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RESEARCH ARTICLE

A Blockchain-Based Approach to Securing the Pharmaceutical Supply Chain

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A Blockchain-Based Approach to Securing the Pharmaceutical Supply Chain

SUMMARY

Securing the pharmaceutical supply chain is a significant global challenge, as the integrity of drug distribution is critical for patient safety. Traditional supply chain systems are often opaque, making it difficult to track and verify the authenticity of pharmaceutical products. This lack of transparency leads to vulnerabilities where counterfeit drugs can infiltrate the market, posing severe health risks to millions of patients worldwide. Data manipulation and lack of accountability in centralized systems further exacerbate these issues, undermining trust in the pharmaceutical supply chain. Algerian industrial companies are confronted with numerous changes and challenges impacting their various activities, particularly in the drug distribution sector. In this paper, we propose a new Blockchain-based system to ensure the security and transparency of the drug distribution process. Blockchain technology provides a decentralized, tamper-resistant record that enhances security in drug distribution. This system offers transparency and security across all transaction stages, addressing core issues in the pharmaceutical supply chain.

Key Words: *Pharmaceutical Supply Chain, Drug Distribution, Transparency, Security, Counterfeit Drugs, Blockchain, Data Integrity, Decentralized Systems, Patient Safety, Data Manipulation, Transaction Records.*

İlaç Tedarik Zincirinin Güvenliğini Sağlamak İçin Blokzincir Tabanlı Bir Yaklaşım

ÖZ

İlaç tedarik zincirinin güvenliğini sağlamak, ilaç dağıtımının bütünlüğünün hasta güvenliği açısından kritik olması nedeniyle küresel çapta önemli bir zorluktur. Geleneksel tedarik zinciri sistemleri genellikle şeffaf olmayıp, farmasötik ürünlerin orijinalliğinin takibini ve doğrulanmasını zorlaştırmaktadır. Bu şeffaflık eksikliği, sahte ilaçların pazara sızmasına ve dünya çapında milyonlarca hasta için ciddi sağlık riskleri oluşturmasına yol açabilen güvenlik açıklarına yol açar. Merkezi sistemlerdeki veri manipülasyonu ve hesap verebilirlik eksikliği bu sorunları daha da kötüleştirerek ilaç tedarik zincirine olan güveni zedeler. Cezayir'deki sanayi şirketleri, özellikle ilaç dağıtım sektöründe, çeşitli faaliyetlerini etkileyen çok sayıda değişim ve zorlukla karşı karşıyadır. Bu çalışmada, ilaç dağıtım sürecinin güvenliğini ve şeffaflığını sağlamak için yeni bir Blockchain tabanlı sistem öneriyoruz. Blockchain teknolojisi, ilaç dağıtımında güvenliği artıran, merkezi olmayan, müdahaleye karşı dayanıklı bir kayıt sağlamaktadır. Bu sistem, ilaç tedarik zincirindeki temel sorunları ele alarak tüm işlem aşamalarında şeffaflık ve güvenlik sunmaktadır.

Anahtar Kelimeler: *İlaç Tedarik Zinciri, İlaç İletimi, Şeffaflık, Güvenlik, Sahte İlaçlar, Blokzincir, Veri Bütünlüğü, Merkezi olmayan sistemler, Hasta Güvenliği, Veri Manipülasyonu, İşlem Kayıtları.*

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INTRODUCTION

In recent years, the pharmaceutical industry has encountered significant challenges in maintaining the authenticity, security, and efficiency of its supply chain operations. One of the most pressing concerns is the rise of counterfeit drugs, which not only jeopardizes patient safety but also results in significant financial losses for manufacturers. It is estimated that counterfeit medicines account for over 15% of the global pharmaceutical market, posing severe risks to public health and creating distrust in pharmaceutical systems (Tiwari et al., 2024). These counterfeit products can enter the supply chain at various stages, exploiting vulnerabilities in tracking and verification processes.

Beyond the issue of counterfeiting, inefficiencies within the supply chain—such as delivery delays, inaccurate inventory management, and the absence of real-time monitoring—have also become significant challenges. Traditional supply chain systems often lack the transparency required for stakeholders to monitor the movement of drugs across different stages, from manufacturers to pharmacies, creating opportunities for errors or malicious tampering (Tiwari et al., 2024; Musamih et al., 2021).

Blockchain technology presents an effective solution to these challenges due to its decentralized and tamper-proof nature. By creating an immutable record of transactions, Blockchain can provide complete transparency and traceability in the supply chain. Every stakeholder, including manufacturers, distributors, and pharmacists, has access to a shared ledger, ensuring that any changes or discrepancies are immediately visible and verifiable. Furthermore, Blockchain's use of cryptographic hashing mechanisms prevents unauthorized modifications, making it nearly impossible for counterfeit drugs to enter the system undetected (Abdallah et al., 2023; Farooq et al., 2020). Blockchain's features make it ideal for ensuring security, transparency, and efficiency in pharmaceutical supply chain management.

The proliferation of counterfeit drugs and inefficiencies in real-time tracking and verification pose significant challenges to the pharmaceutical supply chain. Counterfeit drugs are a significant threat to public health and safety, infiltrating global markets and undermining consumer trust. Traditional supply chain systems lack the transparency and traceability required to effectively track pharmaceuticals from production to delivery, allowing counterfeit drugs to enter the market undetected (Gligor et al., 2022; Jadhav et al., 2022).

The pharmaceutical supply chain, which involves distributors, pharmacists, and patients, is typically managed by a centralized system. However, this traditional approach has several drawbacks. Maintaining accurate records can be difficult, leading to data inconsistencies, delays, and challenges in monitoring shipping or theft issues. Relying on a single central server reduces efficiency, increases maintenance costs, and makes the system more vulnerable to cyber-attacks and breakdowns. Furthermore, these centralized networks lack transparency and traceability, as users have no control over the data, which is often unreliable and lacks proper authentication. Therefore, transitioning away from this model is essential for a more secure and efficient supply chain (Akram et al., 2024).

Blockchain technology facilitates the exchange and transfer of distributed data among organizations without the need for a central authority (Akram et al., 2024; Raparthi et al., 2021). This fosters direct engagements between participants in the supply chain, eliminating the reliance on trust in a central entity. These secure direct communications enhance transparency, clarity, and efficiency while reducing the costs and risks of tracking shipments.

Our Blockchain-based system provides a secure, decentralized ledger that improves traceability for pharmaceutical products. With this approach, each transaction is recorded and verified in real-time, preventing counterfeit drugs from entering the supply chain. Furthermore, our system eliminates the inefficiencies associated with traditional systems, where real-time monitoring is often fragmented or non-existent.

In this paper, we have refined the problem definition to address two significant issues in the pharmaceutical supply chain: counterfeit drugs and inefficiencies in real-time tracking. Focusing on these key challenges, we underline the need for a secure, transparent system to manage and track pharmaceutical products. The scope of our project is clearly defined, emphasizing the application of Blockchain technology to enhance traceability, visibility, and security within the supply chain. Our system is designed to mitigate the risk of counterfeit drugs and improve real-time tracking for safer pharmaceutical delivery. Additionally, we recognize that aspects such as regulatory compliance and broader supply chain management practices fall outside the scope of this project.

Several research studies have been conducted to address these concerns and enhance the transparency and visibility of supply chains. A notable approach involves the elimination of a central authority by utilizing innovative technologies such as Blockchain (Gomasta et al., 2023; Mishra et al., 2024; Faulkner et al., 2020). Through its distributed ledger technology (a distributed database that records transactions across multiple nodes), Blockchain can revolutionize supply chain operations, resulting in improved efficiency, transparency, and security by ensuring trust and security.

