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Research Article

BLOCKCHAIN-POWERED ACCOUNTABILITY IN PHARMACEUTICAL SUPPLY CHAINS

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Abstract

A healthcare supply chain is made when an organization and businesses work together to increase and manage supply related to healthcare products, equipment, and drugs for the patients' lives. The complexity of these networks can make it challenging to circulate healthcare supplies. This is because their structure is not transparent, and they are involved in unauthorized pharmaceutical activities. Technology can improve the pharmaceutical supply chain sector by increasing transparency and establishing oversight mechanisms. Integrating technology can strengthen drug traceability and security measures, enhancing safety and system efficiency. The objective is to leverage technology solutions to implement traceability methods for drug distribution. In addition, we employ sophisticated tools to incorporate blockchain technology into the pharmaceutical supply chain seamlessly. Through rigorous experimentation, our methodology enhances transparency, accountability, and security across pharmaceutical supply chains. The results of our study highlight the significant impact of blockchain technology in addressing critical challenges within the pharmaceutical industry. Our research contributes to theoretical knowledge and practical implications, paving the way for the transformation of pharmaceutical supply chains. This transformation will ensure the integrity and security of the entire system.

Keywords: Pharmaceutical supply chain (PSC); Blockchain; Drugs; Traceability.
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1. INTRODUCTION

Enlighten the experienced and associated aspects of The Pharmaceutical Supply Chain (PSC), encompassing many participants like industrialists, distributors, retailers, pharmacies, and health service providers. Figure 1 illustrates various interconnections of PSC components. However, the economic strength of pharmaceutical industries and patient safety endangers are severely affected by the intimidation of counterfeit drugs, which is a significant challenge PSC faces (Reinhardt et al., 2020). Moreover, the competence and efficacy of the supply chain are facing hurdles due to many factors like pricing pressure, regulatory hindrances, and drug shortages. Blockchain is a valuable solution for stakeholders to combat such hindering issues and to stand parallel in this rapidly growing technological era (Xu et al., 2020). However, despite healthcare supply chains encountering several challenges regarding corruption, fake drugs, and drug seepage just because of unsatisfactory transparency and management procedures, they participate actively part in supplying life-saving medications to the public. Counterfeit drugs account for a considerable fraction of remedies disbursed in developing countries, highlighting the necessity for better quality and authentication processes (Uddin at al., 2021).

Globally, drug production is encountering a serious challenge: the shortage of transparency and liability in its complex supply chain. The journey of pharmaceuticals from production to consumption is immensely trashed by offering a transparent and immutable solution, which is why blockchain technology distracts the status quo. The pharmaceutical industry is a crucial component of the healthcare ecosystem, incorporating pharmaceutical products' production, dispersal, and consumption (Sinclair et al., 2019). The prevalence of counterfeit drugs, unsuccessful tracing of products, and inefficient stock management are some of the challenges the industry faces. However, it is crucial in ensuring patient safety and well-being (Alzahraniet al., 2018). Such challenges threaten patient safety and destabilize the pharmaceutical industry's confidence and reliability, posing considerable commercial damages for the pharma industry (Toorajipour et al., 2022). The pharmaceutical industry is a vital sector with a prominent impact on public health. Despite considerable innovations in drug distribution systems over the past few decades, there is still a need to strengthen market forces concerning medication authentication, availability, and real-time management (Blaettchen et al., 2024). The lack of a consolidated managing structure constructs cracks that may be a reason for organizational inadequacies and marketplace disasters (Siyal et al., 2019). There has been cumulative awareness in developing skills to discourse such concerns and augment the traceability of medications throughout the supply chain. Blockchain technology has gathered substantial consideration as a transformative solution in various domains. Meanwhile, Blockchain has prolonged its prospect, illustrative widespread presentations elsewhere in cardinal exchanges, initially aided by the introductory expertise behind cryptocurrencies like Bitcoin (Alharthi et al., 2020).

