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Blockchain Technology for Drug Fraud Detection and Tracking

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Abstract: *As concerns about medication safety have increased, so too has the demand for traceability and transparency in pharmaceutical supply chains. Traditional systems are based on distributed or centralized databases, however these often face problems including poor stakeholder confidence and data manipulation. Furthermore, issues with data privacy, transparency, and authenticity plague centralized systems. Our method leverages smart contracts to provide a secure, immutable transaction record accessible to all participants, eliminating intermediaries and ensuring data provenance. We provide a detailed description of the system's architecture and operation, demonstrating how it increases supply chain confidence and transparency. Testing and validation confirm the system's effectiveness, and cost and security assessments show that it is both safe and effective. This decentralized approach offers a practical means of eliminating counterfeits and ensuring safe, verifiable pharmaceutical supply from production to end use.*

Keywords: Blockchain, healthcare, traceability, trust, security, medicine counterfeiting

I. INTRODUCTION

Essential services for day-to-day living are based on the medical supply chain. The system's intrinsic complexity may bring some impurities, such imprecise data, a lack of transparency, and a restricted number of data sources. Counterfeit medications are one consequence of the present supply chain restrictions, which have a negative impact on human health and cause the healthcare sector to suffer large financial losses.[1]. Drug traceability is crucial for the welfare and health of patients, businesses, and the government. A trustworthy traceability system would make it easy for patients and other drug supply chain participants to find the whereabouts of a medication. With blockchain technology, transaction data may be disseminated and stored on a distributed shared data platform. A fundamental foundation for important services in day-to-day living is the medical supply chain. Counterfeit drugs, which have a negative impact on human health and cause the healthcare sector to suffer large financial losses, are one outcome of the existing supply chain restrictions. [2]. Cryptocurrency is based on blockchain technology, which has applications in supply chains, finance, commodities, and energy [3].

In addition, counterfeit medications are one of the main causes of mortality in development of many countries, in accordance to the WHO, with children usually being the victims [4].

Additionally, the negative results on human life, the pharmaceutical industry loses a lot of money because of fake drug.

An illustration of a pharmaceutical supply chain distribution process is provided in Figure 1. The producer either packages the drugs in a lot or sends them to be repackaged. The primary factor causing counterfeit drugs to enter the end-user market is the compounded structure of a healthcare supply chain.

IPFS makes this process easier by enabling the safe distribution and storage of sensitive data, including as user and transaction information [5]. For security purposes, to encrypt the hash's value we have generated the hash data using the SHA-256 algorithm. [6]. This paper presents one of the earliest attempts at blockchain-based pharmaceutical supply chain traceability. Although our method is similar to this endeavor in that it focuses on and makes use of blockchains, it adopts a holistic perspective of the pharmaceutical logistics and provides an one after the other solution for medication traceability.

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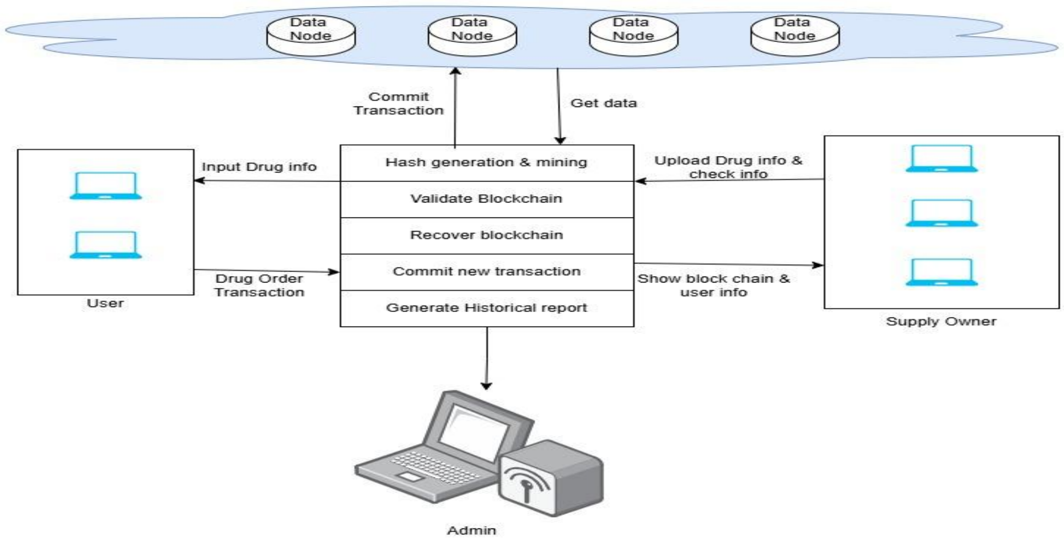

FIGURE 1. Participants and their relationships in drug supply management.

This technology has the potential to enhance medical medicine distribution and in a number ways in supply chain management. It can verify who owns medicine lots, increase confidence, data integrity, transparency, and trace a medication's whole life cycle in an unchangeable manner [7]. Blockchain has the potential to address those issues because to its special features, which include immutability, transparency, security, etc. (Liu et al., 2020). So, blockchain is still used in the medication supply chain [8].

The recommended approach for medication tracking in the pharmaceutical supply chain includes identifying and involving important stakeholders, defining links between them, and using smart contract technology for real-time tracking with push notifications. Compared to previous approaches, which included shortcomings including manual medication, receipt confirmation, ambiguous interactions, and stakeholder representation, this one is superior.

The proposed technique is applicable to different supply chains and ledger and store blockchain data. You may maintain network consensus by participating in the validation and verification of new transactions and blocks. Ensuring data availability and integrity: the chain is maintained by the remaining nodes in the case of a node failure, preventing data loss.