Traditional supply chain management solutions have typically relied on barcodes and RFID tags for identification. Wireless Sensor Networks (WSN) have been employed for data collection, along with Electronic Product Codes (EPC), which serve the functions of identifying, capturing, and sharing product information to facilitate the tracking of goods across different stages (Gruchmann et al., 2024; Akram et al., 2024). Smart-Track (Al Huraimel et al., 2020; Gomasta et al., 2023) functions within this framework by leveraging GS1 standard barcodes, which include unique serialized product identifiers along with lot production and expiration dates. In (Abdallah et al., 2023), the authors explored the application of Blockchain technology to address various issues in the healthcare sector, but the discussion lacked technical details or specific applications.

In (Tiwari et al., 2024; Alla et al., 2024), the authors have put forward traceability solutions; however, these rely on centralized databases, making it relatively easy to tamper with goods information and challenging to detect such tampering. Moreover, utilizing various types of centralized databases can lead to issues with interoperability and scalability in the proposed solutions. (Mishra et al., 2024; Faulkner et al., 2020) propose an NFC-driven mechanism designed to enhance transparency across various stages of the pharmaceutical distribution network. Every pharmaceutical product undergoes registration and validation through a unique key value, with an NFC label affixed for identification purposes. Like previous solutions, individuals or patients can verify the authenticity and origin of medication by scanning the assigned NFC label using a mobile application.

This section examines recent research aimed at improving supply chain transparency and security, emphasizing the vulnerabilities of traditional centralized methods, including their susceptibility to tampering and lack of interoperability.

Differences Between Traditional Databases and Blockchain Technology

Blockchain, a distributed ledger technology (DLT), integrates digital systems to record asset transactions across multiple locations simultaneously. It is a widely recognized DLT that facilitates direct data exchange between different parties within a network, eliminating the need for intermediaries. Blockchain technology has applications across various domains, such as voting, banking, and healthcare. A Blockchain comprises a series of blocks that store diverse types of information. It is often defined as a transparent, secure technology that operates without a central control body (Ayati et al., 2020). Each block in the Blockchain contains two parts: the body, which includes recorded transactions or facts (like medical data or monetary transactions), and the header, which includes details such as the transaction hash, timestamp, and the hash of the previous block. These linked blocks form a sequential chain, making the Blockchain tamper-proof due to the difficulty of altering the chain (Faulkner et al., 2020). For a malicious user to modify a transaction, they would need to adjust all subsequent blocks due to their interconnected hashes and change the version of the Blockchain stored by each participating node, making tampering highly impractical.

Unlike traditional databases that operate on centralized servers and allow for modifications such as Create, Read, Update, and Delete (CRUD) operations, Blockchain technology only permits data to be added, enhancing its security and immutability. Traditional databases rely on a central administrator who can modify or delete records, making them more vulnerable to cyberattacks and internal threats due to the potential for a single point of failure. In contrast, Blockchain's decentralized structure replicates data across multiple nodes, requiring consensus among participants for any changes, thereby reducing the risk of unauthorized alterations. Furthermore, while traditional databases rely on integrity rules that administrators can bypass, Blockchain ensures data security through cryptographic hashing, making any alterations easily detectable and providing a more robust and transparent solution for applications requiring high data integrity. This section explains the foundational aspects of Blockchain technology, including its decentralized structure, tamper-resistant nature, and advantages over traditional databases.

Pharmaceutical Supply Chain Infrastructure

The pharmaceutical supply chain must facilitate the delivery of pharmaceutical products to patients, ensuring safety and traceability in compliance with the extensive regulations governing pharmaceutical products and their distribution (Tiwari et al., 2024).

The pharmaceutical distribution cycle (as shown in Figure 1) encompasses nine primary activities:

- ***Pharmaceutical Procurement:*** The process entails the acquisition of goods and services at the optimal total cost of ownership, ensuring the appropriate quality and quantity, timely delivery, and sourcing from the correct provider for direct advantages. The effectiveness of procurement plays a pivotal role in ensuring the availability of drugs and managing the overall expenses of pharmaceuticals.
- ***Port Clearing:*** Efficient port clearance is crucial for the smooth operation of pharmaceutical procurement in public organizations, ensuring the rapid and hassle-free movement of goods through customs.
- ***Receipt and Inspection:*** Inbound management involves receiving and inspecting goods upon arrival to ensure they are stored correctly in the warehouse. This procedure involves a comprehensive assessment of each shipment from either the port or local suppliers to verify compliance with contractual obligations. Prompt and precise inspections are essential for upholding quality standards.
- ***Inventory Control:*** This process focuses on optimizing stock management to maximize returns while minimizing inventory costs, ensuring efficient resource utilization and maintaining high customer satisfaction.
- ***Storage:*** The warehousing of pharmaceutical products allows for necessary testing before their introduction to the market, ensuring adherence to quality standards and regulatory requirements.
- ***Supplier Requisition:*** The requisition system, whether manual, computerized, or a combination of both, is structured to streamline the distribution process, aiding in inventory management and offering an audit trail to monitor the drug flow, thereby enhancing transparency and accountability.

- ***Delivery:*** Pharmaceuticals can be transported directly from the warehouse or collected by healthcare facility personnel using various transportation modes such as air or river. Transportation managers must meticulously plan routes and deliveries to guarantee punctual and cost-efficient services.
- ***Distribution to Patients:*** Efficient dispensing practices are essential for the rational use of drugs. The distribution mechanism must facilitate the delivery of medications to hospital departments, outpatient facilities, health clinics, and community health workers, ensuring appropriate administration to patients in doctors' care. Adopting of point-of-care drug dispensation has emerged as a secure, effective, and economically viable approach to bolster patient treatment initiatives.
- ***Consumption Reports:*** The reporting of data on drug consumption and inventory status back to the procurement unit represents the final stage in the distribution chain. This information is instrumental in forecasting future procurement requirements and maintaining an uninterrupted supply chain.

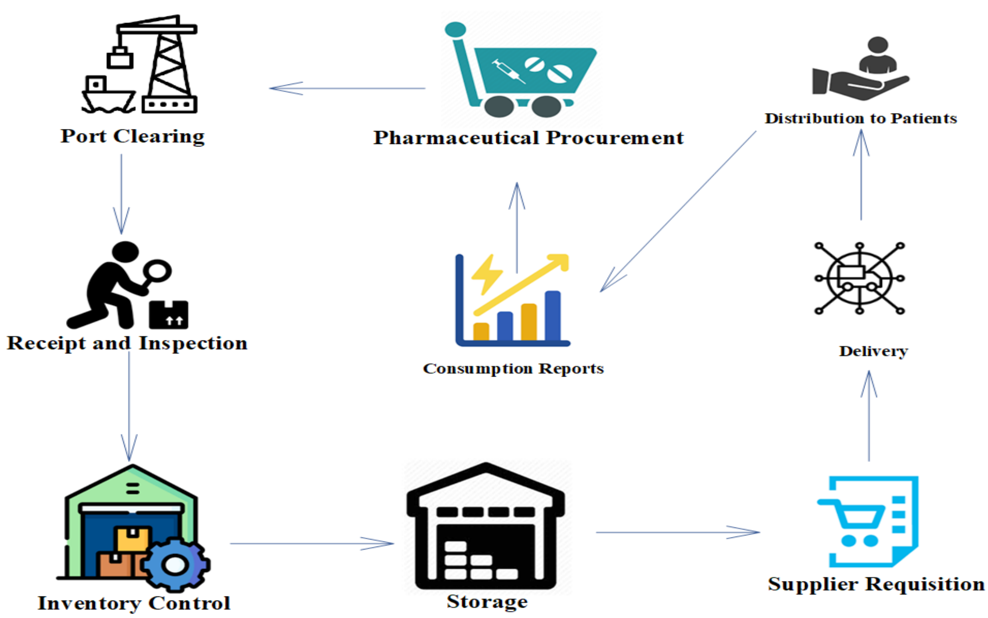

Figure 1. Pharmaceutical supply chain.

