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Blockchain-Based Drug Supply Chain Management: A Secure Approach Using Hyperledger Fabric

Jayashree S. Mohite[1], Dr. Vijay K. Kale[2]

[1]Research Student, Dr. G. Y. Pathrikar College of Computer Science and Information Technology, MGM University, Chh. Sambhajinagar, Maharashtra, India
[2]Associate Professor, Dr. G. Y. Pathrikar College of Computer Science and Information Technology, MGM University, Chh. Sambhajinagar, Maharashtra, India

Abstract
Counterfeit drug production and distribution pose a significant global threat, particularly in developing countries, with the market value of pharmaceutical counterfeiting reaching billions annually. One of the primary causes is the inefficient and fragmented supply chain, where drugs pass through multiple intermediaries manufacturers, including wholesalers, distributors, and pharmacists, without proper traceability and visibility. The lack of data sharing prevents manufacturers and regulatory authorities from tracking drugs, complicating recalls and limiting patient follow-ups. Blockchain technology, a decentralized and secure system initially introduced through Bitcoin, has since revolutionized various industries, including e-governance, e-commerce, and asset management. Its application in supply chain management presents an innovative strategy to ensure data integrity, transparency, security, and privacy. The proposed system leverages Hyperledger Fabric, a permissioned blockchain, allowing only trusted parties to record and verify transactions. This ensures end-to-end tracking of drugs from manufacturing to patient delivery while maintaining privacy and security. The study also explores blockchain's broader application in supply chain management, particularly in industries like pharmaceutical drug production, highlighting its potential to offer a less-corruptible and more efficient alternative to traditional systems. Ultimately, permissioned blockchain platforms strike a balance between public blockchain transparency and traditional web security, ensuring a more secure, transparent, and reliable supply chain ecosystem across industries.

Keywords: Counterfeit Drug, Supply Chain, Blockchain, Hyperledger Fabric, Permissioned Blockchain

1. Introduction

Pharmaceutical Research & Development is a highly intricate and time-consuming process, taking several years to move from the initial stages of drug discovery to development and regulatory approval. Once a safe and effective drug has been developed, the next significant challenge for manufacturers is ensuring the product reaches the intended customers in its original form. It's essential to guarantee that customers receive the genuine product created by the legitimate manufacturer, rather than a counterfeit version produced by illegal sources. However, the current Supply Chain Management (SCM) system in the pharmaceutical industry is outdated and lacks the necessary tools for manufacturers and regulatory authorities to track, monitor, and control the distribution of drugs effectively. This lack of visibility and oversight, combined with vulnerabilities to modern cyber-security threats, leaves the industry exposed to the risk of counterfeit drugs entering the market. As a result, counterfeit drugs are being produced, distributed, and consumed, jeopardizing public health and the integrity of the pharmaceutical industry. Counterfeit drugs pose a major public health risk, and this issue is becoming increasingly serious worldwide, especially in developing countries. These fake medications harm health in both direct and indirect ways. Indirectly, counterfeit drugs often don’t contain the right amount of the active ingredient needed to treat the disease. This can lead to drug-resistant strains of illnesses, making even the original medicines ineffective in the future. More directly, counterfeit drugs may contain the correct active ingredients, but in improper amounts—either too little or too much—or they may be made with harmful impurities and toxins. This can lead to serious health problems, including poisoning or worsening of the condition being treated [1]. Manufacturers of counterfeit drugs sometimes copy the brand logos of legitimate companies and create fake products that are used in everyday life, which may cause less harm. However, in many cases, they target critical medications such as cancer treatments, painkillers, antibiotics, contraceptives, and drugs for heart conditions. These counterfeit versions can have severe and even life-threatening consequences [2]. It is estimated that counterfeit pharmaceuticals make up between 10 to 15 percent of the global drug supply, with around 30% of the drugs sold in developing countries being counterfeit [2]. The World Health Organization (WHO) estimates that out of the 1 million people who die from malaria each year, approximately 0.2 million of those deaths are caused by counterfeit anti-malarial drugs [3]. Counterfeit drugs for diseases like tuberculosis and malaria cause around 700,000 deaths every year [1]. Counterfeiting is one of the oldest and most profitable illegal businesses, and with advancements in technology, it has become easier for counterfeiters to operate [4]. This is why the FBI refers to counterfeiting as the crime of the 21st century [5]. With new technology, counterfeit goods can be produced and distributed quickly and in large quantities. The International Anti-Counterfeiting Coalition (IACC) reports that counterfeiting has become one of the world's largest and fastest-growing criminal industries, with an estimated annual value exceeding US$ 600 billion [6].

