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Blockchain Technology as the Foundation for Transparent Pharmaceutical Supply Chains

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Abstract:

Purpose: *Contemporary pharmaceutical supply chains face numerous challenges, including combating drug falsification and ensuring compliance with evolving legal regulations. This study aims to explore the potential of blockchain technology as a solution to these challenges.*
Design/Methodology/Approach: *The study evaluates the application of blockchain technology, integrated with the Internet of Things (IoT), to enhance transparency and security in pharmaceutical logistics. Using simulations programmed in Python, the research investigates the effectiveness of the SHA-256 cryptographic algorithm in ensuring data integrity. The simulations involve scenarios of data manipulation, breaches in cold chain requirements, and attempts to introduce counterfeit products, demonstrating the blockchain system's resilience and utility in identifying and mitigating risks.*
Findings: *Blockchain technology, utilizing the SHA-256 algorithm, provides a decentralized and immutable system for tracking drug distribution processes. The integration with IoT enables real-time monitoring of environmental conditions, ensuring the safety and integrity of pharmaceutical products.*
Practical Implications: *The proposed solution has practical implications in preventing counterfeiting, improving transparency, and maintaining the integrity of the cold chain in pharmaceutical logistics.*
Originality/Value: *This study highlights an innovative approach to addressing significant challenges in the pharmaceutical industry by leveraging blockchain technology combined with IoT.*

Keywords: *Blockchain, Internet of Things, Pharmaceutical Supply Chain, Cold Chain, Drug Falsification.*

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1. Introduction

Pharmaceutical supply chains encompass primary manufacturers, secondary manufacturers, logistics service providers, healthcare providers, and retail points of sale (Ding, 2018). At each stage, this process is subject to stringent regulatory frameworks designed to ensure patient safety, maintain the quality of pharmaceutical products, and prevent counterfeiting and tampering. In developing countries, the standards for medicinal products are often not as rigorous or consistently enforced.

The lack of adequate regulations or their limited enforcement increases the risk of counterfeit products and deterioration in the quality of medicinal products. International organizations, such as the World Health Organization, strive to support these countries in implementing guidelines such as Good Distribution Practices (WHO, 2024; GDP, 1994).

The issue of counterfeit pharmaceutical products and improper transportation affects both developing and developed countries. Despite the implementation of stringent regulations and extensive control systems, counterfeit drugs, or those not distributed under the required conditions, still infiltrate legal supply chains, posing a threat to patient health and safety.

Moreover, a significant proportion of dishonest supply chain participants focus their activities on English-speaking countries, highlighting the need for intensified research and the development of more effective mechanisms to ensure patient safety and reduce the risk of unauthorized circulation of pharmaceutical products (Mackey and Nayyar, 2016).

Industry standards require, among other things, the maintenance of proper conditions for the reception, storage, and transportation of pharmaceutical products. This obligation applies to all medicinal products and is of critical importance for drugs that require the preservation of the cold chain. The list of drugs and substances used in their production that require the maintenance of the cold chain is extensive and includes both biological and chemical products, such as vaccines, insulins, blood-derived products, selected antibiotics, and many others (WHO, 2024; Richter, Bongaerts, and Metzendorf, 2023; Rusnack, 2021; Zhang *et al.*, 2012).

The temperature range required in the cold chain includes both standard refrigeration conditions (2–8°C) and cryogenic temperatures (-160°C to -180°C). At every stage of the transport of raw materials or finished drugs, the temperature must be controlled and documented. Detailed documentation should allow for the identification of each product from its production to its delivery to the patient, ensuring transparency regarding each stage of the product's movement. In this context, the challenge remains to ensure the integrity of the data, which are susceptible to manipulation in conventional systems used within the industry (WHO, 1999; Mackey and Liang, 2011).

Blockchain technology, with its transparency, decentralization, and immutability of records, represents a promising tool for managing pharmaceutical supply chains (Bamakan *et al.*, 2021). Through the use of a distributed ledger, it is possible to precisely document each stage of both the transportation and storage of pharmaceutical products, ensuring compliance with legal regulations and enhancing the transparency of the entire system.

The aim of this paper is to demonstrate the practical application of blockchain technology in pharmaceutical supply chains, with a focus on its potential to combat counterfeiting and ensure effective monitoring of drug distribution conditions, particularly in the cold chain.