Function in the Flow: Transactions are hashed and validated as users or supply owners engage with the system (for example, while inputting drug information or placing medication orders). The blockchain ledger is then updated with these transactions. The data nodes are required to obtain and validate the information each time a request for data or transaction validation is made.

In conclusion, Data Nodes use blockchain technology to guarantee safe, reliable, and unchangeable documentation in this medication supply chain system.

To stop the spread of fake drugs, the pharmaceutical industry has tried several times to solve the well-known issue of achieving traceability.

II. RELATED WORK

Blockchain in healthcare: This marks the start of the revolution [1] In past few years, a number of industry sectors have pursued ways to incorporate blockchain technology into their operations, demonstrating its remarkable adaptability, as the author of this article explains. In order to illustrate the possible impacts, goals, and possibilities associated with this disruptive technology, this article uses examples pertaining to the management of and falsified medicines.

Suggestions for implementing technology of blockchain in pharmaceutical supply networks are shown in the case of Bayer Pharmaceuticals.

I also look may be used in supply chain in at how blockchain technology Bayer's pharmaceutical division, a life sciences company.

Blockchain might benefit Bayer and the sector at large.

big. for instance, blockchain makes it possible for open information sharing without disclosing trade secrets, product transparency and security, and effective, secure, and private transactions. For the first time, it is possible to create a platform that allows all parties involved to transact value and information at the same time.

Drugledger: A useful blockchain platform for tracking down and regulating drugs:

[3] The Author suggests Drug traceability systems are crucial for pharmaceutical businesses' operations and public drug security because they track the whereabouts of drugs

and their journey through the medication supply chain... Drugledger is more reliable than traditional solutions because of its peer-to-peer design.

Additionally, Drug ledger's p2p design makes it more robust than conventional solutions. Additionally, Drug ledger might effectively reduce its capacity, resulting in a blockchain storage that is at last reliable and palatable. The best of our knowledge, it is the first thorough investigation of the possible technology and practical design of a blockchain system for drug control and traceability.

The blockchain's unalterable, dependable openness and transparency may allow for the secure transfer of more data [11].

III. KEY CHALLENGES OF CURRENT SYTEM

One of the company's biggest concerns lately has been the blockchain technology.

Intricate interactions between parties issues are still very much present because of. Furthermore, this pandemic disrupted almost every economic sector and had an impact on the global socioeconomic system

When drugs are administered under unsuitable conditions for human use, transparency is compromised. consumption, when a phony prescription drug is shipped, or when costs increase without explanation.

Regulations, however, are always changing. Businesses will gradually need to improve their supply chain, customs, and internal control in order to reach a new standard.

• Raw Material Scarcity: Poor preparation may result in

several problems obtaining raw materials during a pandemic.

• Common technological challenges include: In the past, the pharmaceutical sector has been wary and slow to adopt new ideas. Despite the enormous advancements over the past decade, certain obstacles still stand in the way of utilizing new technology to their fullest [10].

IV. BLOCKCHAIN TECHNOLOGY FOR PHARMACEUTICAL SUPPLY CHAINS IN DRUG TRACEABILITY SYSTEM

Figure 2 depicts the macro-level architecture, stakeholders, and interactions between the smart contract and the proposed pharmaceutical traceability system.

For supply chain transaction data, the Decentralized Storage System (IPFS) offers an affordable off-chain storage option that guarantees the integrity, dependability, and accessibility. The distinct hashes for every file uploaded are then shown. The Ethereum Smart Contract oversees the supply chain's implementation. Important functions carried out by the smart contract include maintaining hashes from the decentralized storage server that provides users with access to supply chain data and keeping track of transaction history. The responsibilities of the different supply chain participants are likewise specified by the smart contract, and authorized persons are given access to these roles through the usage of modifiers.

Ethereum Smart Contracts are used to manage the supply chain deployment.

A modifier helps to add extra features or limitations to a function in order to adorn it. Transactions l involving the sale of medicine lots or cartons are also managed through the smart contract.

The outputs and triggers produced by the smart contract are on-chain:
Rather, the system's components are designed to cooperate to trace the drug's history and verify its legitimacy. A drug lot's whereabouts may be tracked in real time using a variety of techniques.
The interactions between different supply chain participants in the proposed system are depicted in Figure 3. Three phases may be used to generally classify it; they are explained below.
Manufacturing: The process of converting raw materials into medicines is handled by the medication distribution data input component of the system [11]. Typically, a producer requests FDA permission before starting to manufacture a medicine batch. As soon as the FDA approves the request, the manufacturer begins production, and all parties are notified of the event.