For the prevention of counterfeit drugs, the pharmaceutical industry needs a reliable and efficient supply chain management system. The best solution for creating such a system is Blockchain technology. Blockchain is a type of digital record-keeping system, first introduced by the pseudonym Satoshi Nakamoto in 2008 [7]. In recent years, it has gained widespread use across many industries due to its ability to securely track and verify transactions. As a result, many sectors are looking for ways to use Blockchain's features to improve their operations and ensure greater transparency and security. While most of the focus on Blockchain technology has traditionally been in the financial services industry, it is now being used in other areas like healthcare, energy, and legal services. One important application that has recently gained attention is supply chain security. Blockchain is particularly useful for products that go through sensitive production processes and are tied to strong reputational concerns. In these cases, Blockchain’s ability to ensure secure, transparent tracking of products offers clear benefits. It is especially valuable in situations where privacy and data security are top priorities. Because of these features, Blockchain is also a great fit for improving the security and transparency of the pharmaceutical supply chain.

2. Related Work

2.1 In Supply Chain

K. Toyoda et al. [8] proposed a blockchain-based Product Ownership Management System (POMS) to prevent counterfeit products in the post-supply chain. It ensures only legitimate owners can prove product possession using RFID tags. Customers can reject counterfeit items even if they have genuine tags. A proof-of-concept on Ethereum shows the system is cost-effective, with ownership transfers costing under $1 for up to six transfers.

Ma et al. [9] presents a blockchain-based system to prevent product counterfeiting, allowing consumers to verify authenticity without relying on merchants. Manufacturers can ensure product genuineness without operating direct stores, reducing quality assurance costs.

Huang et al. [10] presents Drugledger, a blockchain system for drug tracking and regulation. It improves service by separating providers, ensuring data security and smooth operation. The system follows real drug processes like packaging and repackaging. Expired drug data is removed to keep storage stable and efficient.

K. Salah et al. [12] proposes a blockchain-based framework using Ethereum and smart contracts to trace and track soybean supply chains by eliminating intermediaries. The system's architecture, design, and implementation are detailed, showing its applicability to any agricultural produce.

Traceability is vital for transparency and quality assurance in multi-tier textile and clothing production. **Agrawal et al.** [13] propose a blockchain-based system using smart contracts to verify product authenticity and enable secure information sharing, ensuring trust and sustainability in the supply chain. Similarly, **Chen et al.** [14] present a Hyperledger Fabric-based solution that integrates blockchain with ECDSA encryption and BAN logic to prevent counterfeiting, enhance identity verification, and improve supply chain transparency.

A Marchese et al. [15] proposed blockchain-based agri-food supply chain traceability system ensures secure, immutable, and automated management of traceability information. It eliminates reliance on a single entity, enhancing scalability and preventing failures. The system enables flexible quality control and provides a complete view of product life cycles, ensuring transparency and provenance verification.

Blockchain and machine learning enhance drug supply chains by improving security, transparency, and efficiency. **Abbas et al.** [16] demonstrate their effectiveness in preventing counterfeit drugs and optimizing pharmaceutical operations.

Padmavathi et al. [17] propose a Hyperledger Fabric-based system where manufacturers, wholesalers, and retailers can update records while consumers verify them via a web app using digital certificates. Though performance drops with more users, the approach shows promise for scalability and cross-chain integration.

SS Gomasta et al. [22] present PharmaChain, a blockchain system using smart contracts, encryption, and secure storage to improve drug traceability, prevent counterfeiting, and enable safe medical data sharing among stakeholders.

D Ravi et al. [23] explore Hyperledger Fabric in the coffee supply chain, demonstrating how permissioned blockchains enhance transparency, security, privacy, and performance. They suggest its applicability to other supply chains as well.