Problem Definition and Project Aims

Counterfeit pharmaceuticals pose significant public health risks, including ineffective treatment and heightened drug resistance, at the same time the complexities of tracking the origin and movement of goods across the supply chain contribute to inefficiencies.

To address these challenges, we propose a Blockchain-based system to improve transparency, traceability, and security. Our solution utilizes an immutable, decentralized ledger to enhance product authenticity verification and enable real-time tracking of pharmaceuticals across the supply chain.This system directly combats the issue of counterfeit drugs and inefficiencies by offering secure, verifiable records of transactions. The scope of our project is clearly defined to focus on the application of Blockchain technology to enhance the traceability and security of pharmaceutical products. Broader aspects, such as regulatory compliance and overall supply chain management practices, are outside the current scope of this work but remain areas for future research.

This section describes the key stages of the pharmaceutical supply chain and its challenges, particularly with counterfeit drugs and inefficiencies in tracking. The proposed Blockchain-based solution aims to improve transparency, traceability, and security by providing an immutable, decentralized ledger for real-time tracking and product verification.

MATERIALS AND METHODS

Blockchain Integration in Pharmaceutical Supply Chains

Drug fraud presents a notable challenge within the pharmaceutical sector. As indicated by the World Health Organization (WHO), approximately 15% of medications distributed worldwide are counterfeit. The prevalence of fake drugs poses serious risks to patients' well-being, potentially resulting in treatment inefficacies, adverse effects, and even mortality (Xu et al., 2023). The integration of Blockchain technology provides a significant benefit in improving drug traceability. By allowing for precise monitoring of pharmaceutical items across the complete supply chain, Blockchain establishes a secure and transparent framework. This innovation guarantees a closed loop impenetrable to fraudulent products, thus upholding the credibility of the distribution network and ensuring patient safety. Through the provision of an unalterable and verifiable account of each transaction, Blockchain not only enhances transparency but also nurtures trust among all involved parties in the pharmaceutical sector (Raparthi et al., 2021).

Moreover, Blockchain technology enables patients to authenticate the source of their prescribed medications. Pharmaceutical corporations can create their individual Blockchain networks, documenting each package of pharmaceuticals within the distribution channel. Details about each medication are modified within the Blockchain to portray alterations in whereabouts, facilitating pharmacists in validating the authenticity of drugs originating from accredited laboratories. This framework additionally empowers patients to oversee the credibility of the voyage undertaken by their prescribed medications. Furthermore, in the event of a pharmaceutical product recall, pharmacists can quickly identify affected patients and notify them, ensuring their safety and well-being (Xu et al., 2023).

Several pharmaceutical companies have successfully implemented Blockchain technology to improve supply chain transparency and security. Pfizer's partnership with Chronicled and the MediLedger Project have focused on tracking drug authenticity and preventing counterfeits (Akram et al., 2024).

VeChain and Bayer China have utilized Blockchain to manage clinical trial data, ensuring its integrity and traceability (Hossain et al., 2021). Modum has employed Blockchain and IoT to monitor temperature-sensitive products, ensuring compliance with cold chain regulations. These case studies demonstrate the potential of Blockchain to revolutionize the pharmaceutical supply chain by enhancing efficiency, security, and trust.

Challenges and Limitations: Case Study Insights

The pharmaceutical supply chain represents one of the most intricate and stringently regulated systems globally, encountering a multitude of challenges that jeopardize its integrity and operational efficacy. Some of the primary concerns include:

1. **Counterfeit Drugs:** A critical issue is the encroachment of counterfeit pharmaceuticals, which can pose significant health risks to patients and result in substantial financial detriments for legitimate pharmaceutical enterprises. The presence of counterfeit medications not only undermines patient safety but also erodes public confidence in the healthcare infrastructure.
2. **Supply Chain Complexity:** The pharmaceutical supply chain encompasses a variety of intermediaries, including manufacturers, distributors, and retailers, each fulfilling specific functions. This inherent complexity may precipitate inefficiencies, inaccuracies, and increased susceptibility to fraud or tampering at various junctures within the chain.

3. **Data Security and Privacy:** The management of sensitive information, encompassing patient data and proprietary drug formulations, necessitates the implementation of rigorous data security measures. Conventional data-sharing frameworks generally depend on centralized entities, which may be vulnerable to data breaches or unauthorized access, particularly in international transactions.
4. **Regulatory Compliance:** Every phase of the supply chain is governed by regulatory stipulations to ensure product safety and effectiveness. Nonetheless, maintaining compliance across all stakeholders can prove to be arduous, particularly when regulatory frameworks differ across various jurisdictions.

Blockchain's Role in Addressing These Challenges

Blockchain technology provides innovative solutions to numerous challenges inherent within the pharmaceutical supply chain by capitalizing on its distinctive attributes, including decentralization, immutability, and transparency. Some of the principal applications encompass:

1. **Augmented Traceability:** Blockchain facilitates real-time monitoring of pharmaceuticals throughout the supply chain, encompassing production, distribution, and retail phases. With an immutable ledger, stakeholders are empowered to trace each batch of pharmaceuticals back to its source, thereby simplifying the identification of counterfeit products and executing product recalls when warranted.
2. **Data Security and Privacy:** Blockchain's decentralized ledger enhances data security by distributing data across the network, making it more resilient to attacks. Sensitive data can be disseminated exclusively among authorized participants, mitigating the risk of data breaches and ensuring adherence to privacy regulations. Furthermore, sophisticated encryption methods guarantee that data remains protected even during cross-border transactions.
3. **Transparency and Accountability:** Blockchain furnishes a collective, unalterable record of every transaction within the supply chain. This transparency fosters accountability among all participants, diminishing opportunities for fraudulent activities and assuring that each stakeholder can rely on the integrity of the data they engage with.
4. **Smart Contracts for Regulatory Compliance:** Smart contracts, defined as self-executing agreements on the Blockchain, automate the verification of regulatory compliance at various stages within the supply chain. For example, a smart contract can be designed to verify that specific conditions (such as temperature and handling specifications) are satisfied before progression to the subsequent phase, thus minimizing human error and aiding in preserving regulatory compliance.

Pfizer and Chronicled's blockchain initiatives, as well as other projects like MediLedger and VeChain, encountered significant challenges that have slowed their widespread adoption in the pharmaceutical supply chain (Akram et al., 2024). These challenges include scalability limitations, integration difficulties, high costs, regulatory hurdles, privacy concerns, and the need for full stakeholder participation. Overcoming these obstacles is crucial for realizing the full potential of Blockchain technology in the pharmaceutical industry.

This sub-section has highlighted the significant role of Blockchain technology in enhancing transparency, traceability, and security within the pharmaceutical supply chain. By addressing issues such as counterfeit drugs, supply chain complexity, data security, and regulatory compliance, Blockchain offers solutions that ensure patient safety, improve operational efficiency, and foster trust.