As part of the research on the application of blockchain technology in transparent pharmaceutical supply chains, computer simulations were conducted to evaluate the practical application of this solution in identifying and eliminating potential risks. The primary focus was on detecting issues such as document falsification, violations of refrigeration requirements, and attempts to introduce unauthorized products into the supply chain. The effectiveness of the SHA-256 algorithm in ensuring data integrity was assessed throughout the simulations.

A Python program was developed using cryptographic libraries and visualization tools. The simulations involved generating unique identifiers for transportation condition data, verifying data integrity using SHA-256, and analyzing the system's response to data modifications. IoT data samples, datasets representing product flow within the supply chain, and scenarios involving integrity violations, such as metadata manipulations, were used. The input data was processed, hashed, and verified, with the results recorded in a simulated blockchain register.

2. Selected Issues in Global Pharmaceutical Supply Chains

Currently, over two billion people worldwide lack access to essential medicines, vaccines, and medical devices (Ozawa *et al.*, 2019). This situation facilitates the introduction of counterfeit pharmaceutical products into the market, which fail to meet the required quality and safety standards, posing a threat to both public health and the integrity of healthcare systems (Sweileh, 2021).

This issue is further exacerbated by the growing complexity of global supply chains, where products manufactured in one country may be packaged in another and then distributed to destination markets in third countries (PharmaSource, 2024) Moreover, the dynamic growth of e-commerce also contributes to the intensification of counterfeiting, often facilitating the purchase of counterfeit medicines from unauthorized sources by unsuspecting consumers.

Counterfeit medicines are defined as products whose identity, source, or history have been dishonestly represented (WHO, 2024). This includes the falsification of the name, composition, packaging, manufacturer, country of origin, and distribution channel documentation. Counterfeit products may contain incorrect ingredients, lack active substances, or even include harmful substances. When these products infiltrate the legitimate supply chain, they increase the risk to patients and undermine trust in the healthcare system.

Global pharmaceutical supply chains have a complex structure, involving various stakeholders. At each stage of this process, there is a potential risk of unauthorized products entering the market. Within the EU, in accordance with the requirements of Directive 2011/62/EU, mechanisms have been implemented to prevent the entry of counterfeit products into the legal supply chain.

One of these mechanisms includes mandatory security features, such as unique identifiers that enable verification of authenticity and tracking of individual medicine packaging. EU law mandates all parties involved in the supply chain to implement measures to prevent manipulation and counterfeiting, as well as the obligation to report any suspicions regarding illegal products (Directive 2011/62/EU, 2011). However, in the absence of interoperable and cohesive monitoring systems at the international level, ensuring the integrity and transparency of the supply chain remains a challenge. The diversity of regulations and standards applied by individual countries globally further complicates effective oversight.

3. Counterfeit Medicines and the Limitations of Traditional Systems

Counterfeit medicines represent a significant challenge both in terms of public health and the reliability of pharmaceutical supply chains. Traditional methods of document management, such as manual records, isolated databases, and archiving systems with limited interoperability, do not provide adequate protection against data manipulation. Manual management of documentation, lacking automation and data integration mechanisms, leads to an increased risk of errors and delays, and also fosters dishonest practices.

These limitations significantly hinder the identification of issues, negatively affecting the ability to respond swiftly in crisis situations. The difficulty in preventing the infiltration of counterfeit medicines into the market also arises from the complexity of the distribution network, which involves numerous participants in the process, including manufacturers, wholesalers, distributors, and retail points of sale (Dégardin, Roggo, and Margot, 2014).

Each stage in this chain creates a potential risk of introducing unauthorized products into circulation, especially in the absence of harmonized and interoperable monitoring systems. The complexity of logistics operations, the variety of procedures used by different entities, and the lack of uniform regulatory standards at the international level significantly hinder the maintenance of integrity and transparency in the pharmaceutical supply chain. To address these challenges in pharmaceutical logistics, technologies such as the Internet of Things (IoT) are increasingly being implemented, enabling real-time monitoring and management of processes (Pachayappan, Rajesh, and Saravanan, 2016; Sharma, Kaur, and Singh, 2020; Singh *et al.*, 2020).