Several productions, comprising pharmaceuticals, emerged as a better solution, as represented by the advent of blockchain technology, which is notorious for its success with Bitcoin. On behalf of addressing PSC challenges, Blockchain's disseminated record structure offers clearness, safety, and tamper-proof records, making it a perfect choice (Sarkar, 2022). It renders the finest option for improving information control and discussion within businesses, and its devolved and transparent nature, encouraged by cryptography, warrants damage resistance and immutability. The connotation of blockchain lies in its capacity to revolutionize traditional record-keeping methods. Its prompt, transparent, and accurate capabilities surpass conventional approaches, while its permissioned network structure safeguards confidential information, limiting access to authorized members (Koberg et al., 2019). By leveraging blockchain's decentralized and transparent nature, our goal is to construct a tamper-proof system that qualifies for end-to-end traceability, confirming the legitimacy and security of pharmaceutical products. The study's primary purpose is to investigate prevailing challenges inside the supply chain, the implications, adoption challenges, restrictions of traditional traceability methods, and potential future developments associated with assimilating blockchain technology (Lingayat et al., 2021).

The current solutions for pharmaceutical PSCs are overwhelmed by a deficiency of transparency, resulting in inefficiencies and insecurity about drug authenticity and security. This leads to the prevalence of drug counterfeiting, alteration, and black-marketing of medicines. Blockchain deals with recent efficacies and prospects by making records and locating perilous business information, like production, payments, transactions, and accounts. Profound perceptions are in the industry set-ups, up-to-date judgments, and construct trust among clients, contractors, and partners. Promoting transparency, confidence, and reliability and eventually strengthening the whole pharmaceutical network can be done by implementing blockchain technology in the PSC. The primary purpose of this research is to explore the perspective regarding blockchain technology in addressing the accountability tasks inside the PSC:

- Suggest an innovative PSC model that uses blockchain technology to overcome prevailing restrictions.
- By intending and employing a model to manage and control the PSC.
- It estimated the suggested model by consuming real-world data from a counterfeit Pharma supply chain and assessing its efficiency and precision.

The influence of the said study bounces elsewhere the limitations faced by the pharmaceutical sector, edging the broader setting of supply chain management and its safety. By presenting the perspective related to blockchain technology through hybrid architectures, cryptographic procedures, and compromised devices, the prevailing study is capable of providing precious visions to investors pursuing optimal traceability, enhance working effectiveness and security improvement. The said research unwraps opportunities, a revolutionary period of flexibility, modernization, and justifiable performance through its widespread consideration.

2. Review of Literature

Initially popularized as the underlying technology for cryptocurrencies like Bitcoin, blockchain technology has rapidly emerged as a transformative force in various industries, including healthcare. In recent years, researchers, healthcare providers, and technology companies have explored the potential applications of blockchain in healthcare to address critical challenges, such as interoperability, data security, and patient privacy. This part presents a comprehensive examination of current research and developments related to the execution of blockchain technology in the healthcare industry.

A study by (Wu et al., 2017) proposed a design that combines private distributed ledgers with a single block-chain public ledger. Private ledgers enable the traders involved in a shipment to share custody events confidentially. When we deal with higher products like chemicals and drugs, our main focus is only on privacy because it's on top. The objective is to create a model for data and access control regulations in the drug supply chain. They have found that this technique provides an opportunity for compliance verification through prototyping, although it has some limitations.

In a study by (Zhu et al., 2020) the proposal to use technology to monitor medication along the supply chain to prevent counterfeit products was put forward. This method ensures transparency and integrity in the supply chain by leveraging the blockchain's tamper-proof characteristics, traceability, and collaborative node maintenance. With the help of contracts, access control measures safeguard the confidentiality and security of data within the blockchain network. Additionally, a point accumulation system is implemented to enhance the consensus mechanism. This proposed solution eliminates the need for centralized institutions and third-party organizations, providing a complete record of the pharmaceutical circulation process. The simulation results indicate that the enhancements to the consensus technique and access control mechanism improve efficiency and security. The work of (Ding et al.,2019) Presented a permissioned blockchain-based traceability of goods system that employs a double-layer structure to overcome scalability and performance problems with blockchain-based product traceability platforms. The study by (Ma et al.,2020) proposed an anti-counterfeit identification solution for small and medium-sized enterprises (SMEs) in

PSC by using an architecture for blockchain provided by Ethereum to track the ownership of products.