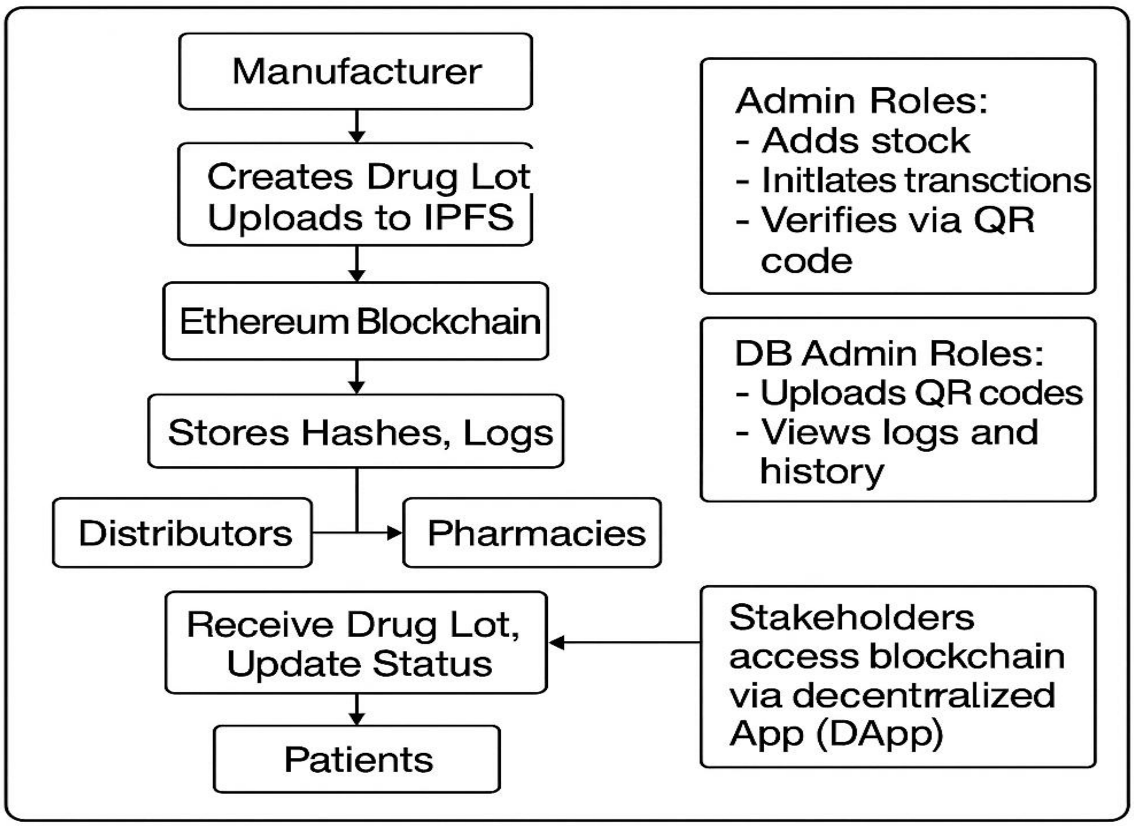

FIGURE 2. An outline of the architecture of the suggested blockchain-based pharmaceutical supply chain system

Distribution: After then, the dissemination process begins. The distributor creates a hash for the smart contract by packing the pharmaceutical lot and uploading a photo of the box to IPFS.
.Purchase/Use The connection between the patients and the pharmacist is what the sequence diagram's last stage is about. The pharmacy will alert all supply chain players and begin selling the medication lot box in this scenario. Structured as a series of sequential actions, this process guarantees that every transaction is recorded and can later be accessed by all supply chain stakeholders to verify the authenticity and integrity of the products.

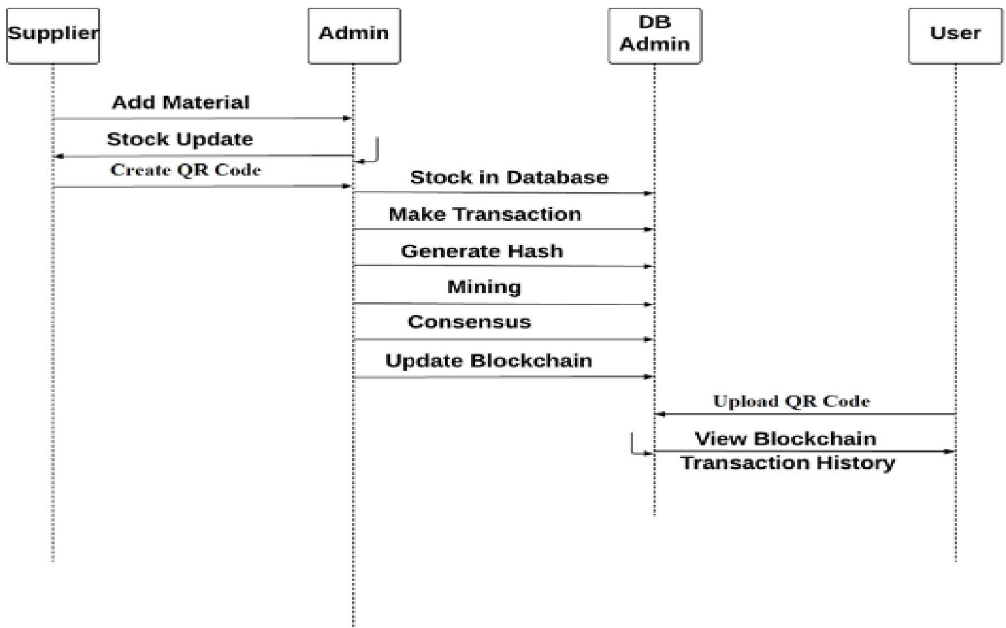

FIGURE 3. Sequence diagram illustrating how the smart contract's involved entities interact with one another.

The schematic illustrates the sequential interactions between system components in a supply chain system powered by blockchain technology for managing pharmaceutical products or raw materials. Let's dismantle it:

Actors and Participants:

Stock is updated, and materials are added by the supplier.

Admin: Manages transactions and engages with blockchain technology.

Data entry and QR code uploading are handled by the DB administrator.

The person who examines blockchain data, such as transaction history and product legitimacy, is known as the user.

Specific detailed Procedure:

1. Supplier: Add Content: The supplier updates the system with new content, like medication inventories.

Stock Update: Adds new stock details, such as types and amounts.

Create a QR Code: A distinct QR code is assigned to the material. This facilitates future tracking.

2. Admin: Stock in Database: Admin enters the stock data into the main database.

To add this information to the blockchain, the administrator must first start a transaction.

Create Hash: The information is transformed into a hash using cryptography.

Mining: To verify this transaction and add it to the blockchain, the system mines.

Consensus: The transaction is validated by the agreement of many nodes.

Blockchain Update: Once validation is successfully completed, the newly verified block is added to the existing chain of records.