These solutions, combined with blockchain technology, represent a promising approach to ensuring full transparency and monitoring of the storage and transport conditions of pharmaceuticals (Chen *et al.*, 2023; Nanda, Panda and Dash, 2023; Premkumar and Srimathi, 2020). The application of IoT tools in pharmaceutical supply chains allows for the real-time tracking of environmental parameters. IoT devices, including sensors connected to systems that monitor specific parameters and conditions, enable the acquisition of data in real time, which is then automatically integrated into supply chain management systems, supporting operational efficiency and precision.

Examples of IoT devices include temperature sensors for monitoring vaccine transport, humidity sensors for biological products, and GPS trackers for ensuring product location accuracy, all of which record critical environmental and logistical data directly onto the blockchain for enhanced transparency and security. The implementation of blockchain technology, which ensures data storage in an immutable and transparent ledger, provides comprehensive verifiability and guarantees the authenticity of the data generated during processes, effectively eliminating the risk of tampering and counterfeiting.

IoT technologies, by supporting real-time quality monitoring, enable the immediate detection and response to deviations from defined standards. These solutions significantly increase operational efficiency, enhance regulatory compliance, and minimize the risk of human error. The integration of IoT with blockchain technology in pharmaceutical logistics can lay the foundation for secure and transparent supply chains.

4. Comparison of Counterfeit Prevention Mechanisms

In order to assess the effectiveness of solutions used in pharmaceutical logistics to counteract counterfeiting, a comparative analysis of three systems was conducted: blockchain technology based on the SHA-256 algorithm, traditional data archiving systems, and integrated ERP systems (Table 1).

The analysis covered key criteria such as data integrity, the ability to track the origin of pharmaceutical products (traceability), and protection against tampering. Additionally, aspects related to implementation costs and the practical limitations of each solution in the context of modern security requirements in pharmaceutical supply chains were also considered.

Table 1. *Comparison of blockchain technology, traditional archiving systems, and ERP systems in terms of data integrity and process transparency.*

Evaluation Criteria	**Traditional Archiving Systems**	**ERP Systems**	**Blockchain (SHA-256)**
Immutability and Transparency	Data is susceptible to modifications and damage.	Data can be modified by authorized users in the system.	Data remains immutable due to cryptographic protections, e.g., SHA-256.
Tracking the Origin of Medicines	Manual tracking of processes increases the risk of errors.	Tracking depends on the quality of data integration.	Complete backward tracking with unique identifiers for each product.
Protection Against Tampering	Lack of integrity verification mechanisms.	Data can be modified by users with administrative access.	Cryptographic mechanisms prevent unauthorized data changes.
Implementation Costs	Low costs, but limited functionality.	Variable costs depending on the range of functions.	Relatively high initial implementation costs for the technology.

Source: *Own study.*

Traditional archiving systems, although easy to implement, are highly susceptible to modifications and damage. The lack of integrity verification mechanisms and difficulties in verifying changes further increase the risk of data manipulation, limiting their effectiveness in combating counterfeiting.

ERP systems perform complex transactional operations, process multidimensional data, and support decision-making processes based on advanced analysis of available information. However, their performance is largely dependent on the quality of the data entered and processed (Koh, Gunasekaran and Goodman, 2011) Despite a centralized database, these systems allow for data modification by users with appropriate permissions, which may lead to errors and abuse, thus limiting process transparency.

Although audit tools are provided, their effectiveness is dependent on the proper configuration and integration of the system within the organization (Salur and Kattar, 2021). The distribution history, recorded immutably from the point of production to the sales point, enables the rapid recall of defective batches and intervention in case of violations of established conditions. In systems such as ERP, process tracking is limited to the organization level and often does not include full automation of data generated at different levels by supply chain participants.

The diversity of systems used by individual partners and errors arising from data integration between modules or the lack of data integration between separate systems further complicates the verification of key parameters, such as origin, temperature, humidity, or storage time. In this context, blockchain stands out as a solution that allows for consistent, immutable, and automated data recording, independent of the use of diverse systems.

Blockchain technology, through the application of the cryptographic algorithm SHA-256, ensures the immutability of data. The distributed architecture of the system eliminates a central control point, providing transparency for all authorized participants in the network. All transactions are irreversibly recorded and visible, preventing any modification, deletion, or replacement of data.