Data integrity and drug traceability are crucial parts of PSC management. By allowing end-to-end drug tracking, blockchain has shown interest in this field. The work of (Liu et al.,2021) introduced a five-layer Blockchain and Internet of Things-based intelligent tracking and tracing system (BIoT3) that would allow different parts of the medication supply chain to be tracked without a central authority. Following the five-layer blockchain platform architecture, a workable plan is given for the drug industry to create, develop, use, and evaluate blockchain. On-chain and off-chain methods, IoT-based medicine identity management, and intelligent contract-enabled drug services are three crucial factors that make this possible. Using actual data from partner companies, the Hyperledger Fabric blockchain has been used to prove that the BIoT3 technology works and can be used. The case study provides valuable insights into optimizing blockchain performance by setting transaction sizes and proposes a blockchain-based drug tracking and monitoring solution. The study by (Musamih et al., 2021) demonstrated utilizing Ethereum block-chain intelligent contracts and shared off-chain storage to streamline tracking goods in the healthcare supply chain. The smart contract ensures that data originates from reliable sources, eliminates the need for intermediaries, and provides a safe, immutable record of all transactions to all parties involved.

The work of (Mezquita et al., 2023) presented an approach focusing on excellent compatibility for enhanced information accuracy and openness in the pharmaceutical industry when managing goods across different blockchain-based supply chain systems.

The study by (Turki et al., 2023) provided an open-source drug tracing system that uses intelligent agreements and IoT devices. Non-fungible tokens (NFTs) guarantee the security and authenticity of information. Through effectively managing access for users, their approach improves privacy and transparency across the PSC.

This paper's Review of Literature part presents an in-depth review of blockchain applications in the healthcare industry. Hence, the significant issue of traceability in the pharmaceutical industry doesn't seem adequately addressed in the available literature. In particular, the current study lacks pharmaceutical product tracking from industrial sources to end customers, allowing users to validate the authenticity of drugs while getting real-time spatial information. Additionally, there is an apparent absence of proposed methods that enable pharmaceutical businesses to track and control the manufacturing of drugs, including every step from acquiring initial supplies to drug delivery. This study aims to address the limitations of current models by providing a revolutionary approach that ensures transparency and traceability of pharmaceutical products throughout their lifecycle. The recommended strategy has significant implications for the security and effectiveness of the pharmaceutical industry and aims to improve the accuracy, safety, and trust in PSC.

3. Materials and Methods

In the experimentation, all aspects were geared to respond to the concerns in the research questions. They include the structural experiment design, data collection methods, and implementation of blockchain technology. Therefore, the above sections elaborate on how traceability issues in the drug supply chain can be addressed.

3.1. Pharmaceutical Supply Chain Sector

As an integral component of the healthcare system, the pharmaceutical industry fulfils a unique function through research, innovation, and the production of necessary medical treatment. By contributing to the complex process of drug discovery, implementation, and dispersion, pharmaceuticals are indispensable for preserving the health of the population at large, as well as promoting medical science (Sunny et al., 2020). Defining supply chain management these are the strategic coordination process of sourcing, creating, and delivering products (Nazam et al., 2022). The pharmaceutical supply chain carefully harmonizes raw material sourcing, manufacturing, quality assurance, packaging, and distribution networks. Pharmaceutical supply chain management has numerous elements that support the availability of drugs while complying with rigorous regulations. The pharmaceutical industry's supply chain comprises manufacturers, wholesalers, brokers, healthcare providers, and drug regulating authorities. This complex framework fosters the streamlined delivery of medicines from the source to the end-user (Pettit et al., 2019). Effectively managing this complex network is critical to maintaining the integrity of products, meeting patient needs, and adhering to industry regulations. This is a transformative phase for pharmaceutical supply chain management as the industry is at a crossroads as blockchain technology converges with it. Blockchain's key characteristics, such as transparency, immutability, and cryptographic security, transform how integrity and traceability are managed. Combined with the ability to share real-time data and a consensus mechanism that creates an unchangeable record among all stakeholders, these technologies take PSCM to new levels of security, performance, and compliance (Lingayat et al., 2021). An industry evolution that offers increased protection against counterfeit drugs, improved regulatory compliance, and better collaboration among different stakeholders.

3.2. Architecture of the System

The model is based on a blockchain system that is highly implementable and scalable with a proper, well-defined structure, which overcomes some of the limitations of traditional blockchain implementations. The system architecture of the blockchain as it appears in the model is designed as follows:

Nodes: The model displays nodes that are individual constituents of the blockchain network. Each node is responsible for having a copy of the blockchain and engaging in the validation and consensus protocols. The nodes interact via a peer-to-peer network, where they exchange details of transactions, blocking, and other meaningful info. The model includes methods to create and supervise notes, manage network interaction, and synchronise blockchain.