2.2 Other Works

Cai et al. [25] show how blockchain improves reputation systems by preventing fraud in cases like loan applications, resisting bad-mouthing and whitewashing attacks but struggling with rating fraud and advanced manipulations like Sybil attacks.

Chen et al. [27] describe blockchain's potential in education for securely storing learning records, tracking performance, and protecting intellectual property, promoting privacy, trust, and equal access despite existing challenges.

Zhou et al. [28] present Ledgerdata Refiner, a query platform for permissioned blockchains like Hyperledger Fabric, enabling enhanced data extraction, synchronization, and analysis.

Soelman et al. [29] examine Hyperledger Fabric's endorsement policies, addressing risks of false data, and propose strategies for balancing integrity, confidentiality, and multi-tenancy to ease adoption.

3. Preliminaries

This section provides a basic introduction to the proposed system, covering the fundamentals of blockchain technology, Hyperledger Fabric, and Hyperledger Caliper.

3.1 Blockchain technology

Blockchain provides a shared and distributed storage system, removing the risk of a single-point failure seen in centralized systems. It ensures trust and transparency because all peers can see the transactions. Data is stored securely and cannot be changed.

Key components of blockchain:

- **Consensus Mechanism:** Transactions are approved using protocols like SOLO, KAFKA, and RAFT.
- **Cryptographic Hashing:** Creates a secure link between blocks using hash functions.
- **Immutable Ledger:** Transactions cannot be altered once recorded.
- **Peer-to-Peer Network:** Data is shared and updated among all participants.
- **Mining:** Miners solve challenges to add blocks and earn rewards.

Blockchain networks can be permissionless (public), where anyone can join by solving a challenge, or permissioned (private), where only authorized users can participate. Public blockchains often use Ethereum and smart contracts, while private blockchains commonly use Hyperledger Fabric.

3.2 Hyperledger Fabric

Hyperledger Fabric is a modular blockchain project managed by The Linux Foundation, designed for permissioned networks with smart contract (chaincode) support. It is widely used for various applications due to its flexibility and security.

Key Components:

- **Identity Management:** Authenticates participants.
- **Ledger Management:** Stores blockchain data.
- **Transaction Management:** Handles and validates transactions.
- **Smart Contracts (Chaincode):** Executes business logic securely.

The network consists of peers (nodes) that store data and execute chaincodes. Only authenticated peers can access chaincodes via Fabric channels, ensuring privacy. Each peer's identity is verified using cryptographic methods. An ordering service (orderer) ensures proper transaction sequencing across channels. Chaincode transactions run inside Docker containers for isolation. Data is stored using LevelDB or CouchDB, with key-value pairs updated by chaincode functions.

Using Hyperledger Fabric for pharmaceutical drug supply chain management improves performance compared to Ethereum. Fabric offers better control over consensus, making it more efficient for large networks by avoiding bottlenecks.

Its permissioned system ensures better scalability, privacy, and transparency. Unlike Bitcoin and Ethereum, Fabric can provide full anonymity while maintaining security.

3.3. Hyperledger Caliper

Blockchain users care about performance, but there is no universal tool to compare different blockchain technologies fairly. Some studies exist, but no widely accepted benchmarking tool. Hyperledger Caliper is a benchmarking tool that measures blockchain performance. It generates reports on TPS, transaction latency, and resource usage. Caliper helps Hyperledger projects improve their applications and build blockchains that meet specific user needs.

4. Overview of the pharmaceutical drug supply chain

Figure1 illustrates the traditional drug supply chain, starting from raw material sourcing to manufacturing, distribution, and delivery to patients. Strict regulations ensure safety and prevent counterfeits. Managing logistics, especially for temperature-sensitive drugs, is important. Blockchain and other digital technologies can improve transparency and efficiency.

Supplier (Raw Material Provider)

Suppliers provide raw materials to manufacturers, with key details like quality and shipment date recorded on the blockchain for authenticity. Hyperledger Fabric smart contracts ensure only approved suppliers meet standards.

Manufacturer

Manufacturers turn raw materials into drugs and log each batch on the blockchain with a unique ID, including details like composition and expiry date. Once packaged, shipments to wholesalers are updated in real time. Smart contracts automate quality checks and ensure compliance, helping prevent counterfeits and enabling regulator oversight.