3. DB Admin: Add QR Code: This adds the previously generated QR code to the database linked to the material transaction or blockchain. View Transaction History/Blockchain: The database administrator (or user) can obtain and inspect the blockchain ledger and the item's whole history.

4. User: Despite not being actively involved in the aforementioned actions, the User gets access to the final data: View the Blockchain and Transaction History

This helps the consumer verify the product's validity, origin, and supply chain path.

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A blockchain-based drug control and traceability system is presented in this study. Eventually, it attains dependable blockchain storage. Additionally, algorithms that mimic the actual pharmaceutical supply chain workflow have been developed [13].

Benchmarking the Proposed Solution with Current Alternatives

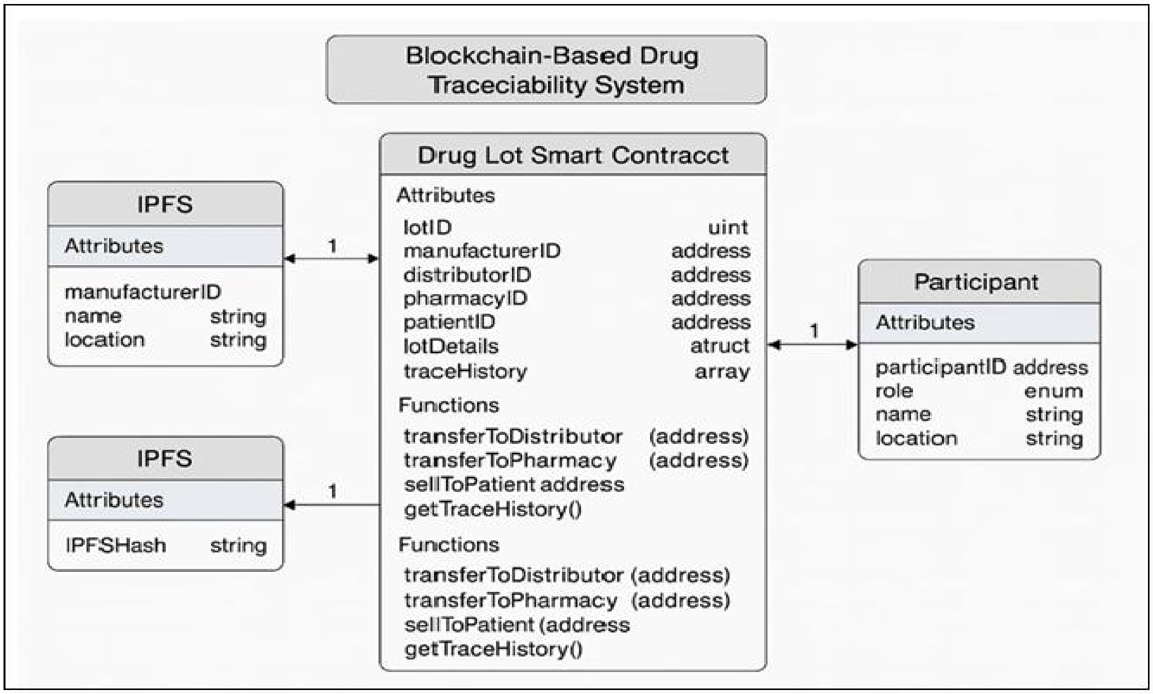

FIGURE 4. Entity Relationship Diagram.

Hyperledger-Fabric is utilized in blockchain and solutions. A characteristic of Hyperledger-fabric is that it operates in private permissioned mode, whereas our method operates in public permissioned mode as well. Although it doesn't have a currency, it uses Bitcoin. However, in [9], the approach does not provide a programmable module.

V. PROPOSED TRACEABILITY SYSTEM IMPLEMENTATION

The proposed solution is developed using Ethereum blockchain technology. As a permissionless public blockchain, Ethereum allows unrestricted access, enabling anyone to pticipate in the network Code 1 is now fully available to the public.

All supply chain parties are notified when the manufacturer installs a smart contract containing medicine lot details. New participants can follow the Lot's history and access the events. For visual examination, the manufacturer can send a picture of the lot to IPFS. The manufacturer notifies interested parties of availability prior to sale, and they can purchase through a dedicated feature.

An event announces the new owner after the sale. The smart contract does not incorporate FDA approval.

Allowable users include manufacturers, wholesalers, and pharmacies, among other smart contract functionalities. To finish the manufacturing and selling procedures for the Lots, the smart contract also carries out a number of functions. In order to extract useful information and make informed decisions, drug traceability systems must use certain data mining and analysis methodologies.

Matching judgments, Numerous domains, such as anomaly identification, trend analysis, and risk assessment, can benefit from the use of data mining and analytic techniques [11].

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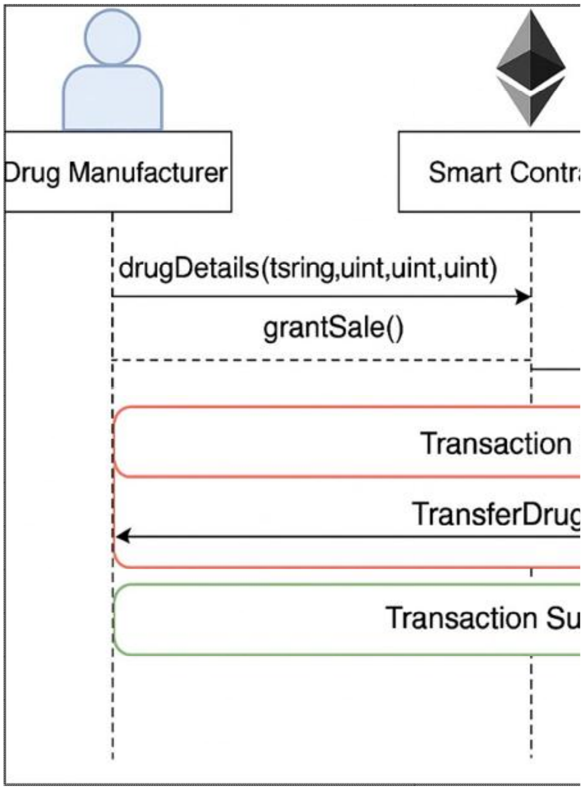

FIGURE 5. Event calls and function calls for two distinct lot sale scenarios

Figure 5 shown The Organizations Involved: Pharmaceutical Manufacturer: the company that manufactures and distributes the medication.