Blocks: A block is a container for several transactions that work as a unit in the blockchain. Blocks are the structural components that make up the Blockchain. Every block is connected to the previous block through its hash, making it a chain link in an immutable sequence. This model introduces a block consisting of transaction data, timestamps, and block numbers; several functions are used as metadata to link blocks together as a blockchain, such as checking if a block is valid or adding append Rights to cease to exist blocks.

Transactions: Transactions are primarily the operations carried out in the blockchain system. Types of data included in a transaction are referred to as financial transactions, intelligent contract interactions, or any other activity deemed relevant, depending on the blockchain application. Regarding the model, the transaction will have the sender, receiver, transaction amount, digital signatures, and other additional information relative to the blockchain application. The model will also have functions for validating transactions and storing them.

Validators: Validators ensure the accuracy and validity of transactions and the agreement within the blockchain. They confirm incoming transactions by verifying they meet specific requirements established by the consensus model, including provisions such as digital signatures and the capacity to do so. A validator suggests blocks to be added to the chain based on validated transactions. It is based on the Proof of Stake mechanism, which lets validators compete. They must buy and lock tokens before participating in the Play-to-earn ecosystem.

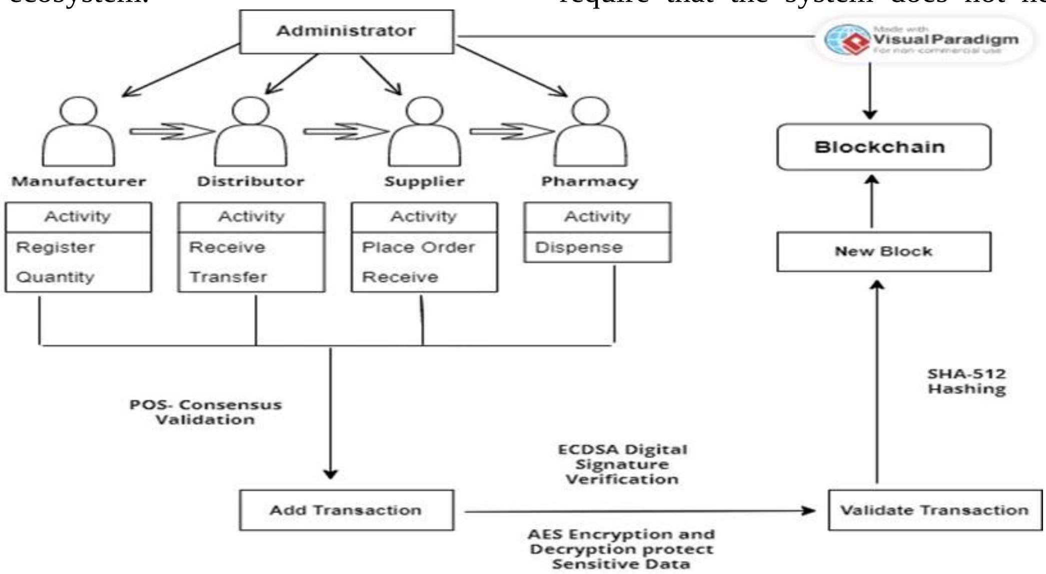

Figure 1. Architecture of the proposed model

3.3. Proposed Model

Traceability is a pivotal concept within the pharmaceutical supply chain, involving the possibility of tracking and authenticating drugs from manufacturing to the patient. This approach guarantees the authenticity of the provided drugs, optimization of quality management, and readiness to react to re-calls and problematic products on time. The proposed model is a unique approach to the problem and a groundbreaking initiative. The model is a set of cutting-edge technologies and algorithms that upgrade traceability and monitoring of the medicine flow in the supply chain. This way, pharmaceutical logistics can be modified, resulting in increased patient safety and more compliance with the laws for manufacturers and distributors.

3.4. Public Blockchain Elements

In this study, the following elements from public blockchains were incorporated into our framework to promote the reliability of the system: The Components above were selected to benefit from the high level of security and transparency provided by public blockchains. This improves the overall integrity of the research.

Open Node Participation: Any system that meets the criteria for nodes to participate in block creation and validation. This may require that the system does not need a system operated by a company, such as public blockchains.

Transparency: Generally, public blockchains are famous for their high level of transparency. All transaction data that connects to the network is available to each user. A public blockchain allows everyone access to the transaction history. That includes details such as the sender, the recipient, and the quantity of a transaction made by the parties involved.