Wholesaler/Distributor

Wholesalers link manufacturers to pharmacies and hospitals. They verify shipments via blockchain, accepting genuine drugs and rejecting fakes. Blockchain tracks drug movement, helps manage inventory, ensures fair pricing, and improves supply transparency.

Pharmacist/Hospital

Pharmacists and hospitals receive verified drugs through blockchain. They check batch details and expiry before dispensing, reducing counterfeit risks. Only licensed personnel can transact, and recalls trigger instant alerts. Blockchain ensures safety and regulatory compliance.

Consumer (Patient)

Consumers can scan a QR code on drug packages to verify authenticity via blockchain. They view key details like manufacturing and expiry dates, ensuring the product is genuine. Hyperledger Fabric protects sensitive data while building trust through full supply chain visibility.

Regulatory Authorities

Authorities like the FDA use blockchain for real-time oversight of drug production and distribution. They can trace counterfeits, issue recalls, and enforce compliance with smart contracts. This improves safety, prevents fraud, and ensures approved drugs reach the market.

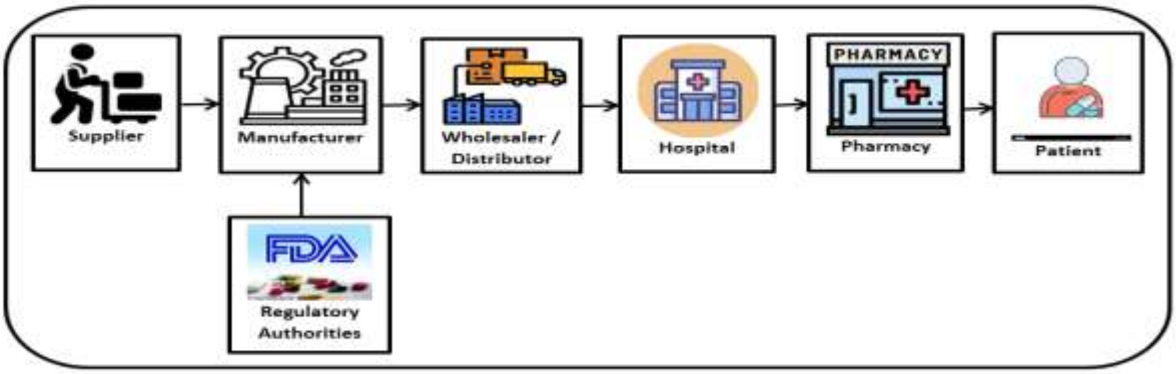

Figure 1: Traditional Pharmaceutical Drug Supply Chain System

By examining the supply chain process in the pharmaceutical industry, it is clear that each stage contains important information that should be more accessible to end users. To improve the visibility of this data, a permissioned blockchain using Hyperledger Fabric is used, as shown in figure 2. More details about this work are explained in the next section.

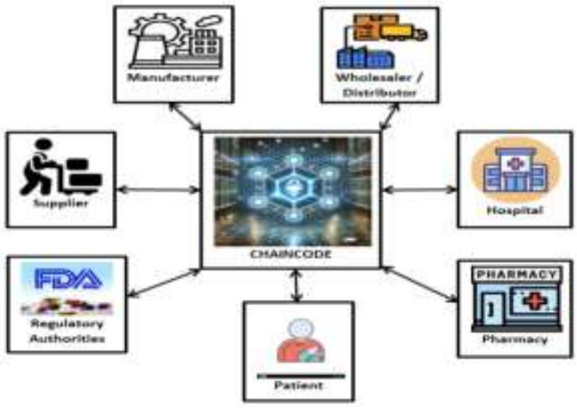

Figure 2: Pharmaceutical Drug Supply Chain using Hyperledger Fabric

5. Proposed System

The participants' details are represented using a class diagram, as illustrated in the figure 3. The relationships describe how entities interact in a pharmaceutical supply chain.