Proposed System

This section presents our proposed system, which integrates key stakeholders involved in patient care, including physicians, pharmacists, producers, distributors, and patients. The primary rationales behind the incorporation of Blockchain technology in our system are as follows:

- ***Security:*** Blockchain technology provides heightened security in contrast to conventional database systems, rendering it notably less vulnerable to cyber attacks. This ensures the security of medications and grants patients transparency and confidence in relation to their pharmaceuticals.
- ***Interoperability:*** Blockchain facilitates improved interoperability among diverse stakeholders in the pharmaceutical distribution network, such as pharmacists, producers, distributors, physicians, and patients. Blockchain fosters seamless cooperation within a unified system.
- ***Transparency:*** Blockchain offers increased transparency, empowering patients with a clear view of their medication's journey. Moreover, the inherent characteristics of Blockchain offer safeguards against deliberate tampering and human error, thereby bolstering the reliability of the system.

A robust database is essential for storing critical medication data, including manufacturing and expiration dates, batch numbers, and distribution records. This database serves as the backbone of our system, ensuring that all essential information is securely stored and easily accessible to authorized parties.

Our system eliminates the traditional need for trust between manufacturers, distributors, pharmacists, and patients. This is where Blockchain technology becomes a highly suitable solution, as it inherently provides a trustless environment. Blockchain's decentralized nature ensures that all transactions and data entries are verified and immutable, meaning that no single party can alter the records without consensus. This greatly reduces the risk of data manipulation or fraud, which is particularly crucial in the pharmaceutical industry, where the integrity of information can directly impact patient safety.

The decision to deploy a private Blockchain was made with careful consideration of our need for centralized control while still reaping the benefits of Blockchain's decentralized features. A private Blockchain allows us to maintain oversight and enforce strict access controls, ensuring only authorized entities can participate in the network. This centralized control is crucial for regulatory compliance, data security, and maintaining the integrity of the pharmaceutical supply chain. At the same time, the use of Blockchain technology enhances transparency, traceability, and security, providing a comprehensive solution that addresses the unique challenges of managing pharmaceutical data.

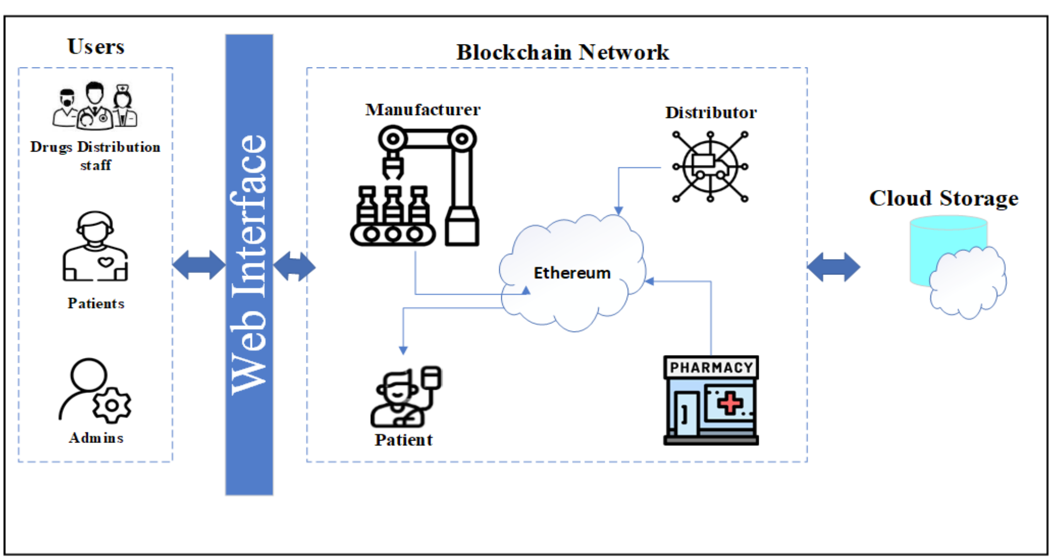

Figure 2. System architecture.

System Architecture

The system architecture is established on the Ethereum Blockchain, utilizing intelligent contracts to obviate the necessity for intermediary oversight. Our application revolves around an Ethereum intelligent contract responsible for managing essential supply chain functions. This arrangement also affords the capacity to archive and retrieve data from the Blockchain ledger, facilitating product tracking and ensuring data integrity and tamper resistance.

The suggested architecture, as illustrated in Figure 2, integrates various stakeholders in the pharmaceutical distribution sector, each assigned specific duties and responsibilities by public health regulations:

- Administrators: Responsible for overseeing the system's overall operations and adherence to public health standards.
- Patients: End-users benefiting from the secure and transparent delivery of pharmaceuticals.
- Manufacturers: Interested in a supply chain that efficiently delivers their products to target markets at a reasonable cost.
- Distributors: Crucial in ensuring sustainable access to high-quality medications, justifying distribution expenses with the benefits conferred to the public and health organizations.
- Retailers: Encompassing public and private pharmacies, drugstores, online merchants, supermarkets, and prescribing physicians, all tasked with dispensing medications to patients.
- Storage: Encompasses decentralized and distributed data management, guaranteeing secure information storage throughout the Blockchain network.
- Blockchain Network: The foundational infrastructure supporting these operations, ensuring transparency, security, and dependability throughout the supply chain.

This comprehensive framework ensures that each participant in the pharmaceutical distribution network complies with their designated responsibilities, thereby enhancing the overall efficiency, transparency, and security of the pharmaceutical supply chain.

Practical Applications: Real-World Cases of Blockchain and Smart Contracts

Blockchain acts as a decentralized, immutable ledger where all transactions between participants (e.g., manufacturers, distributors, wholesalers, pharmacies) are recorded transparently. Each entity communicates through the Blockchain network, ensuring that every step in the supply chain is securely documented, as shown in Figure 3:

- ***Manufacturers:*** Add new drug batches to the Blockchain and initiate smart contract verification.
- ***Distributors:*** Transport drugs and participate in smart contract verification at each handoff.
- ***Wholesalers:*** Receive drugs and verify their authenticity using smart contracts.
- ***Pharmacies:*** Receive drugs and validate transactions using smart contracts.
- ***Patients:*** Can verify the authenticity of their medication using Blockchain technology.
- ***Authority:*** Regulatory bodies that monitor and approve transactions on the Blockchain.
- ***Consensus Mechanism:*** Ensures the validity of all transactions and maintains Blockchain integrity.
- ***Smart contracts:*** Automate various aspects of the pharmaceutical supply chain, including drug verification, payment processing, and shipment tracking, by using self-executing code to enforce predefined terms and conditions.