Public Key Cryptography: All participants have public and private keys in public blockchains. The former is used to sign transactions, which can later be verified using the public key. Therefore, one of the goals of a public blockchain is to ensure that a transaction has occurred between the parties, that it is valid, and that it has not been altered.

Shared blockchain structure: Blockchain infrastructure is shared among everyone in public blockchains. Each node maintains its version of the entire blockchain, which is ultimately agreed upon and updated through the consensus mechanism. This achieves the objective of all entities having the exact copy of the truth.

Private Blockchain elements: Private Blockchain elements were integrated within the system to secure access and privacy of sensitive information. Private blockchains utilize permissioned blockchains, which allowed the research to restrict the network to only authorized participants while retaining the blockchain's virtues of security and integrity. The following are the possible key constituents:

- Restricted Validators
- Permissioned Transactions
- Controlled Access-Menu Driven

Restricted Validators: Private Blockchains have predefined validators responsible for validating transactions and creating new blocks. Validators are selected in advance, usually by invitation of the controlling body or consortium.

Permissioned Transactions: In private blockchains, transactions need permission to access the network before conducting the transaction. This permission approach guaranteed that only permitted organizations could transact and access blockchain data.

Controlled Access-menu Driven: Private blockchains deal with menu-driven access. A menu-driven system provides access and regulates the participants and features accessed.

3.5. Experimental setup

This section presents the deployment of a novel proof-of-concept PSC model inspired by blockchain. The model aims to demonstrate the approach's feasibility by testing it on a sample dataset of drugs, with the records of transactions added and stored on the blockchain to ensure traceability and transparency. As a result, the following performance measures, transaction processing speed, and data accuracy are used to monitor the blockchain system's applicability and efficacy. This research proposes an extended experimental setup, including actual PSC use cases, and employs more significant performance measures to assess the system's impact more accurately. The system was developed on a PyCharm integrated development environment and programmed using Python. The presented model helps reduce the risks associated with counterfeit drugs, prevent product integrity, and enhance the PSC's overall efficiency and dependability.

4. Results Discussion

This section offers an in-depth analysis and interpretation of the results to satisfy the research goals. Thus, the outcomes of data analysis, experiments, or other research approaches are presented in a structured manner and supplemented with relevant figures. Furthermore, the analysis chapter suggests a discussion and comparison of the results based on the literature and theoretical basis to identify any existing patterns, trends, or possible interpretations.

4.1. Pharmaceuticals manufacturers

Pharmaceutical manufacturers are the architects of modern healthcare, designing, manufacturing, and delivering the life-saving medications integral to maintaining patient health. These industry players conduct complex research using groundbreaking technologies to create new and exciting drugs to treat various health conditions. By adhering to product-based regulatory standards, pharmaceutical manufacturers keep their products safe, effective, and of high quality, positively impacting global public health. Their supply chain complexity and quality control practices are evidence of their dedication to offering safe and effective medication to individuals worldwide (Chien et al., 2020).

Distributors are vital in the pharmaceutical chain, as they link manufacturers and end-users with the extensive network of medication flows. Using complicated logistics and supply chain coordination, these organizations help transport medications to pharmacies, hospitals, and other facilities as quickly as possible. Being regulated to protect the quality and authenticity of products, distributors also fulfill numerous inventory programs to minimize surplus and guarantee the needs of multiple facilities. Their role links production and access, significantly affecting the key delivery objective (Babu et al., 2022).

4.2. Blockchain-based PSC traceability assessment

Modern research demonstrates the efficiency of traceability implementation in a blockchain-based pharmaceutical supply chain. The seamless incorporation of blockchain in the system substantially improved transparency and accountability levels within the supply chain. The essence of the outcomes of the traceability introduction was the ability to trace and verify all drugs in circulation, significantly reducing the possibility of counterfeit drug production and counterfeit medicines in the market, thereby increasing patient safety. Below is an outline of the research results.

4.3. PSC Navigation Panel

After the user enters the validator credentials, the menu panel with the options presented for the user's selection appears. They are divided into various choices related to drug production, tracking, and blockchain viewing. The next step of the user's action is to enter the number of their choice, as presented in Figure 2 below.

```
------ Pharmaceutical Drug Supply Chain ------
1. Produce drugs
2. Ship drugs from manufacturer to distributor
3. Distribute drugs from distributor to pharmacies
4. Ship drugs from distributor to a specific pharmacy
5. Dispense drugs from a pharmacy
6. Track drug Transactions
7. Current Status of Raw Material Inventory
8. Drug Inventory Status
9. Display blockchain
10. Quit
```

Figure 2. Navigation panel.