Smart Contract (Blockchain Layer): The self-governing software installed on the blockchain that controls transactions, upholds security, and maintains transparency.

Purchaser of Drugs: the final consumer or someone who wants to buy the medication.

Interaction sequence: 1. drug details (string, unit)

Starter: Pharmaceutical Producer

Action: To supply details about the medication, the manufacturer invokes the smart contract's drug Details() function.

Among the parameters are:

A string (probably the name or description of the medicine),

Three unsigned integers that could stand for the batch number, price, amount, expiration date, or medication ID.

This serves to register the medication for upcoming sales in the blockchain system.

2. grant Sale() Starter: Pharmaceutical Producer

Action: To approve the sale of the specified medication, the manufacturer invokes the grant Sale() function.

Objective: This ensures that only approved drugs are offered for sale. It protects against dishonest business dealings.

Two things might occur from here:

Option 1: The deal didn't work out.

If any of the following checks don't work:

It is forbidden to sell drugs (grant Sale() is not called).

The buyer does not supply enough money.

The drug's details are either invalid or missing.

The transaction is ended via the automated on-chain contract.

The manufacturer and the customer receive a "Transaction Failed" notification.

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No money is moved.
Option 2: Successful Transaction
If the buyer makes the right payment and all the terms are met: Transfer Drug Price, which is triggered by the smart contract, securely moves the money from the buyer to the manufacturer on the blockchain.
The transaction is recorded as successful once the payment has been confirmed. The message "Transaction Successful" is displayed

Algorithm 1: Building a Smart Contract Drug Lot
The drug's name is - drugName; the price is the total prize of the drug lot.
Package price per package - packagePrice: The total number of packages in the lot
The public key on the Ethereum network that calls the function is <Caller`.
- manufacturerID: Address of an authorized pharmaceutical manufacturer
Film:
- Event: Making a drug lot
Event: Information/image uploaded for a drug lot
Information:
Then, if Caller == manufacturerID
Update {drugName`, lotPrice, Num Packages, packagePrice
Store {IPFShash`Emit event: The creation of a drug cacheInformation on the drug was posted to IPFS.
Otherwise, the transaction would be reverted. Display an error regarding illegal access.

Algorithm 2 : for Lot Sales
A signal indicating the beginning of the sale for the lot.
Caller == ownerID, thus
Notify stakeholders that the lot is now for sale
Otherwise
Go back to display an error.

Algorithm 3: Smart Contract Input for Purchasing a Drug Lot
manufacturerID: The current owner of the drug lot's Ethereum Public Address
Purchaser: Public Ethereum address of the purchaser
Vendor: Public Ethereum address of the vendor
(should match manufacturerID)
lotsPrice: Medication lot's price
Result:
Event: A lot of drugs were sold.Information
ManufacturerID: Present medication lot owner
Buyer: A new buyer for the property
Seller: The current manufacturer that owns the lot
Starting up:
Ascertain if Buyer!= Seller AND TransferredAmount == lotPrice.
If so, the following actions will take place: a. Give the seller the lot price; b. Give the buyer the manufacturer ID; and c. Send out the event "Drug lot has been sold."
Alternatively: a. Return to the original contract state b. Display the error message "Invalid transaction – either price mismatch or invalid buyer."
It is in charge of initiating events and recording them on the ledger using a specially created smart contract. Every medication lot has a different Ethereum address. Consequently, a QR code—which is easily detected by smartphones—

is employed. Smartphones are able to scan QR codes, which are two-dimensional barcodes that might contain more than 4,000 characters.

The procedures for confirming a drug's legitimacy are shown in Figure 6. Users greatly benefit from the Ethereum node's duplicate of the ledger, which streamlines and simplifies the process by removing the time-consuming task of setting up own Ethereum node. Initially, the service user may access the pharmacy Ethereum by using the lotSold event.

The Ethereum network and the way in which the nodes exchange information are depicted in Figure 7. Each node in the network stores an immutable ledger replica, which ensures that any data accessed from the ledger is authentic and unaltered. When the desired events and ownership change data are retrieved from the Ethereum network and synchronized with the Ethereum gateway. Through these application use case, we show how effective our proposed system is at tracking and tracing supply chain.

According to the proposed approach, a pharmaceutical company will manufacture drugs with details such the drug's name, ingredients, time stamp, and usage and secure permission from the regulatory agencies that oversee the healthcare sector [12].

Step 1: The DApp scans the drug lot's QR code

A user (such as a customer, regulator, or pharmacist) scans the QR code on the medication lot using a mobile or web-based DApp.

The unique Ethereum address contained in the QR code is linked to the smart contract of the medicine batch.

Step 2: Engaging with the Infura Ethereum Gateway

Infura acts as a gateway to the Ethereum blockchain after receiving the scanned Ethereum address.

You can retrieve data with Infura without having to run a whole Ethereum node.

Step 3: Submit a query to the Ethereum Network

The Ethereum address is linked to the smart contract that manages the medication batch.

