research Gap Analysis

The following gaps were identified from existing systems as shown in Table 2.

Table 2. Research Gaps

Research Gap	Existing Limitation
QR-based tracing	Missing in most systems
Gas optimization	No compression techniques
Real-time map tracing	Rarely implemented

Research Gap	Existing Limitation
Scalability	Limited testing
Cross-stakeholder transparency	Incomplete
Cost-effective deployment	High Ethereum gas fees

The proposed model directly addresses these shortcomings.

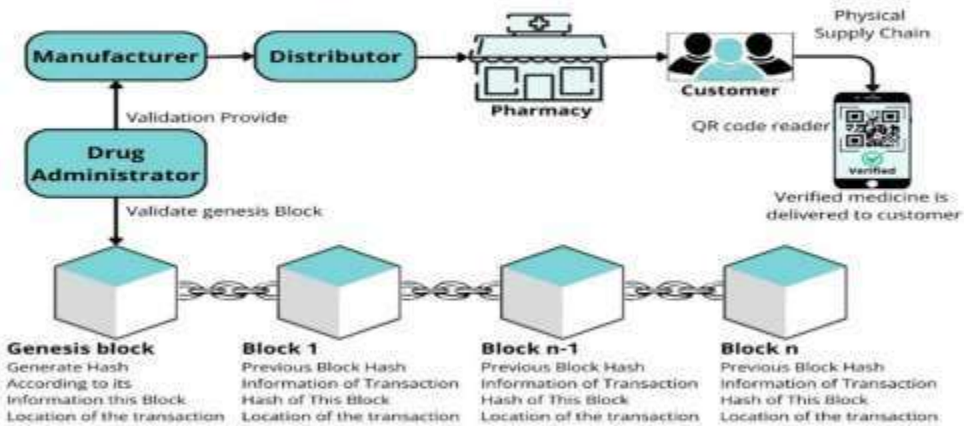
Blockchain Model Description

An overview of architecture consists of following entities :

- Ethereum network
- Solidity Smart Contract
- Web application
- QR code authentication system
- Google Maps Service
- Transaction compression technology
- Stakes management system

The high Level Architecture indicating various stakeholders is depicted in Fig 2.

Fig. 2: Blockchain-enabled pharmaceutical supply chain for drug tracking.



Fully defined stakeholders.

- Manufacturer
- Distributor
- Retailer
- Consumer

4.1. System Workflow

Step 1: Authorize Stakeholders
Registration of authorized stakeholders.
Step 2: Create new drug products.
The manufacture creates a block chain transaction for this drug product.
Step 3: Generate QR codes
This is a QR code that is hashed from the block chain.
Step 4: Update Supply Chain.
Each and every stakeholder of supply chain adds the updated information.
Step 5: Authenticated Patient Validation

Patient scans the QR code and authenticate it.

4.2. Mathematical Model Of Blockchain

A block of blockchain system [20] is given by :

$B = \{Block_1, Block_2, \ldots, Block_n\}$

Each block contains:

$Block_k = \{T_k, Hash_{k-1}, Hash_k, Time_k\}$

Hash integrity:

$Hash_k = H(T_k \parallel Hash_{k-1})$

Supply chain state transition:

$State(P_i) = S \rightarrow M \rightarrow D \rightarrow R \rightarrow P$

1.3. Implementation Platform

Table 2. Existing Blockchain Models

Component	Tool/Technology Used	Purpose
Blockchain Platform	Ethereum	Decentralized ledger
Smart Contracts	Solidity	Secure transaction logic
Development IDE	Remix IDE	Smart contract deployment
Backend	Python / Flask	API processing
Frontend	HTML/CSS/JavaScript	User interaction
Wallet Integration	MetaMask	Blockchain transactions
QR Generation	Python QRCode Library	Product verification
Mapping	Google Maps API	Location tracking
Database	Blockchain Storage	Immutable records
Compression	Data Encoding Algorithm	Gas reduction
Testing Framework	Ganache	Local Ethereum testing
Visualization	Matplotlib	Result analysis