The figure 4 represents a Drug Supply Chain Blockchain Network, showing how medicines move from suppliers to patients while ensuring security and transparency. At the top, the blockchain layer records transactions in blocks, making the process tamper-proof. It includes access control to restrict unauthorized actions, smart contracts to automate rules, and data encryption to protect sensitive information. The middle section explains the supply chain process, which starts with suppliers providing raw materials to manufacturers who produce the drugs. These drugs are then sent to distributors, who transport them to hospitals, doctors, and pharmacies. Finally, these drugs reach the patients for consumption. The bottom section highlights the key participants, including suppliers, manufacturers, distributors, hospitals, doctors, pharmacies, and patients. By using blockchain, the system ensures drug authenticity, prevents counterfeit medicines, and provides complete traceability of each drug. This technology increases trust, efficiency, and security in the pharmaceutical industry.

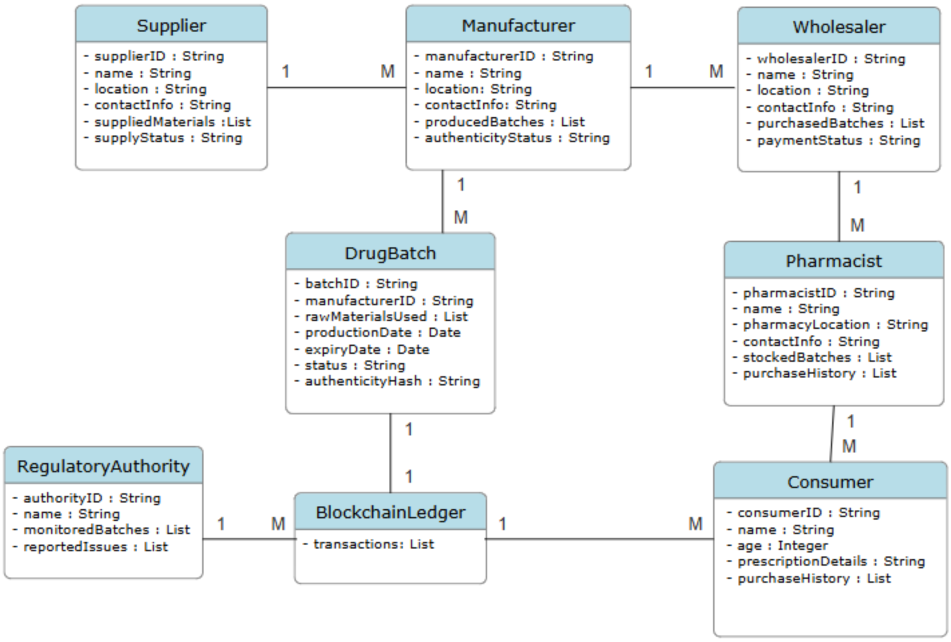

Figure 3: Class Diagram of the Pharmaceutical Drug Supply Chain System

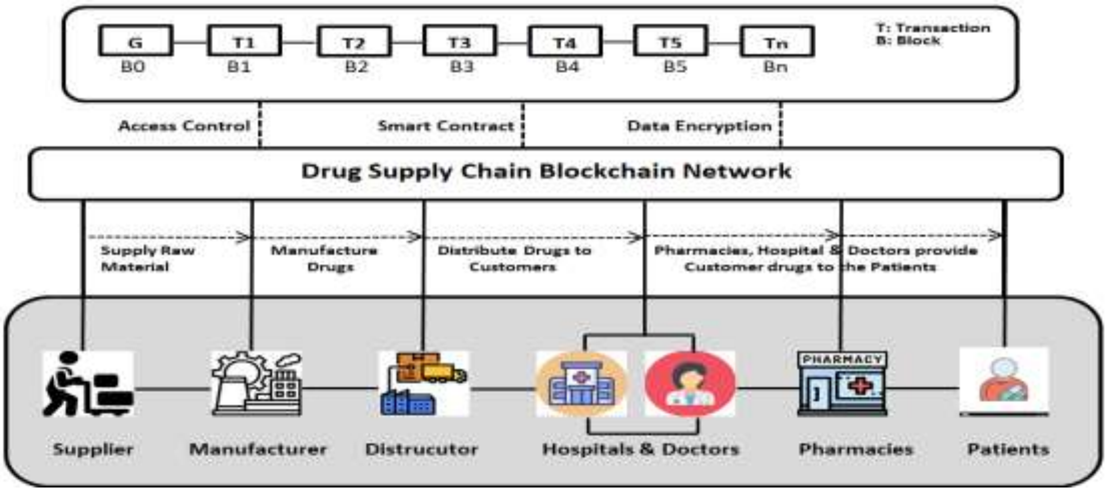

Figure 4: Proposed Architecture of Pharmaceutical Drug Supply Chain System

5.1 Network Architecture

Figure 5 represents the blockchain network architecture for the pharmaceutical drug supply chain using Hyperledger Fabric. In this system, all organizations involved in the supply chain are part of a single channel, which is linked to a shared ledger. Each organization has access to the same ledger, ensuring transparency and secure record-keeping. Since the system is based on Distributed Ledger Technology (DLT), the data is immutable and tamper-proof, guaranteeing integrity. Each organization has multiple peers to store redundant copies of the ledger for extra security. Peers within an organization can freely communicate with each other. For communication between different organizations, a designated anchor peer is responsible for exchanging information. If the anchor peer fails, another peer automatically takes over, ensuring uninterrupted communication. This design prevents data loss and ensures a smooth and efficient supply chain.