The network is queried to retrieve pertinent data, such as ownership, manufacturing information, and transaction history.

Obtain Information on Events and Ownership in Step Four Ownership records and events that the smart contract emits, such creation, sale, and transfer, are accessible over the blockchain.

All transactions and ownership changes pertaining to the pharmaceutical lot are covered by this data.

In Step Five, provide the DApp user with data.

The information and events that were obtained are returned to the DApp interface. The user may view the entire traceability history to confirm authenticity and help combat counterfeit drugs

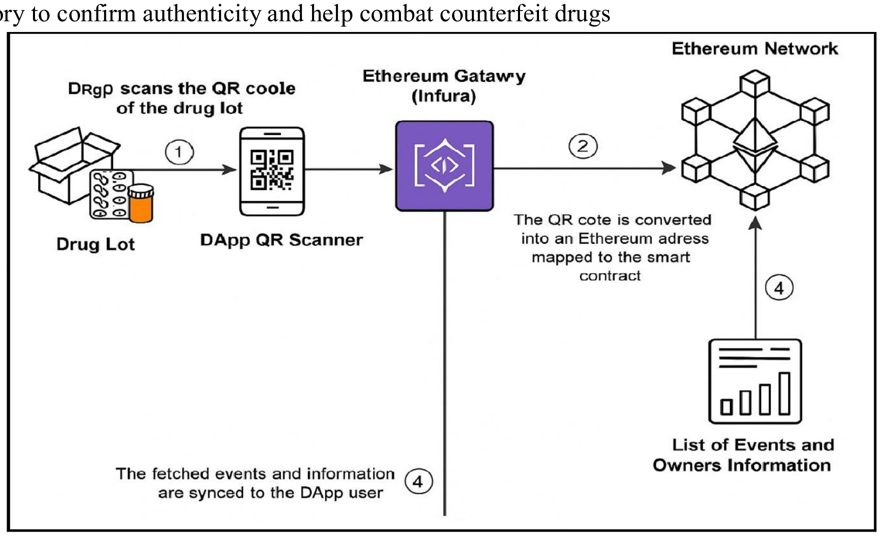

FIGURE 6. The blockchain-based solution's application use case

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V. TESTING AND VALIDATION

For the Blockchain-based Drug Traceability System, the roles of manufacturing, distribution, retail, and consumers in the supply chain were all thoroughly investigated. Every module's data integrity and functional correctness were examined, with special care paid to blockchain immutability.

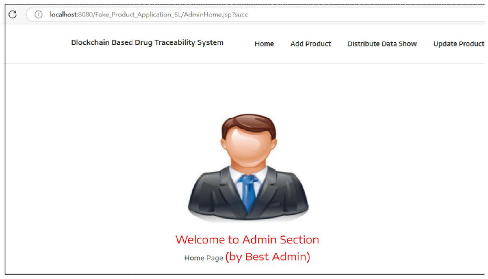


FIGURE 7 . Successful execution of Admin panel.

The admin panel was tested by opening it and navigating between the various modules (manufacturer, distributor, etc.).

Anticipated Results: A system overview is displayed, all modules are accessible, and the user interface transitions smoothly.

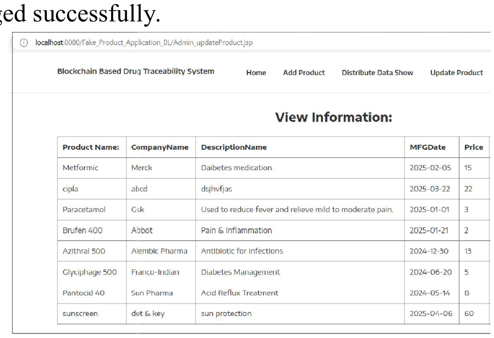
As a result, the admin panel operated as planned.

Manufacturer: Add Drug

A new medication with a valid name, batch ID, and expiration date was added.

Anticipated Outcome: Drug detected; blockchain adds a new block; info appears immediately.

Result: Drug added and logged successfully.



localhost:8080/Fake_Product_Application_BL/Admin_updateProduct.jsp

Blockchain Based Drug Traceability System — Home | Add Product | Distribute Data Show | Update Product

View Information:

Product Name:	CompanyName	DescriptionName	MFGDate	Price
Metformic	Merck	Daibetes medication	2025-02-05	15
cipla	abcd	dsjhvfjas	2025-03-22	22
Paracetamol	Gsk	Used to reduce fever and relieve mild to moderate pain.	2025-01-01	3
Brufen 400	Abbot	Pain & Inflammation	2025-01-21	2
Azithral 500	Alembic Pharma	Antibiotic for Infections	2024-12-30	13
Glyciphage 500	Franco-Indian	Diabetes Management	2024-06-20	5
Pantocid 40	Sun Pharma	Acid Reflux Treatment	2024-05-14	8
sunscreen	dot & key	sun protection	2025-04-06	60

FIGURE 8. Successful execution drug information.

Test Performed: To get complete details, click on any listed medicine.

The batch ID, manufacturer details, and creation timestamp were displayed. Outcome: Accurate block and drug information is shown.

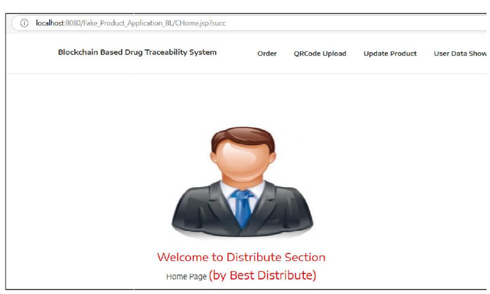


FIGURE 9. Successful execution of Distributor section.

Demonstrates how the distributor transfers medications to the retailer after obtaining them from the manufacturer. The goal of validation and testing confirms the receipt of drugs.