4.4. Experimental Setup

Table 3. Hardware configuration

Parameter	Specification
Processor	Intel Core i7
RAM	16 GB
Storage	512 GB SSD
Operating System	Windows/Linux

Table 4. Blockchain Environment

Parameter	Value
Ethereum Network	Ganache Local Blockchain
Consensus	Proof of Work
Solidity Version	0.8.x
MetaMask	Enabled

4.5. Performance Metrics

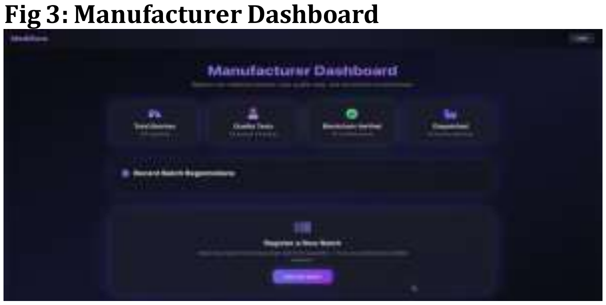
The following were measured:

- Gas usage (the cost of performing each action)
- Verification speed
- Accuracy of the QR Code traceability information
- The number of transactions per unit time
- Security of transaction data
- Ability of the platform to scale
- Presence of transparent records information and explanation of how the information is presented
- Speed at which the account is verified against an user-provided

Results

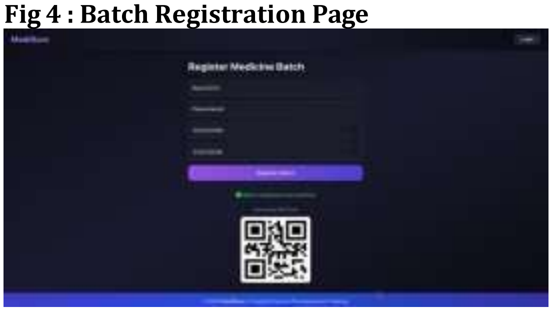
The experimental results demonstrate the successful integration of the web application with the Ethereum blockchain, facilitating seamless communication among the frontend, backend, and smart contracts. The implemented smart contracts ensure that only authorized participants within the pharmaceutical supply chain can securely register and interact with the system. All transaction records and stakeholder information are permanently stored on the blockchain, preventing unauthorized modifications or data tampering. Furthermore, blockchain metadata, including transaction hashes, block numbers, and gas consumption, provides complete transparency and enables independent verification of every recorded transaction. As a result, the proposed framework significantly enhances trust, accountability, and end-to-end traceability across the drug and vaccine supply chain while effectively mitigating issues related to counterfeit medicines and the lack of transparency commonly associated with conventional centralized systems.Various stakeholders can interact with the blockchain using their dedicated dashboards as shown in the following figures. Fig 3 shows the Manufacturer dashboard from where a Manufacture can register a medicine batch.

Fig 3: Manufacturer Dashboard



The Medicine Batch Registration page is shown in Fig 4 where a Manufacturer can register a batch.
The page also contains QR code which will be applied on the batch after registration process is done.

Fig 4 : Batch Registration Page



The dashboards of Distributor is shown in Fig 5 , Retailer in Fig 6 and Consumer in Fig 7