The network follows the Raft consensus protocol, where a leader node manages updates and synchronizes data across all follower nodes. When a majority of servers approve a transaction, it is confirmed and executed, ensuring reliability. Hyperledger Fabric exclusively uses Raft due to its higher success rate and efficiency compared to Kafka, making the supply chain more secure and resilient.

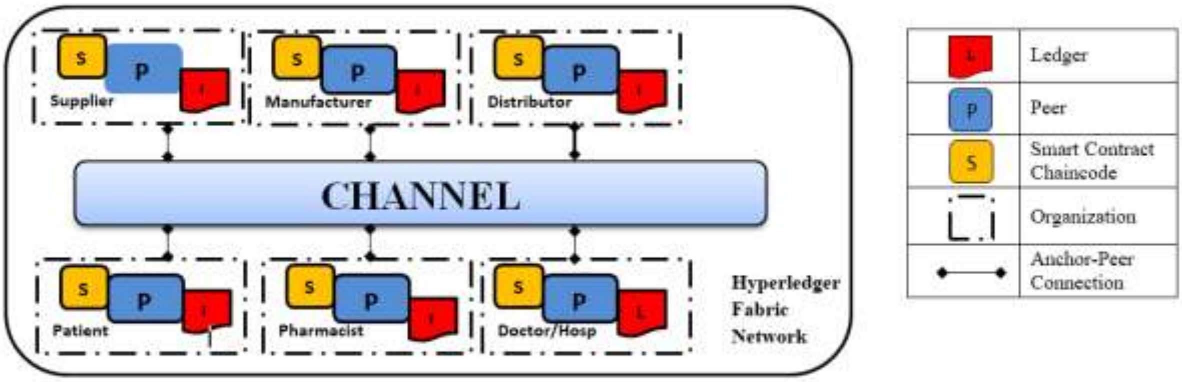

Figure 5: Proposed Network Architecture of Pharmaceutical Drug Supply Chain System

5.2 Environmental Set up

The proposed system is built using Hyperledger Fabric, an open-source, permissioned blockchain platform, to ensure secure and transparent management of the pharmaceutical drug supply chain. It is deployed on an Ubuntu 20.04 operating system, equipped with 8 GB of RAM and powered by an Intel Core i3 processor, providing a stable and efficient environment for blockchain operations. To manage and run the system, Docker version 24.0 is used for creating and managing containers, while Docker Compose version 1.29 is employed for organizing and running multi-container applications. The system ensures reliable transaction processing by implementing the RAFT consensus mechanism, which enhances fault tolerance and ensures smooth communication between network nodes. This setup helps maintain a secure, efficient, and tamper-proof drug supply chain.

5.3 Implemented Contract

Algorithm 1 Supplier confirms raw material order

```
Input: orderId

procedure CONFIRMORDER():
    if orderID EXISTS in PendingOrders then
        UPDATE supplyStatus TO 'Confirmed'
        return true
    else
        return false
```

Algorithm1 checks if a given orderID exists in the PendingOrders list. If the order is found, it updates its supplyStatus to "Confirmed" and returns TRUE, indicating a successful confirmation. If the order does not exist, the function returns FALSE, signaling that the order could not be confirmed. This ensures that only valid orders are updated while preventing incorrect modifications.