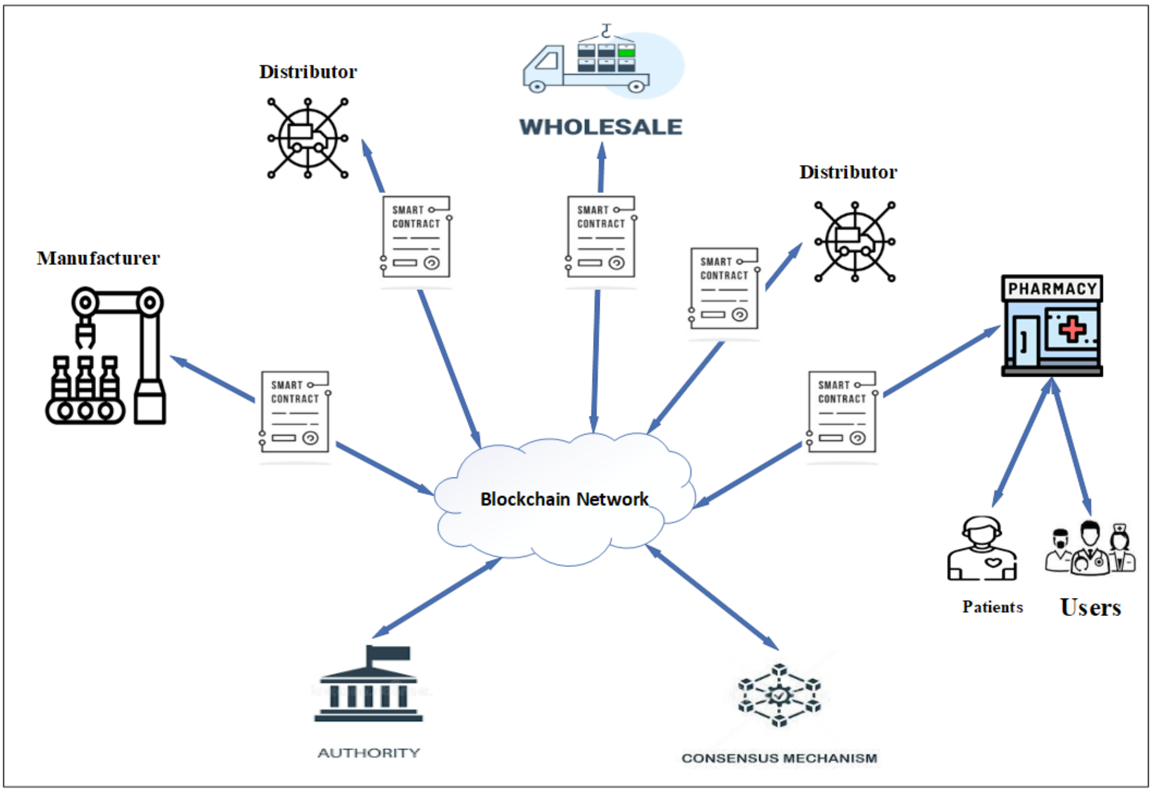

Figure 3. Blockchain Network in Pharmaceutical Supply Chain.

System Components

The primary component is Blockchain technology, which enhances transparency and accuracy in tracking the supply chain, playing a crucial role in reducing drug counterfeiting. The monitoring of the complete production process, from manufacturing to final delivery or end-user usage, is enabled through a combination of physical digitization and a decentralized, unchangeable ledger that securely logs all transactions. Through granting all supply chain participants equal access to shared data, the Blockchain network effectively diminishes the chances of communication mistakes or inconsistencies in data transmission.

Secondly, smart contracts are automated software programs used by all participants in the supply chain to initiate, manage, and execute transactions seamlessly. These contracts are programmed to autonomously enforce the terms of an agreement autonomously, guaranteeing the precise execution of each transaction without the necessity of intermediaries. Once the smart contracts are created, they are deployed on an Ethereum test network called Ropsten. Ropsten replicates the primary Ethereum network (mainnet) and functions according to the same protocol, providing an optimal setting for testing and validating smart contracts before their deployment on the mainnet. Figure 4 shows the smart contract sequence diagram and the relationship among the participants.

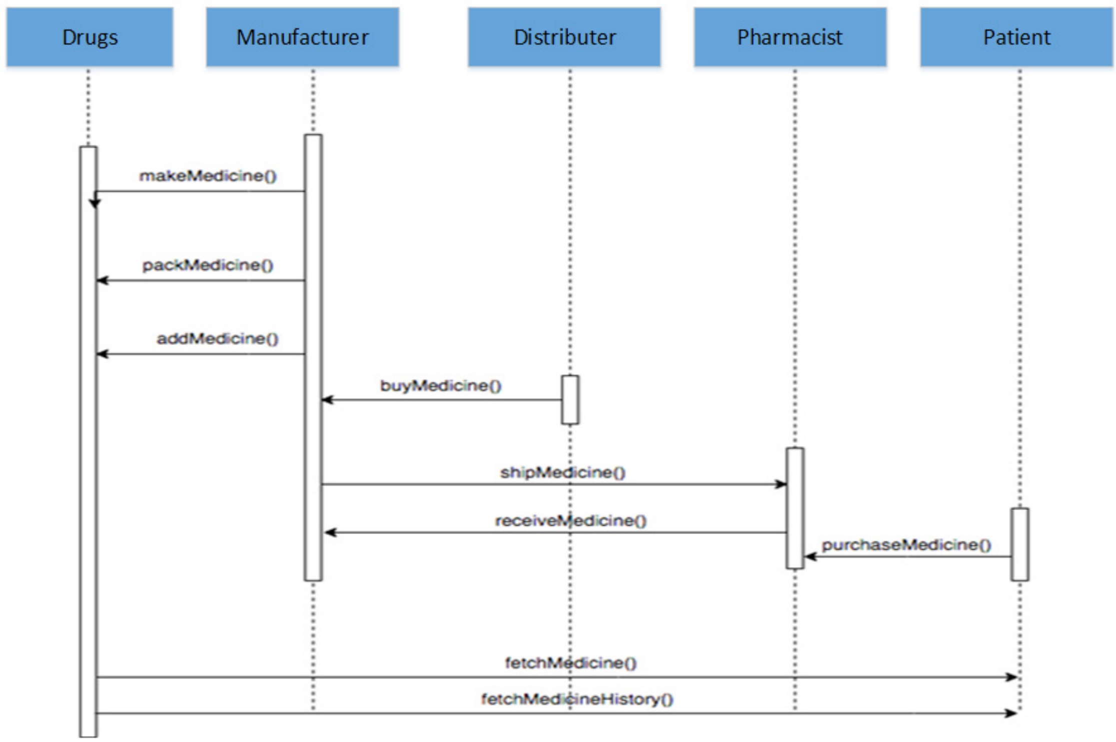

Figure 4. Sequence Diagram of Smart Contract Function.

To deploy the smart contract, a connection is established with a specific node on the Ropsten network. This connection enables the contract to be directly published to that node, allowing for monitoring and validation of its performance within a controlled testing environment. Through these assessments on Ropsten, any potential issues can be identified and resolved, ensuring the dependable and secure operation of the smart contracts before their integration into the live Ethereum network. Figure 5 shows the smart contract functions activity diagram.

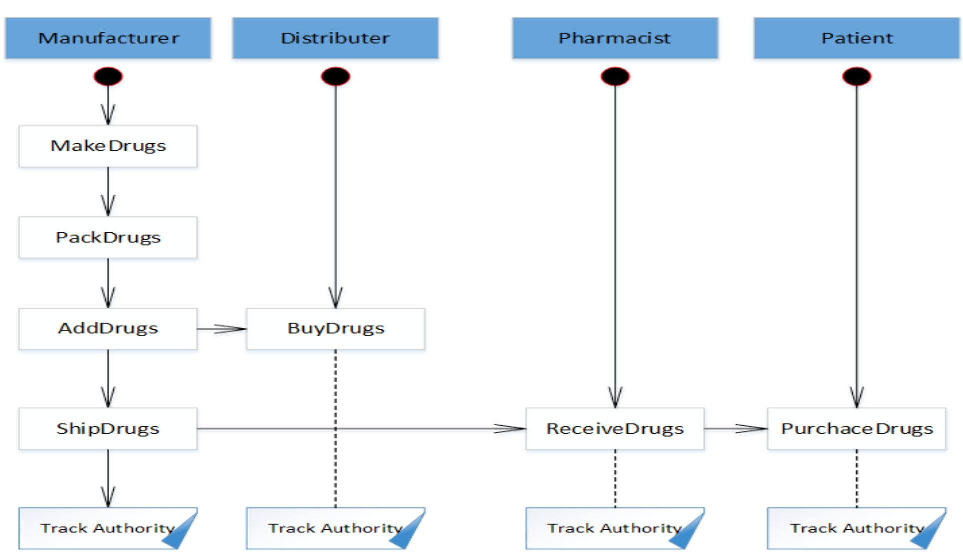

Figure 5. Activity Diagram of Smart Contract Function.