The cryptographic signatures used in blockchain technology effectively prevent unauthorized data modification. Compared to traditional systems, blockchain stands out for its ability to ensure data integrity and process transparency, making it an effective tool in combating counterfeiting in pharmaceutical supply chains.

5. Technologies Supporting Transparency in Supply Chains

Ensuring the integrity of pharmaceutical supply chains requires the use of advanced technologies that enable precise monitoring of the flow of goods and information. Tools such as blockchain, RFID, data analysis systems, and enterprise resource planning (ERP) systems play a crucial role in minimizing the risks of counterfeiting and unethical practices. Additionally, IoT technologies, smart pallets, and QR codes provide real-time access to data on the location and condition of products, significantly enhancing both supply chain control and operational efficiency. In the pharmaceutical industry, which is characterized by exceptionally high standards of quality and safety, management tools such as ERP systems, databases, and traditional paper-based documentation are also crucial.

ERP systems integrate key processes, enabling effective resource management and monitoring the flow of information, while databases ensure precise storage and quick access to critical information. Despite technological advancements, paper documentation still plays an important role in meeting regulatory requirements and ensuring the ability to audit actions throughout the supply chain (Guide to Quality Audits, 2024). The integration of these tools with traditional mechanisms, such as audits and multilateral initiatives, supports collaboration between various stakeholders and strengthens the foundation of transparency in global pharmaceutical supply chains. This transparency enables compliance with regulatory requirements, builds trust among partners, and enhances the competitiveness of businesses in international markets.

6. Blockchain Technology as a Solution

Blockchain is defined as a database technology based on a distributed ledger system, maintained across a computer network. Entries in this ledger, called "blocks" are linked chronologically, creating a secure and immutable chain. The foundation of blockchain's operation is public key cryptography, which ensures the security and transparency of transactions. Users possess a pair of cryptographic keys: a public key, visible to all participants, and a private key, stored only on the user's device.

During a logistics transaction, the supplier provides the recipient with the public key, which is used to confirm the authenticity of data related to the shipment. Blockchain technology, with its transparency, decentralization, and immutability of records, offers a promising solution to these issues. Blockchain enables full traceability of the flow of medicines, which significantly enhances the effectiveness of combating counterfeiting and streamlines the process of monitoring key storage parameters, such as temperature and humidity.

Blockchain is a dynamically developing technology that is increasingly being applied in logistics. This technology uses consensus mechanisms, such as Proof of Work (PoW) and Proof of Authority (PoA), as well as cryptographic algorithms like SHA-256, which ensure the security of transactions and stored data, and also support the monitoring of transportation conditions (Aleksieva *et al.,* 2024). Ethereum is one of the most widely used blockchains, which supports smart contracts (Kushwaha *et al.,* 2022).

In logistics, it is used to create applications that enable transparent, secure, and automated management of supply chain data. Ethereum allows for tracking transactions and the provenance of products, monitoring the flow of goods, and automating contracts through smart contracts (Alqarni *et al.*, 2023). Hyperledger Fabric, a "permissioned" blockchain, has been designed with business applications in mind, particularly in supply chain management, where access control to data and transaction privacy are crucial. It enables collaboration among multiple organizations within a single supply chain, ensuring secure and confidential information exchange (Capocasale *et al.*, 2021).

IOTA is a blockchain platform designed for integration with Internet of Things (IoT) devices (Khrais, 2020). In logistics, IOTA allows for the automatic collection of data from sensors, such as those monitoring transportation conditions, and records this data on the blockchain in a transparent manner (Lin *et al.,* 2023). It is particularly useful in real-time data management, such as monitoring the transportation of products that require specific storage conditions, such as medicines or food. The integration of blockchain with IoT devices allows for the automatic logging of real-time data, eliminating the risk of human errors and tampering. This technology can significantly improve regulatory compliance, enhance patient safety, and contribute to the development of more trusted and efficient pharmaceutical supply chains.

Blockchain, due to its decentralized structure and built-in resistance to manipulation, has the potential to become a key technology in logistics, particularly in tracking the provenance of products and managing supply chains. Technologies such as Ethereum, Hyperledger Fabric, and IOTA support supply chain management by enhancing transparency, automating processes, and ensuring precise control over data. In addition, these technologies enable continuous monitoring of goods and data flow, ensuring security, regulatory compliance, and operational efficiency.