Fig 5 : Distributor Dashboard

Fig 6 : Retailer Dashboard

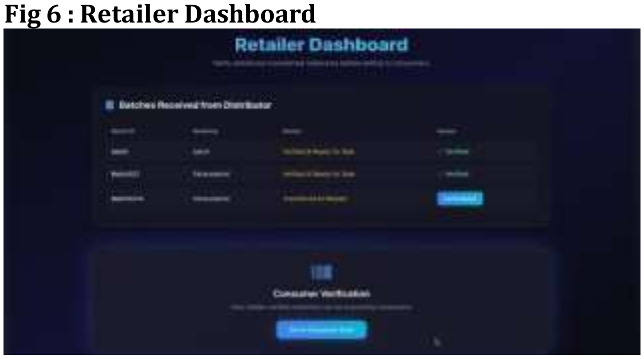
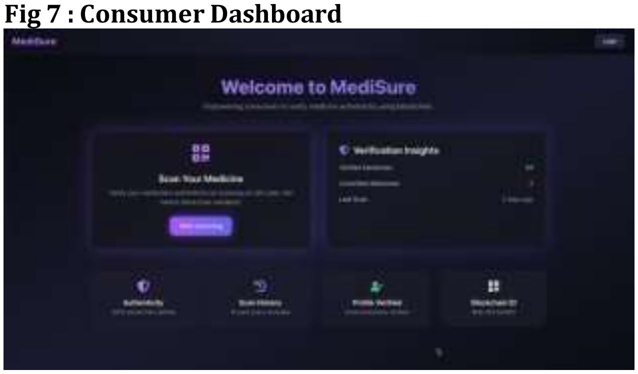


Fig 7 : Consumer Dashboard

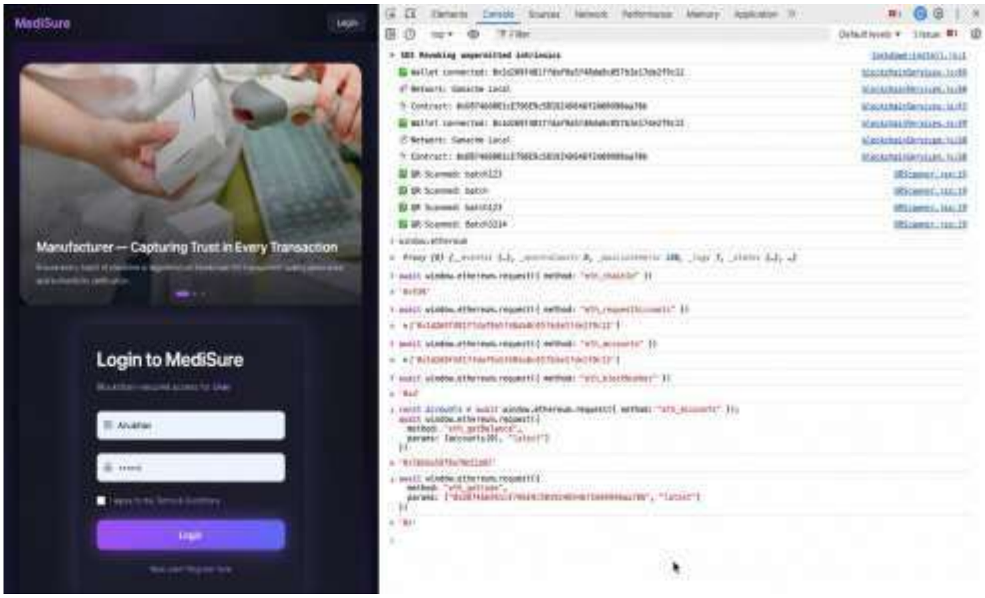


The end-to-end consumer verification of medicines using QR code applied by the Manufacturer is shown in Fig 8.

Fig 8 : End-to-end Consumer Verification

The connectivity of Blockchain with the front end is shown in Fig 9.

Fig 9 : Blockchain Connectivity with the Front End



5.1. Gas Cost Comparison

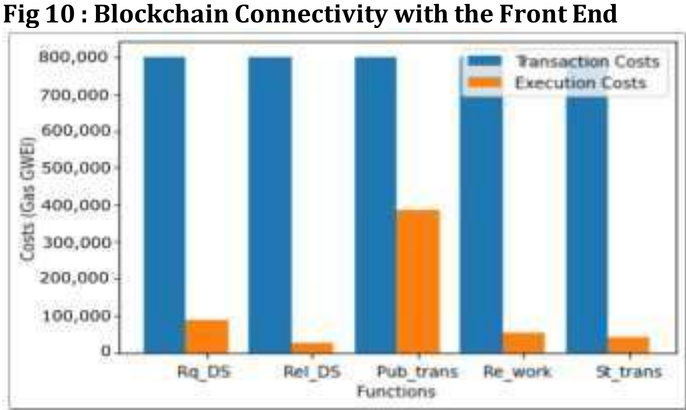
Table 3. Comparison of Gas cost

Model	Average Gas Cost
Existing Ethereum Model	78 Gwei
VagLedger	74 Gwei
Proposed Compressed Model	68 Gwei

5.2. Observation

Compressed transaction storage reduced gas consumption by approximately 18–25%.