Tests are sent to the store.

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Verifies blockchain entry following a transfer.
Status: Experimented and functioning as anticipated.

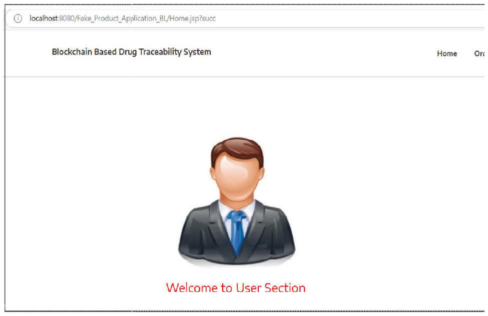
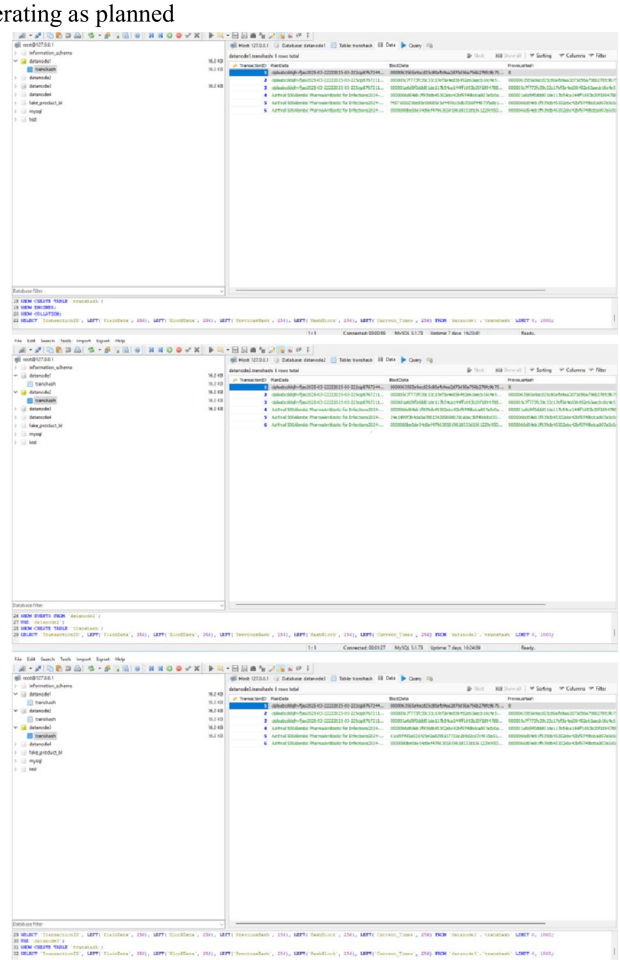


FIGURE 10. Successful execution of User section.

lets the customer verify the origin, batch history, and supply chain journey of a medication by displaying its full traceability.

To validate the medicine, the testing and validation process makes use of a QR code or medicine ID. shows all of the history that the blockchain has supported. ensures transparency and traceability that cannot be tampered with. Current state: Tested and operating as planned



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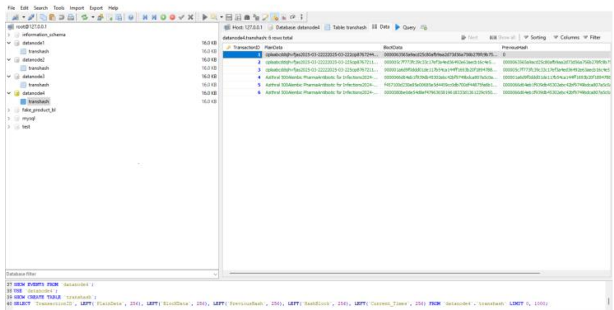

FIGURE 11. execution of the blockchain ledger view successfully.

Test Performed: Viewed the entire blockchain ledger in Blockchain Ledger View.

All transactions with a block number, hash, and timestamp are displayed in the expected output.

All data nodes have same information.

Outcome: Every data block is visible and unscathed

VI. DISCUSSION AND EVALUATION

This section provides an analysis of the costs and security considerations for drug traceability in supply chains. It also highlights the challenges posed by blockchain technology in supply chain applications and discusses the potential for scaling the proposed solution based on the Ethereum blockchain[15].

A. GENERALIZATION

For instance, while being transported from one location to another, certain pharmaceutical products need very particular conditions, such temperature and humidity. However, the requirements for a supply chain for replacement components, for instance, may differ significantly.

Stakeholders in the supply chain must modify their roles based on the specific use of the chain, such as food, replacement components, or another use. Finally, the on-chain resources can be modified to meet the needs of the proposed application; for example, a money transfer setup, payment system, and reputation system might not be necessary. In these cases, the on-chain storage will be more than enough to keep the parties' transaction records intact.

You may also alter the entity relationship diagram. For example, it must be introduced and its connection with the other entities may be described if a supply chain application has to employ several parent smart contracts. Another situation is when several goods are being developed at the same time, necessitating the extension of capabilities to accommodate the new items. The existing smart contract may be changed to do this.

B. Security analysis for the blockchain-based healthcare supply chain's

• Integrity:

This is achieved by recording every event—such as production, stakeholder transfers, and verification—on an immutable blockchain ledger, which guarantees that the information is never altered or tampered with. Blockchain's distributed and decentralized architecture may improve the security of pharmaceutical supply chains [16]. The increasing usage of blockchain technology for information traceability is making it increasingly difficult for single-chain solutions to meet the requirements of complex situations.