4.4. Pharmaceutical Flow Optimization

Once drugs have been effectively added to the network, the system enables them to be transported from the manufacturer to a selected distributor. Notably, the respective record in the supply chain is updated to indicate which distributor has received the drugs accurately. The system stores critical information such as the manufacturer's name, the distributor's name, the shipment unit, and the shipment's timestamp. The supply chain records are later updated to accurately reflect the distribution of the same drugs from the distributor to the respective pharmaceuticals. The distributor's name, the respective pharmaceuticals' names, the number of drugs distributed to each one, and the distribution's timestamp are duly noted. The data stored is then added to the blockchain, thus creating a continued and transparent record of all drug transfers. In the event scenario that the distributor distributes the shipment directly to one of the pharmacies, excluding multiple-pharmacy distribution, the straightforward transfer from the distributor to the pharmacy is recorded.

Drugs are finally dispensed to patients at the pharmacy level. During this stage, the record should be updated as appropriately as possible to follow the drug distribution, starting from a particular pharmacy. The system captures the pharmacy's name, the patient's name, the drug's unique identifier, and the date and time the drug is dispensed. The information is securely stored, and the system maintains it and later records each as a transaction detail into the patient's account in the blockchain. The effectiveness of auditable and unchangeable records adds impetus to patient safety, adequate drug control, and non-violent regulatory compliance among healthcare institutions.

4.5. Tracking drug transactions

The system provides a feature that allows users to track a drug's movement by entering a unique identifier and the name of a specific drug. The system then retrieves information from supply chain records and provides users with a clear real-time history of the drug's movement, accurate to the transaction level. This system function allows users to see how the drug moves and the transactions regarding a specific product. As shown in Figure 3 above, the system enables users to follow the drug transaction quickly and move through the system, promoting transparency and accountability in the pharmaceutical supply chain. The blockchain system ensures that the drug tracking information is accurate and immutable; therefore, stakeholders will make informed decisions and increase the patient safety cycle through proper information on the drug manufacturer and distribution.

Table 1. Real-time status of drugs.

Raw Material Inventory				
Raw Materials	Total Quantity(KG)	Consumed Quantity(KG)	Remaining Quantity(KG)	Utilized in Drug
Acetic Anhydride	100	46	4	Aspirin
Isobutyl benzene	50	20	80	Ibuprofen
===Notification===				
The following materials need to be restocked:				
Acetic Anhydride				

4.6. Real-time Status of Raw Material Inventory

The real-time status of raw material inventory is crucial in determining how efficient and viable the supply chain process is. It will also determine the resources used in the drug-making process and the available resources. The model has a raw material inventory management system that helps monitor the resource quantity and availability. The inventory also has notification systems where when the specific resource amount is less than the required amount, it sends alerts to the system to ensure the stock is recovered before running out.

Table 1 gives the complete information on the raw material inventory, and the conclusion empowers the members to determine the procedure of the raw material, acquisition, production preparation, and resource allocation. The pharmaceutical supply chain can access the real-time status and the notification system to monitor and control future resources and prevent default, leading to limited resources and easy production. This provision ensures the efficient supply chain operation and orderly completion of the product.

4.7. Drug Inventory

Status monitoring of the drug inventory is equally vital to the efficient functioning of the PSC as it provides an insightful view. A comprehensive state of the drug inventory ensures that operations are seamless while providing invaluable insight to optimize the utilization of resources. Subsequently, it is a priority to monitor the quantity of the drug state to ensure a constant and consistent supply of the drug. In this regard, the function that makes this possible is also implemented to offer additional data on the different types of users that have been involved, the number of drugs transferred, the timestamp, the validating approver's name, and the remaining quantity of a unique drug that is available units after a transaction. Consequently, Table 2 on drug inventory status is presented to the concerned stakeholders so they can consult and keep a constant and organized drug supply, thereby implying the efficiency of the PSC.