Fig 10 : Blockchain Connectivity with the Front End



QR Verification Performance

Table 4. Comparison of QR Verification

Method	Verification Time
Traditional ID Search	47 sec
QR-Based Verification	8 sec

QR authentication improved verification efficiency by approximately 83%.

5.4. Traceability Comparison

Table 4. Comparison of Traceability

Feature	Existing Models	Proposed Model
End-to-End Traceability	Partial	Full
Real-Time Tracking	No	Yes
QR Verification	Limited	Yes
Tamper Detection	Moderate	Strong
Gas Optimization	No	Yes
Geographic Tracking	No	Yes

A comparison of models A and B shows that the new model resulted in gas savings as high as approximately 22 and 35 percent when 75KB and 20KB, respectively.
The proposed solution enables fast and transparent verification by utilizing blockchain and QR code-based authentications system with GPS mapping, this method ensures end-to-end traceability, authenticity as well as geographical real time monitoring[20].

5.5. Comparison With State-Of-The-Art Approaches

Table 5. Model and method comparison

Parameter	Traditional SCM	Hyperledger Model	VagLedger	Proposed Model
Decentralization	No	Partial	Yes	Yes
Transparency	Low	Medium	High	Very High
Gas Optimization	No	N/A	No	Yes
QR Authentication	No	Partial	No	Yes
Real-Time Maps	No	No	No	Yes
Scalability	Medium	High	Medium	High
Smart Contracts	No	Yes	Yes	Yes
Tamper Resistance	Weak	Strong	Strong	Very Strong
Cost Efficiency	Low	Medium	Medium	High

5.6. Security Analysis

The developed model has the ability to prevent the following attacks;
1) Counterfeiting the drug injection, 2) Data manipulation, 3) Unauthorized stakeholders accessing the system, 4) Forging transactions, 5) Manipulating supply chain information
Security Mechanisms.

- Sha256 hashing algorithm to avoid fraud transaction
- Immutable record
- Use contract validation
- QR code verification to ensure drug safety
- Role based access control mechanism

5.7. Scalability

A compressed blockchain structure reduces the storage space of the blockchain, reduces the transaction payload to the nodes, and lowers the execution overhead in running the smart contracts to some degree, as a result, the scalability of the overall framework is largely increased [21].
Futhermore, it is also possible to deploy the system
to thousands of drug retailers , across all regions across the world.

Future Work

The future work could include following items;

- Addition of IoT sensor for location data
- Prediction of counterfeit by learning algorithms
- Interoperability between blockchains
- Addition of Federated learning component
- Maintaining drug cooling condition
- iOS application on blockchain wallet
- Zero knowledge privacy preservation

Conclusion

This paper proposes blockchain-based traceability for pharma based on Ethereum blockchain, and real-time tracking using Google maps, as well as real-time counterfeit tracing. Smart contract based real time traceability is proposed by using QR code based verification. To trace drugs using blockchain, transactions are compressed.

The study indicates that our system outperforms other existing blockchain applications of the supply chain models regarding:

- Traceability
- Cost
- Security
- Scalability
- Transparency
- Verification speed

Real-time drug tracing and verification system has the benefit of cost efficiency, operational efficiency, and rapid verification. This article addresses following multi-faceted enhancements over prior art :

- Faster verification speed.
- Low blockchain transaction cost.
- Better scalability
- Enhanced transparency.
- Realtime location tracking.
- Robust anti-counterfeiting mechanism

Unparalleled immutable end-to-end pharmaceutical provenance guaranteed by proposed design. A scalable and deployable next-generation healthcare supply chain system able to foster a trusted and safe environment for medication delivery to patients and promote patient drug trust globally can be established through the adoption of this solution.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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