• Accountability:

The address of the entity that carried out each transaction or activity, including the production of drugs, the transfer of ownership, or the verification of traces, is permanently stored on the blockchain. This guarantees that each stakeholder's role—manufacturer, distributor, and retailer— can be easily traced. For example, when a manufacturer uses the add Drug function to generate a drug lot, their Ethereum address is used to record their identify and hold them responsible for the batch information.

• Authorization:

Sensitive functions are shielded from unwanted access by limiting important smart contract activities to authorized parties only. At the smart contract level, role-based limitations are put into place: only authorized distributors and merchants are permitted to dispense drugs or transfer ownership, and only Drug lots can be made by certified manufacturers. This access control mechanism is essential to 1 28 1 1 maintaining integrity and confidence across the healthcare supply chain since it prevents tampering or abuse by unknown individuals. By limiting capability to authorized users, the system ensures that every activity that is recorded originates from a legitimate and accountable source.

• Non-Repudiation:

Every transaction in the system is cryptographically signed using the private key of the entity who initiated it, whether it a manufacturer, distributor, or retailer. These digital signatures ensure that a transaction is always linked to the individual who started it, thanks to Public Key Infrastructure (PKI). The participant cannot later take back or dispute their actions because each one is securely connected to their blockchain identity. This guarantees trust and traceability, especially when verifying the source and movement of pharmaceutical supplies. This investigation introduces a blockchain-based drug control and traceability system for the first time. It progressively rebuilds the whole service architecture to guarantee the secrecy and authenticity of traceable data and eventually produce a dependable blockchain storage system [18].

• Protection Against MITM Attacks:

Any transaction must be digitally signed by the initiator using their private key before it can be finished in the system. Without the proper private key being used to sign it, this cryptographic verification process ensures that the network will reject any changes or interception by an unauthorized person (a Man In-the-Middle). This integrated preventive measure is crucial in the healthcare supply chain, where data tampering might result in the delivery of dangerous or fake pharmaceuticals. Blockchain technology effectively eliminates the possibility of Man-in-the-Middle (MITM) attacks by ensuring that only verified organizations may record or 10 alter transactions.

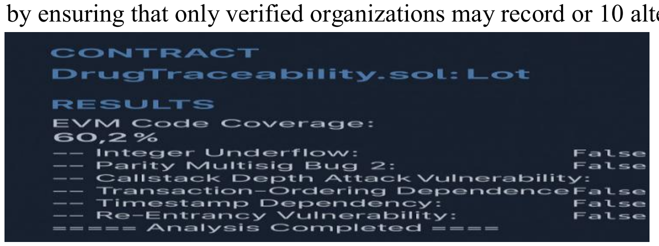

FIGURE 12. Examination of vulnerabilities in smart contracts

C. SMART CONTRACT SECURITY ANALYSIS

Using such technologies in code development iterations improved the reliability of the smart contract. The Remix IDE, which provides run-time error alarms and specific code debugging tools, was used to create the smart contract.

D. RESTRICTIONS IN HEALTHCARE SUPPLY CHAINS BLOCKCHAINS

There are a few potential disadvantages that might lessen the suggested Blockchain-based Drug Traceability System's utility in real healthcare settings, despite its many benefits, which include security, traceability, and immutability. In order to fully comprehend the scope of the system, several limitations need to be considered.

• Immutability:

Blockchain can be troublesome when data is inputted incorrectly, even if its immutability ensures data integrity. A manufacturer may enter inaccurate batch information or expiration dates while producing a medication lot in our system; once entered, these details cannot be altered. The healthcare supply chain may experience unanticipated

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consequences, as inaccurate prescriptions or problems with pharmacy rules, even though this increases confidence in the data.

• Data privacy:

Blockchain technology's permanent and open record-keeping capabilities can conflict with privacy laws like GDPR, which provide individuals the opportunity to see, amend, or delete their data. Although our system does not save sensitive patient data, future improvements may incorporate user authentication or prescription tracking. There may be moral and legal issues with permanently storing patient data, especially in places with strict data protection regulations.

• Scalability:

Every node in our Ethereum-based system has to confirm each transaction. Security is assured, however in high-volume scenarios, such mass production or pandemic pharmaceutical distribution, performance can be affected.

• Interoperability:

Lack of interoperability may prevent smooth integration if healthcare facilities or other stakeholders use blockchain technologies that are implemented on various platforms (such as Hyperledger or Solana). Such systems would need to be unified, and seamless data sharing between institutions would require a standardized or cross-chain communication protocol.

• Efficiency:

The quality of the smart contracts and the consensus process employed determine the system's overall performance and energy usage. Any function in our implementation that is not well optimized, such trace or transfer techniques, could result in delays or expensive gas prices. Smart contracts must be tuned for speed and low resource consumption as the number of participants and medicine batches rises. The validation, blockchain, key generation, and transaction logic components that make up the current prototype were created with JavaScript and the Angular web framework [20].

VII. CONCLUSION

A blockchain-based strategy to improve drug traceability in the pharmaceutical supply chain is suggested in this paper. By utilizing the intrinsic characteristics of blockchain technology, such as immutability and cryptographic integrity, the system facilitates decentralized medication tracking. Supply chain events are transparently and automatically documented with Ethereum smart contracts, producing an auditable, tamper-proof record that is available to all parties involved. Performance assessments demonstrate that the system maintains strong security at a reasonable gas consumption cost. The technology successfully reduces risks associated with data availability, integrity, and non-repudiation, which is crucial in multi-party settings like pharmaceuticals, according to the security study. Future research will concentrate on enhancing end-to-end transparency and drug usage verifiability, even though the technology offers a robust protection against counterfeit medications. The goal of this development is to increase pharmaceutical supply chains' legitimacy and effectiveness even further. All things considered, the suggested approach establishes a framework for creating safe, open, and legal worldwide solutions to guarantee medication safety and regulatory compliance.

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