4.8. Blockchain Services, the PSC

The blockchain serves as a secure, accountable ledger, recording a reliable summary by transaction and Dearborn running hash updates throughout the lifespan of the Pharmaceutical Supply Chain. This option allows details about the current state of affairs of the blockchain. It is feasible because the system shows relevant information about the blockchain, including the results of purchased stakes called records, the action on the fragments of and the name of the vested validators, and further needed information, as shown in Figure 4 below.

```
------ Blockchain Information ------
Block 1
Block Hash: b0397e90a9a1c1393d78f9677c2d825639587587552890 37f9a3de5e2030d6402c00b3736aabcf7365dd7033e013af15adaae
Previous Block Hash: 00000000000000000000000000000000
Validator: MARIAM
Validator Public Key: 7c7620ad7c4a25182292753b7a5e75254b77c0c806429acd5088de80d010a984aaf0752916ea4d2e60b409a6894
Signature: None
Transactions:
  Transaction 1
  Sender: GlaxoSmithKline Pakistan Limited
  Receiver: GlaxoSmithKline Pakistan Limited
  Drug Name: Aspirin
  Quantity: 100
  Tracking Info: TR101
  Timestamp: 2023-07-04 19:55:11
```

Figure 4. Displaying the blockchain

This functionality allows stakeholders in the pharmaceutical supply chain to achieve the integrity of the supply chain activity, the origin of the pharmaceutical, and the identification of authorized vested validators participating in maintaining the record, supporting trust and compliance.

4.9. Comparative Analysis

This research has examined the opportunity for blockchain technology to improve traceability in the Pharmaceutical Supply Chain. As part of analyzing the existing solutions, this research has evaluated their efficiency, security, and scalability. Examining several cryptographic algorithms and consensus mechanisms provides essential insights for stakeholders and market forces. This enables them to make informed decisions on deploying and begin using blockchain technology to create a safe and efficient traceability system. This research has recommended that the hybrid blockchain architecture is preferred over relying entirely on one architecture. This structure combines a public and private blockchain, guaranteeing usability and security (Alkhateeb et al., 2022).

The radical approach offers decentralization, scalability, and interoperability and also improves transparency, immutability, and the visibility of sensitive data, providing a wide possibility of building secure decentralized applications for organizations. When choosing a consensus mechanism, the paper gives the benefit of the doubt to the Proof of Stake algorithm. PoS is considered more energy-saving, does not require such computational power, and is environmentally friendly. In addition, it is more secure, allowing participants to attack the system economically. The criteria for forming a new block are beneficial for a wide area to include participants in maintaining stability, working rapidly with a large volume of transactions, and the perspective of the network (Nguyen et al., 2019). The above analysis shows that cryptographic algorithms are critical in securing blockchain networks due to security, confidentiality, and privacy. These are encryption-based algorithms designed to protect the original information.

Moreover, it enables authentication, digital signature, and identification confirmation. Users use these mechanisms to confirm their identities and prove their involvement in transactions. The SHA-512 method in the research model provides more robust

Table 2. Drug inventory status.

Tracking Data for Drug: Aspirin				
Validator ID	Receiver	Quantity	Remaining in hand	Timestamp
TR1000	GlaxoSmithKline Pakistan Ltd.	100	100	07/23/23 23:12:02
TR1098	Abbott Laboratories Pakistan	20	80	09/09/23 12:34:08
TR3897	Mujahid Pharmacy	10	70	23/12/23 09:12:12
TR2097	Care Pharmacy	5	65	23/06/23 09:12:12
TR1098	Noor	5	60	20/11/23 09:12:12
Total remaining Quantity for Aspirin: 60				

Table 3. Comparative analysis of ECCDSA and RSA Algorithm

Aspect	ECCDSA	RSA
Key Length	Shorter keys for equivalent security	Longer keys for equivalent security
Security	Generally considered more secure	Historically widely used and secure
Performance	Faster computation and more minor signatures	Slower computation and larger signatures
Key Generation	Faster key generation	Slower key generation
Signature Size	Smaller signatures	Larger signatures
Key Distribution	More efficient for constrained environments	Less efficient for constrained environments
Usage	Increasingly favoured in modern cryptography	Widespread usage, but now facing some limitations
Implementation	More complex to implement and deploy	Generally straightforward to implement