The contract outlines the various functions and actions within the supply chain, and we will detail the role of each participant step by step:

- *Manufacturer's Role:* Initially, the manufacturer is responsible for providing the drugs and essential information such as the drug name, code, and quantity. This data is securely stored on the Blockchain, enabling other participants to transparently trace the drug supply chain. After production, the manufacturer packages the drugs and sells them to distributors. From the outset, distributors place the payment into a smart contract. Once the shipping company confirms receipt of the order, the smart contract automatically releases the payment to the manufacturer.
- *Distributor's Role:* After receiving the drugs from the manufacturers, distributors verify the origin of the drugs using a product code (UPC) that is stored on the Blockchain. This allows them to trace back information provided by the manufacturers, such as drug quantities and manufacturing locations. Distributors then validate the received drugs and digitally sign the transaction, which is subsequently recorded on the Blockchain. The signed transactions trigger smart contracts that initiate the shipment of drugs to pharmacists. Once the shipment is confirmed, the smart contract releases payment to the shipping company.
- *Pharmacist's Role:* Pharmacists receive the drugs and can verify their origin using the UPC recorded on the Blockchain. For instance, if a dishonest distributor attempts to tamper with the drugs or delay delivery, any fraudulent activity will invalidate their transaction due to the integrity of the Blockchain records. This allows pharmacists to detect any discrepancies in the transactions immediately. Upon approval of the received drugs, the transaction between the pharmacist and the distributor is recorded on the Blockchain, ensuring a legally binding agreement. Additionally, when pharmacists sell drugs to customers (patients), these transactions are also added to the Blockchain, maintaining transparency and traceability throughout the supply chain.

This system ensures that every step of the drug supply chain is securely recorded and verifiable, preventing fraud and ensuring that all parties are held accountable for their actions.

Thirdly, API Infura provides a direct approach for accessing multiple Blockchain networks without the need to establish a complete node for each one, making it an efficient solution for Blockchain integration. Infura effectively manages its personal infrastructure, offering a smooth and effective means of reaching various Blockchain networks, including Ethereum. Through the utilization of Infura, developers can readily engage with Blockchain platforms via its application programming interfaces (APIs), which are tailored to streamline connections to the Ethereum network and other decentralized systems. Infura accounts empower users to execute code and interact with numerous networks like Mainnet, Ropsten, RinkeBy, and Kovan, all while avoiding the complexities of maintaining a full node. We use the Ropsten Testnet, which mirrors the Ethereum main network, for testing and development before deploying to production.

Fourthly, Web3.js represents a prominent framework utilized for developing decentralized applications (DApps). It streamlines the process of engagement with smart contracts on the Ethereum Blockchain by furnishing a user-friendly interface. Through this JavaScript API, developers can establish communication with an Ethereum node via JSON RPC endpoints, which are reachable through HTTP, IPC, or WebSocket. This functionality allows for smooth data transmission and contract interaction directly from a web page, thus establishing Web3.js as a crucial instrument for advancing Ethereum-based DApps.

Fifthly, the fundamental role of a smart contract is to oversee essential operations and manage funds securely. Nonetheless, to render these contracts accessible to users, an intuitive means for interaction with the Blockchain nodes must be in place. This is where user interfaces assume significance. In our case, we use the Ropsten Testnet, which closely replicates the Ethereum main network, providing an ideal environment for testing and development before deploying to production. React was explicitly selected for its extensive adoption and robust backing, rendering it an optimal choice for crafting responsive and dynamic user interfaces. For the backend infrastructure, we have deployed Node.js in conjunction with Express, alongside MongoDB as the document-oriented database. The API stratum, empowered by Node.js/Express, manages server-side logic and facilitates communication between the front end and the Blockchain. MongoDB stores essential data in a flexible and scalable format. This amalgamation of technologies guarantees that the system is both efficient and scalable, delivering a seamless user experience for individuals engaging with the Blockchain through the web interface.

System implementation and realization

To develop and implement our system, we utilized various essential tools, including Remix IDE, Visual Studio Code, Truffle, Ganache, Node.js, React, and MetaMask. Each of these tools plays a crucial role in different stages of the development process.

Initially, we compiled the smart contract to ensure its functionality and detect potential errors. This step is crucial as it validates the correctness of the contract before deployment, as depicted in Figure 6.

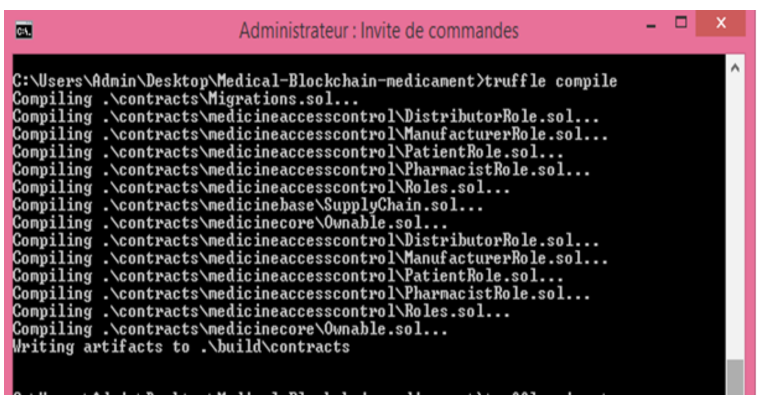

Figure 6. Smart Contract Development and Integration.

Once the contract is successfully compiled, the next step is to deploy it onto the Blockchain network. Deployment requires establishing a connection to the Blockchain, which is illustrated in Figure 7.

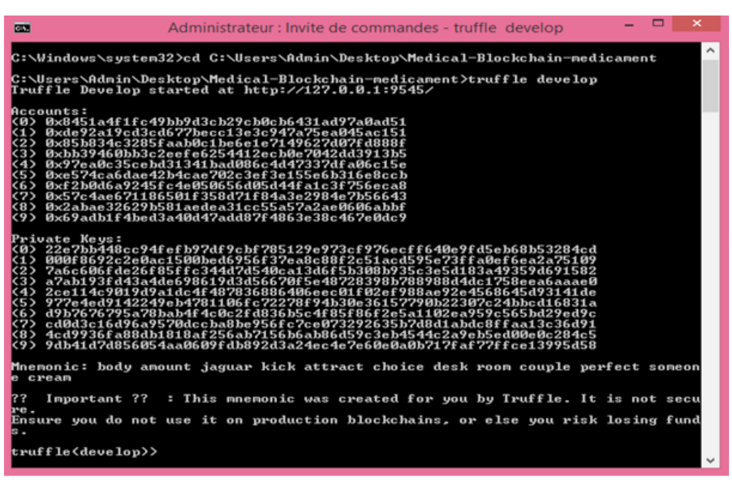

Figure 7. Creating a Blockchain network with Truffle

Testing smart contracts is a vital part of the Blockchain development process, ensuring that the contracts behave as expected under various conditions. The Truffle framework simplifies this testing phase, providing tools that make it easy to write, run, and debug tests, as shown in Figure 8.