Algorithm 2 Supplier dispatches raw materials

```
Input: orderId, manufacturerID

procedure DISPATCHMATERIALS():
    if supplyStatus == 'Confirmed' then
        ADD orderID TO manufacturer's raw material list
        UPDATE supplyStatus TO 'Completed'
        return true
    else
        return false
```

Algorithm 2 ensures that raw materials are sent to the manufacturer only if the supplyStatus of the order is "Confirmed." If the condition is met, the function adds the orderID to the manufacturer's raw material list and updates the supplyStatus to "Completed," indicating successful dispatch. It then returns TRUE. If the supply status is not "Confirmed," the function returns FALSE, preventing unauthorized dispatches.

Algorithm 3 Manufacturer places an order for raw materials

```
Input: supplierID, materialList

procedure PLACERAWMATERIALORDER():
    orderID = GENERATE UNIQUE orderID
    STORE order IN PendingOrders
    return orderID
```

Algorithm 3 allows a manufacturer to order raw materials from a supplier. It generates a unique orderID for the request and stores the order details, including the supplierID and materialList, in the PendingOrders list. The function then returns the generated orderID, which can be used for tracking and future processing of the order.

Algorithm 4 Manufacturer produces a drug batch

```
Input: manufacturerID, rawMaterials

procedure PRODUCEDRUGBATCH():
    if rawMaterials ARE AVAILABLE then
        batchID = GENERATE UNIQUE batchID
        CREATE NEW DrugBatch RECORD
        STORE IN BlockchainLedger
        return batchID
    else
        return "Error: Insufficient raw materials"
```

Algorithm 4 enables a manufacturer to produce a batch of drugs using available raw materials. It first checks if the required raw materials are available. If they are, a unique batchID is generated, and a new drug batch record is created and stored in the BlockchainLedger for transparency and security. The function then returns the batchID. If raw materials are insufficient, it returns an error message, preventing incomplete production.

Algorithm 5 Register a new drug batch on Blockchain

Input: batchID, details

```
procedure REGISTERBATCHONBLOCKCHAIN():
    if batchID NOT EXISTS in BlockchainLedger then
        ADD batch TO BlockchainLedger
        return true
    else
        return false
```

Algorithm 5 ensures that a new drug batch is securely recorded on the blockchain. It first checks if the given batchID already exists in the BlockchainLedger. If not, it adds the batch details to the ledger and returns TRUE, confirming successful registration. If the batch already exists, the function returns FALSE, preventing duplicate entries and ensuring data integrity.

Algorithm 6 Wholesaler places an order for drugs

Input: manufacturerID, batchList

```
procedure PLACEORDER():
    if batchList EXISTS in Manufacturer's Inventory then
        STORE ORDER IN PendingOrders
        return true
    else
        return false
```

Algorithm 6 allows a wholesaler to order drug batches from a manufacturer. It checks if the requested batchList exists in the manufacturer's inventory. If the batches are available, the order is stored in PendingOrders, and the function returns TRUE, indicating a successful order placement. If the batches are not available, the function returns FALSE, preventing invalid orders.

Algorithm 7 Wholesaler, Pharmacist, Consumer verifies drug authenticity

Input: batchID

```
procedure VERIFYDRUGAUTHENTICITY():
    if batchID EXISTS in BlockchainLedger then
        return true
    else
        return false
```

Algorithm 7 allows wholesalers, pharmacists, and consumers to confirm the authenticity of a drug batch using its batchID. It checks whether the batchID exists in the BlockchainLedger, which securely stores verified drug records. If the batch is found, the function returns TRUE, confirming authenticity. Otherwise, it returns FALSE, indicating a potentially counterfeit or unregistered drug. This ensures transparency and trust in the supply chain.