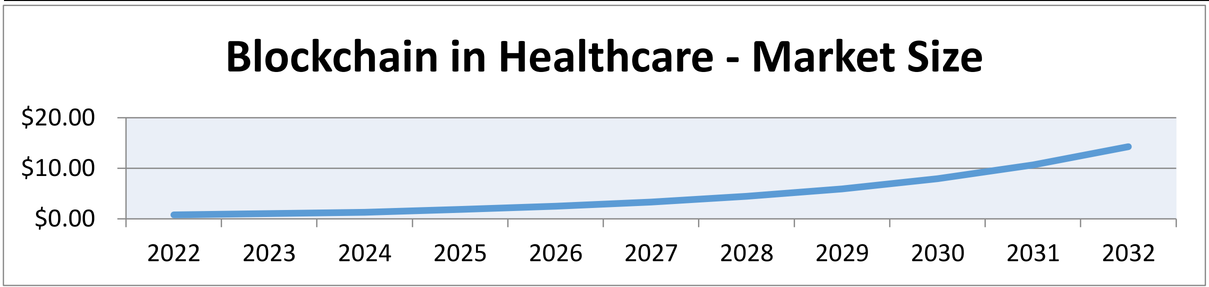

Figure 5. Global Market size- BCT in healthcare.

security and future-proofing against the common SHA-256. It offers better protection against breaches due to its extended 512-bit hash value, making it more difficult for intruders to cause collisions or tamper with the original information, thereby increasing the system's defence against future threats (Velmurugan et al., 2020). ECDSA is also the recommended cryptographic algorithm based on the analysis, especially for the high-performance domain. The study affirms that "ECDSA uses shorter key lengths than RSA to achieve a similar level of security" as shown in Table 3. The implication is that ECDSA ensures smaller signature sizes, which minimizes computational overhead and bandwidth and provides faster processing. Therefore, ECDSA is suitable for high-performance environments (Mehmood et al., 2021; Mehmood et al., 2024).

Regarding data encryption for transactions, AES is a secure symmetric encryption algorithm. AES guarantees confidentiality, is broadly implemented with vast consistency and support, and is computationally effective. In addition, AES is a dependable choice for secure communication and storage between the most suitable security, broad acceptance, and computational efficiency (Hidayat et al., 2021; Mehmood et al., 2023).

Blockchain has swept the healthcare sector, reinventing data security, interactivity, and openness. The recent blockchain industry in healthcare market size in 2022 was approximately USD 0.76 billion, with a commendable growth rate (Mahmood et al., 2019). The market size of the blockchain in Figure 5 below indicates the progression of market size throughout, with significant data points representing market sizes. The considerable increase from 2022 to 2032 implies a compounded annual growth rate of about 34.02 % over the projection period (Agbo et al., 2019).

In conclusion, this paper aligns with a fast-growing history of blockchain's revolutionary experiences in other fields. Addressing knowledge encompassing consensus mechanisms and cryptographic algorithms and encouraging hybrid blockchain structures, this workshop has a lengthy way of giving a preliminary grasp of medication traceability. With a sophomore breakthrough, further study and coordinated frameworks make our pharmaceutical business more challenging, precise, and user-friendly.

5. Conclusion

This study investigated how life-saving medications can be traced in the pharmaceutical supply chain and the impact of technology in overcoming obstacles. By utilizing a model based on technology, the research has demonstrated progress in improving transparency, accountability, and security within the pharmaceutical supply chain. The results highlight how blockchain technology plays a role in transforming the tracing of pharmaceuticals. By harnessing blockchain's nature, this model has significantly enhanced the trustworthiness and reliability of pharmaceutical supply chains. The improved tracking system boosts safety measures. It has benefits in combating counterfeit drugs while improving overall efficiency in healthcare systems.

Moreover, this research contributes insights into integrating technology within the pharmaceutical industry. The findings underscore technology applications in real-world scenarios, providing information for stakeholders involved in drug manufacturing, distribution and regulatory activities. While progress has been made in addressing tracking challenges through this study, it is essential to acknowledge its limitations. The study was conducted in the circumstances; more investigation is needed to evaluate scalability challenges, implementation obstacles and adaptability to healthcare systems. In essence, this research highlights the impact of blockchain on the pharmaceutical sector. The future directions of this research present an opportunity to transform the pharmaceutical supply chain through advancements. By incorporating entities' self-owned identities and blockchain AI-powered, effectiveness and trust can thrive. Tokenization and NFTs validate products, guarantee traceability, and safeguard transactions, introducing a robust pharmaceutical environment. These impending events hold the potential to invigorate the industry framework and pave the path for a resilient pharmaceutical ecosystem.

6. REFERENCESs

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