One of the crucial cryptographic mechanisms used in these systems is the SHA (Secure Hash Algorithm) algorithm (Rana *et al.*, 2022). Its function is to create unique hashes for data stored in the blockchain, ensuring their immutability and resistance to tampering. In the context of logistics, the use of the SHA algorithm in blockchain enables precise real-time monitoring of products, eliminating the risk of counterfeiting and fraud, thereby ensuring full transparency throughout the supply chain.

7. Application of the SHA-256 Algorithm in Ensuring Data Integrity in Pharmaceutical Supply Chains

SHA-256, or Secure Hash Algorithm 256-bit, is a cryptographic algorithm used to generate what is known as "fingerprints" of data. Its main function is to transform any type of information, such as product data, temperature, location, or shipment status, into a unique string of characters known as a "hash". Thanks to this feature, SHA-256 can ensure the security and integrity of data, which is particularly important in the context of supply chains, especially in the pharmaceutical sector.

The fundamental feature of the SHA-256 algorithm is its ability to detect any manipulations in the data. The hashing process creates a unique string of characters that is associated with the input data. Even the smallest change in the data (e.g., a temperature change that does not meet the required pharmaceutical storage conditions) leads to a complete alteration of the generated "fingerprint". As a result, any deviation from the original data causes a mismatch in the generated string, which is easily detected and serves as evidence of potential manipulation.

In the context of pharmaceutical logistics, the SHA-256 algorithm can play a critical role in ensuring the integrity and security of data collected by Internet of Things (IoT) devices. An example of such an application is sensors that monitor the transportation conditions of pharmaceutical products, such as temperature sensors, which log these parameters in real time. The data collected in this way is then subjected to the hashing process using the SHA-256 algorithm, ensuring its unique traceability and enabling its recording in a blockchain.

This allows for the assurance of data security and transparency, as well as resistance to manipulation. Similarly, product-related data, such as batch numbers, manufacturers, or stages of movement in the supply chain, can be secured in the same way. The process of generating unique identifiers for each product batch using the SHA-256 algorithm ensures data integrity at every stage of the supply chain.

Any change in product information, such as its location or inventory status, triggers the generation of a new, unique identifier that is recorded in the distributed system.

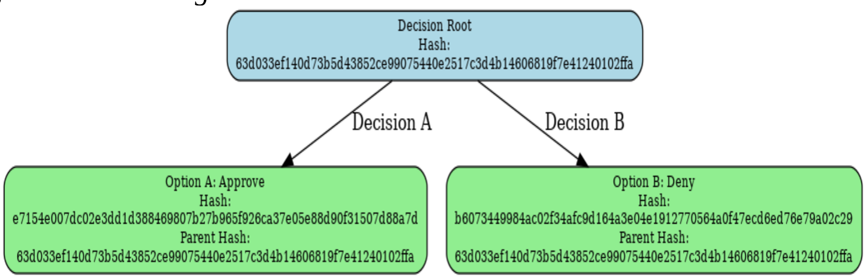
This mechanism eliminates the risk of data manipulation and ensures full traceability, allowing for easy verification of the authenticity and origin of products at every stage of their movement. The Python function that generates a unique block hash identifier in the program created by the authors of the publication is presented below. The function generates a hash code based on the index and creation time of the new block, the data contained in it and the hash identifier of the preceding block:

```
import hashlib
class Block:
# …
    def calculate_hash(self):
        block_string=f"{self.index}{self.timestamp}{self.data}{self.previous_hash}"
        return hashlib.sha256(block_string.encode()).hexdigest()
```

The use of blockchain technology to store data processing results provides an additional level of security, as the data recorded in the blockchain is immutable. This enables manufacturers, distributors, and pharmacies to verify whether a pharmaceutical product has been stored and transported under the appropriate conditions, with any changes in the data being immediately detected. This functionality is particularly important in preventing counterfeiting and ensuring the authenticity of products.

By utilizing the SHA-256 algorithm, logistics systems can also eliminate the risk of data manipulation, such as falsifying storage temperature or altering the origin and location of a shipment. Even if data is altered, a change in the hash value immediately detects the manipulation, allowing for prompt corrective action. In this way, SHA-256 plays a crucial role in ensuring data integrity and monitoring safety at every stage of logistics processes, supporting transparency and control in pharmaceutical supply chains. Figure 1 illustrates the decision tree structure, where data integrity is secured using the SHA-256 cryptographic algorithm.