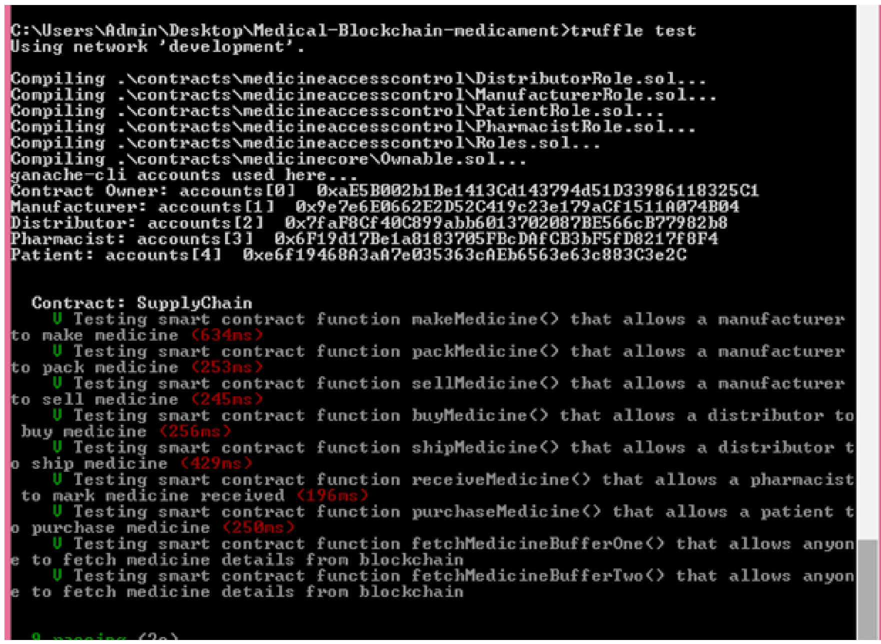

Figure 8. Smart contract test.

Following successful testing, we proceeded with deploying the smart contract on the Ganache local Blockchain, which simulates the Ethereum network for testing and development purposes. Figure 9 demonstrates this deployment process.

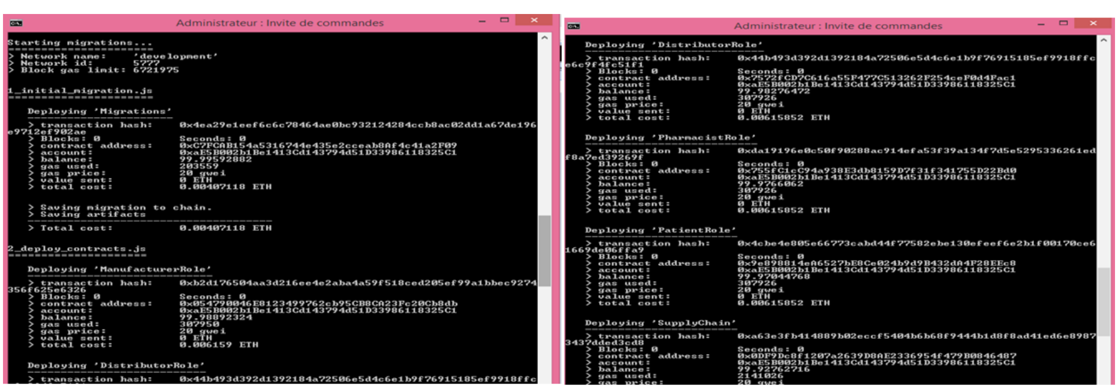

Figure 9. Smart Contract on Ganache.

The Figure 10. displays a snapshot illustrating the execution of a smart contract on the Ethereum Blockchain through the Remix IDE. The contract pertains to a system for managing the supply chain, as evidenced by its designation as "SupplyChain.sol." A manufacturer is being incorporated into the supply chain by the user by inputting an Ethereum address into the addManufacturer function, followed by the execution of the transaction. The transaction is currently pending, as indicated by the console output displayed at the bottom of the interface. The user is currently linked to the Ethereum network using the MetaMask wallet, which is observable on the right-hand side of the interface. Within the MetaMask wallet, it is apparent that the user is connected to the "mainfacture" account, possessing a balance of 0.9975 ETH, and the transaction is undergoing processing on the Ropsten test network.

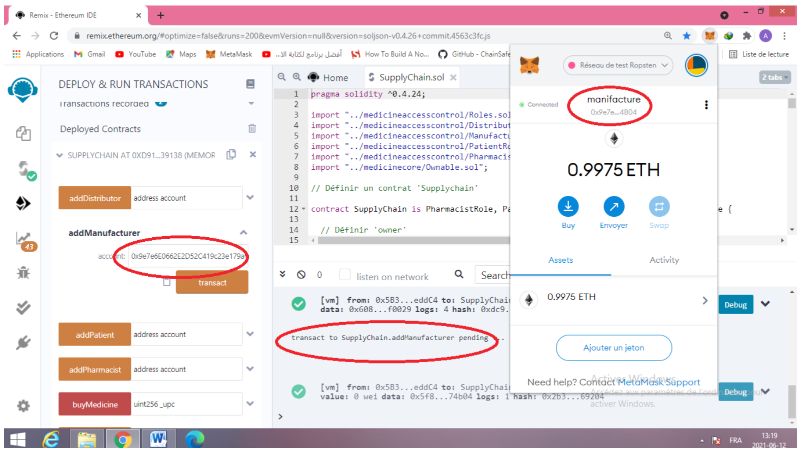

Figure 10. Sample functionalities of the addManufacturer smart contract

On the Manufacturer page, manufacturers can register new drugs into the system by providing detailed information such as the manufacturer's name, product code, drug name, and quantity. Clicking the "Make" button initiates a transaction that securely stores all relevant information on the Blockchain and systematically records it in the MongoDB database, as shown in Figure 11.

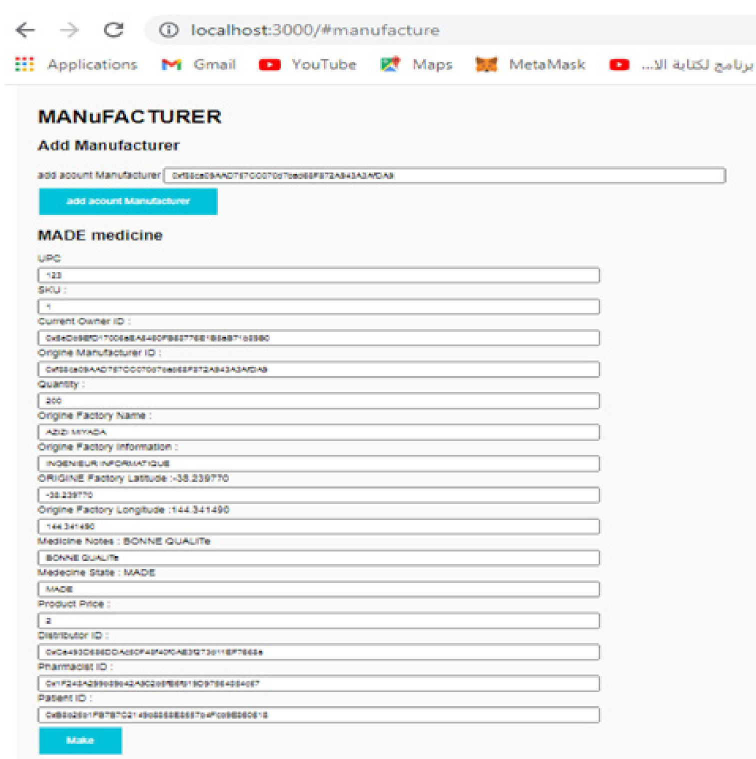

Figure 11. Manufacturer page.