Algorithm 8 Pharmacist sells drugs to consumers

Input: consumerID, batchID

```
procedure SELLDRUGTOCONSUMER():
    if batchID EXISTS in Pharmacist Inventory then
        ADD batchID TO consumer's purchaseHistory
        UPDATE batchStatus TO "Sold"
        return true
    else
        return false
```

Algorithm 8 allows a pharmacist to sell a drug batch to a consumer. It first checks if the specified batchID exists in the pharmacist's inventory. If available, the batch is added to the consumer's purchaseHistory, and its status is updated to "Sold," indicating successful transaction completion. The function then returns TRUE. If the batch is not found, it returns FALSE, preventing unauthorized sales.

Algorithm 9 Regulatory Authority issues a drug recall

Input: batchID

```
procedure INITIATEDRUGRECALL():
    if batchID EXISTS in BlockchainLedger then
        UPDATE STATUS TO 'Recalled'
        return true
    else
        return false
```

Algorithm 9 allows a regulatory authority to recall a specific drug batch. It first checks if the given batchID exists in the BlockchainLedger, ensuring the batch is registered. If found, the batch status is updated to "Recalled," preventing further distribution or sale, and the function returns TRUE. If the batch does not exist, it returns FALSE, ensuring that only valid batches can be recalled.

Algorithm 10 Regulatory Authority blacklists a fraudulent supplier or manufacturer

Input: entityID

```
procedure BLACKLISTENTITY():
    if entityID EXISTS in Supplier OR Manufacturer then
        REMOVE entity FROM Blockchain Network
        return true
    else
        return false
```

Algorithm10 enables the regulatory authority to remove a fraudulent supplier or manufacturer from the blockchain network. It first checks if the given entityID exists in the list of registered suppliers or manufacturers. If found, the entity is removed from the network, preventing further participation in the drug supply chain, and the function returns TRUE. If the entity does not exist, the function returns FALSE, ensuring that only valid entities can be blacklisted.

6. Comparative analysis between proposed solution with existing solutions

Hyperledger Fabric, a permissioned blockchain, is compared with traditional systems (non-blockchain) and public blockchains. As shown in Table 2, Hyperledger Fabric is more practical for enterprise use, especially in supply chain management. Traditional systems lack blockchain benefits, while public blockchains solve issues like centralization, transparency, and reliability but create new problems like lack of privacy, data-sharing restrictions, and inflexibility. Hyperledger Fabric balances these by offering a middle ground. It ensures privacy, modularity, and customization options. Participants are verified before joining and given specific permissions to access only relevant data and perform designated tasks.

Table 1: Comparative analysis between the traditional system, public blockchain and hyperledger fabric [24]

Aspect	Traditional system (non-blockchain)	Public blockchain	Hyperledger DLT
Blockchain log	✗	✓	✓
Pluggable state database	✓	✗	✓
Distributed Ledger	✗	✓	✓
Transparency	✗	✗	✓
Security	✗	✓	✓
Scalability	✓	✗	✓
Modularity	✗	✗	✓
Private Data Sharing	✗	✗	✓
Confidentiality	✗	✗	✓
Consensus Mechanism	✗	✓	✓
Smart Contract	✗	✓	✓

7. Conclusion

The pharmaceutical industry faces significant challenges due to counterfeit drugs, which threaten public health and undermine trust in the supply chain. Traditional supply chain systems lack transparency, security, and traceability, making it difficult to track drug movement and verify authenticity. While public blockchains address some of these issues, they also introduce new concerns like privacy limitations, high operational costs, and lack of modularity. Hyperledger Fabric, a permissioned blockchain, provides a balanced solution by offering transparency, security, and efficient data sharing while maintaining privacy and controlled access. It ensures that only authorized participants can access specific data, reducing risks related to counterfeiting and fraud. By integrating smart contracts and cryptographic techniques, Hyperledger Fabric improves traceability, ensuring that drugs move securely from manufacturers to consumers. This blockchain-based approach strengthens the pharmaceutical supply chain by enabling real-time tracking, preventing unauthorized modifications, and enhancing regulatory oversight. Compared to traditional and public blockchain systems, Hyperledger Fabric is more suitable for enterprise applications due to its modularity, scalability, and permissioned structure. The adoption of this technology can significantly reduce counterfeit drug circulation, increase consumer trust, and improve overall supply chain efficiency.

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