Figure 1. *Mechanism for Data Integrity Verification in a Decision Tree Structure Using the SHA-256 Algorithm.*



Source: *Own study.*

This design is employed in systems that require reliable data integrity verification. The root node represents the top level of the decision tree structure. It contains data and a hash value that is generated from this data. This hash is cryptographically immutable, meaning that any modification of the data in the node will be immediately detected.

Additionally, the root node's hash serves as the reference point for the child nodes, enabling verification of the entire tree's integrity. The leaf nodes (Option A and Option B) represent possible choices or decisions in the decision structure. Each leaf node contains decision data such as "Option A: Approve," a hash value generated from the node's data, and a reference to the parent node's hash value (Root). This mechanism allows for the verification of the entire tree's integrity by comparing the hash values between child and parent nodes, enabling the prompt detection of unauthorized modifications.

Data integrity is ensured through the use of the SHA-256 algorithm, which guarantees that even the smallest change in data within a node will result in a new hash value. This allows the system to immediately detect any potential data integrity violations at any level of the tree, providing high reliability and security for the structure.

8. Simulations

Key information about the blocks in the blockchain was included in Table 2, which presents data such as block name, index, timestamp, product details, location, authorization status, and shortened hashes (the last 8 characters from the 26-character hash generated each time). The analysis results involved evaluating the effectiveness of violation detection, assessing process execution times, and examining the potential for practical integration with IoT devices. The simulations confirmed the effectiveness of the SHA-256 algorithm and demonstrated that blockchain can effectively support transparency and security in pharmaceutical supply chains.

Table 2. *Blockchain Block Data in the Pharmaceutical Supply Chain*

block_name	**index**	**timestamp**	**product_id**	**product_name**	**product_type**	**temperature**	**country**	**location**	**authorized**	**hash_last_8**	**previous_hash_last_8**
Block 0 (Genesis Block)	0	2024-12-07 17:32:15							N/A	c40688ba	0
Block 1	1	2024-12-07 17:32:15	100	Ha gen H	Cold Chain	5C	Country 1	Warehouse	True	f6aa0b6b	c40688ba
Block 2	2	2024-12-07 17:32:15	101	Painkiller C	Cold Chain	***6C***	Country 1	Warehouse	***False***	***75fa2f05***	f6aa0b6b

Block 3	3	2024-12-07 17:32:15	102	Painkiller C	Standard	5C	Country 1	Warehouse	True	196bb8dc	***ea16c780***
Block 4	4	2024-12-07 17:32:15	103	Medicine A	Standard	5C	Country 1	Warehouse	True	ee93133d	196bb8dc
Block 5	5	2024-12-07 17:32:15	104	Opioid J	Cold Chain	5C	Country 1	Warehouse	True	3e2f701d	ee93133d
Block 6	6	2024-12-07 17:32:15	100	Ha gen H	Cold Chain	***10C***	Country 2	Transport	***False***	322db7cd	3e2f701d
Block 7	7	2024-12-07 17:32:15	101	Painkiller C	Cold Chain	5C	Country 2	Transport	True	4a7aa86e	322db7cd
Block 8	8	2024-12-07 17:32:15	102	Painkiller C	Cold Chain	5C	Country 2	Transport	True	32dbb6e9	4a7aa86e
Block 9	9	2024-12-07 17:32:15	103	Medicine A	Cold Chain	5C	Country 2	Transport	True	ced8bb43	32dbb6e9
Block 10	10	2024-12-07 17:32:15	104	Opioid J	Cold Chain	5C	Country 2	Transport	True	df87ac1f	ced8bb43
Block 11	11	2024-12-07 17:32:15	100	Ha gen H	Cold Chain	5C	Country Destination	Pharmacy	True	e85510c6	df87ac1f
Block 12	12	2024-12-07 17:32:15	101	Painkiller C	Cold Chain	5C	Country Destination	Pharmacy	True	3a0421c1	e85510c6
Block 13	13	2024-12-07 17:32:15	102	Painkiller C	Standard	5C	Country Destination	Pharmacy	True	1bc8ff17	3a0421c1
Block 14	14	2024-12-07 17:32:15	103	Medicine A	Standard	5C	Country Destination	Pharmacy	True	f46c101b	1bc8ff17
Block 15	15	2024-12-07 17:32:15	104	Opioid J	Cold Chain	5C	Country Destination	Pharmacy	True	c928af89	f46c101b
Block 16	16	2024-12-07 17:32:15	***Fake001***	Counterfeit Medicine	Standard	N/A	Country 3	Pharmacy	***False***	0f1e5c24	c928af89
Block 17	17	2024-12-07 17:32:15	100	Ha gen H	Cold Chain	5C	Country Destination	Pharmacy	True	d8aa68de	0f1e5c24
Block 18	18	2024-12-07	101	Painkiller C	Cold Chain	5C	Country	Pharmac	True	54f4d1df	d8aa68de