After a drug is registered, the manufacturer can change its status to "packed" after verifying that it has entered the supply chain. Subsequently, the manufacturer can update the drug's status to "sell" by adding the unit price once the drug is confirmed to follow the supply chain. The drug is then marked as "For Sale," allowing a distributor to purchase it. Upon verification, the smart contract facilitates the transfer of payment to the manufacturer, and the drug's status is updated to "Buy," as illustrated in Figure 12.

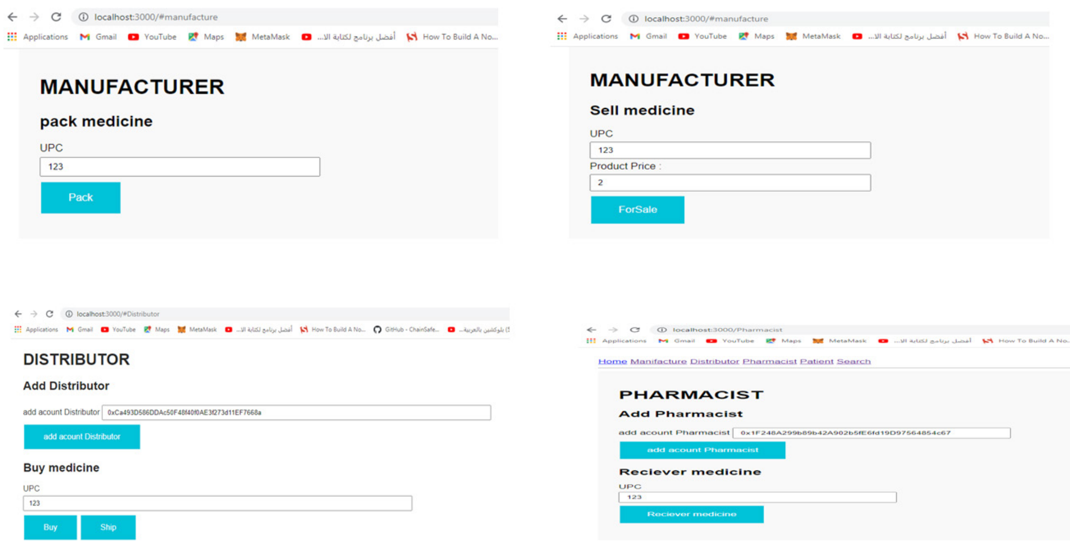

Figure 12. Drug states.

Finally, after the patient verifies the drug's journey through the supply chain, they can change the drug's status to "Purchase," indicating that the transaction is complete and the drug has been successfully acquired by the end-user, as shown in Figure 13.

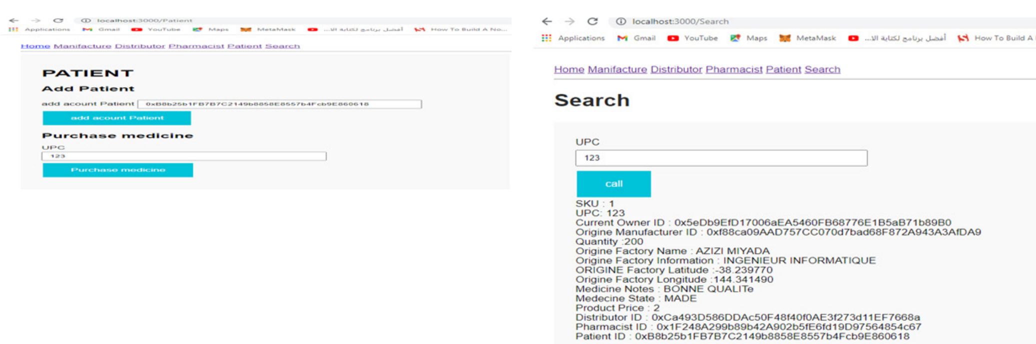

Figure 13. Purchase drugs.

This comprehensive process, supported by the integration of various tools and technologies, ensures a secure, transparent, and efficient drug supply chain, leveraging Blockchain's immutable ledger and smart contracts to manage transactions and maintain trust across all participants.

Difference Between our Proposed System and a Traditional Database

The table highlights several key differences between the proposed Blockchain-based system and traditional databases. In terms of operations, Blockchain only allows data insertion, preventing modifications or deletions, which enhances data security. At the same time, traditional databases support CRUD operations, making them more flexible but potentially vulnerable to tampering. Regarding replication, Blockchain ensures full replication across all peers, promoting decentralization and redundancy, unlike traditional databases that use master-slave or multi-master replication, which introduces central points of failure. Consensus in Blockchain requires agreement among participants before committing data, ensuring trust without central control, whereas traditional databases rely on internal consistency mechanisms. Lastly, Blockchain allows transaction validation by any participant, fostering transparency, while traditional databases depend on integrity constraints managed by administrators, which could be bypassed. Overall, Blockchain offers enhanced security and transparency, making it ideal for sensitive applications like pharmaceutical supply chains. However, traditional databases provide greater flexibility for tasks that require frequent data modifications.

The Table 1 illustrates the fundamental differences between our proposed Blockchain-based system and a traditional database.

Table 1. Differences between our proposed system and a traditional database.

Properties	Our proposed Blockchain-based system	Traditional Database
Operations	It only allows insert operations.	Supports CRUD operations (Create, Read, Update, Delete).
Replication	Full replication for each peer	Uses master-slave or multi-master replication.
Consensus	Achieves consensus on transactions.	Relies on distributed transactions.
Validation	Transactions can be validated by anyone.	Enforces integrity constraints.

CONCLUSION

This paper presents a Blockchain-based system designed to enhance transparency and traceability in the pharmaceutical supply chain by providing verifiable information on the origin and distribution of medications. By enabling producers to authenticate sourcing and distribution without data manipulation risks, the system gives participants access to a drug's complete history, building trust and accountability. Additionally, the Blockchain framework authenticates each product at every stage, preventing counterfeit drugs from entering the market and enhancing patient safety.

A Blockchain-secured supply chain further supports regulatory compliance, reduces supply chain fraud, and strengthens confidence among healthcare providers, patients, and stakeholders. Future research should prioritize regulatory and ethical challenges, integration with current systems, and scalability and cost-efficiency. Expanding these capabilities could also involve Big Data for in-depth analysis, cloud computing for scalable storage, and IoT for real-time monitoring, which would collectively improve the safety and reliability of the pharmaceutical supply chain. Addressing these challenges is crucial to maximizing Blockchain's impact in this sector.

AUTHOR CONTRIBUTION STATEMENT

Ahmed Aloui: Conceptualization, Methodology, Writing – Original Draft. Meftah Zouai: Data Collection, Experiments, Formal Analysis. Samir Bourekkache: Writing – Review & Editing, Visualization, Validation. Okba Kazar: Supervision, Project Administration, Final Approval.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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