		17:32:15					Destination	y			
Block 19	19	2024-12-07 17:32:15	102	Painkiller C	Standard	5C	Country Destination	Pharmacy	True	cdc154ea	54f4d1df
Block 20	20	2024-12-07 17:32:15	103	Medicine A	Standard	5C	Country Destination	Pharmacy	True	bf47497d	cdc154ea

Source: *Own study*

8.1 Falsifying Delivery Documentation

The first simulation test involved falsifying the documentation of the storage conditions of pharmaceutical products. A scenario was simulated in which one participant in the supply chain entered incorrect data regarding the transport temperature of a product requiring refrigeration. The blockchain system recorded the correct storage parameters at each stage of transport. Subsequently, at a later stage, the data in an earlier block was intentionally modified. In the system, when data in one block (e.g., temperature) is changed, the hash of that block is altered, causing an inconsistency with the hashes stored in the subsequent blocks.

 # Simulate tampering
blockchain.chain[2].data["temperature"] = "6C"

The analysis of the results showed that the "*authorized*" field for the given block was marked as false, and the columns "*hash_last_8*" and "*previous_hash_last_8*" revealed an inconsistency. The difference between the current hash's last 8 characters and the previous one confirmed an attempted manipulation. This demonstrates that blockchain effectively detects unauthorized changes in the data, which is crucial for maintaining the integrity of information throughout the system.

8.2 Disruptions in the Cold Chain Supply

The second test focused on the breach of requirements for storing products under controlled temperature conditions. A simulation was conducted for Cold Chain products, such as vaccines, which must be stored at temperatures not exceeding a specified threshold. At one stage, a failure in the refrigeration system was deliberately simulated, causing the temperature to rise to 10°C, which did not meet the required conditions.

The results showed that the "authorized" field for the block containing the event was set to "false," indicating the identification of the issue. Attention was also drawn to the data in the "temperature" column, which clearly demonstrated that the acceptable limits (5°C) for the given product type had been exceeded. Consequently, the system allowed for precise identification of the time and location of the breach in the supply chain, facilitating the prompt implementation of corrective actions.

8.3 Attempt to Insert Counterfeit Drugs

The final test aimed to verify the system's resilience against the introduction of unauthorized products into the supply chain. A simulation was conducted in which a batch of drugs, not previously authorized in the blockchain system, was added to the registry. The details of this simulation, including the product labeled as "Fake001," were provided in the results table.

The results showed that for the block containing data on the counterfeit drugs, the "authorized" field was set to "false," clearly indicating the detection of the issue. Furthermore, the columns "product_id" and "product_name" identified details related to the unauthorized product, which may be helpful in the process of verification and recall of non-compliant batches.

9. Summary of Results - Conclusions

The conducted simulations confirmed the effectiveness of blockchain technology in enhancing the transparency and security of pharmaceutical supply chains. In each of the three tests, the system demonstrated the ability to automatically and reliably identify and flag problematic data. As a result, this technology can significantly reduce the risk of document falsification, violations of storage conditions, and the circulation of unauthorized products.

These results confirm that blockchain is a promising tool for improving the quality of pharmaceutical supply chain management. Implementing such a solution on a larger scale could contribute to increased trust among both market participants and patients, who would receive safe and compliant products.

Further research on the use of blockchain technology in pharmaceutical supply chain management could involve its integration with technologies such as artificial intelligence, big data, and advanced process automation, which would further enhance the security and efficiency of these systems.

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