A Secure Tracking System to Prevent Counterfeit Drugs in the Pharmaceutical Supply Chain

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Abstract—**Counterfeit drugs represent a serious global risk, accounting for about 10% of the medicines worldwide. This percentage increases significantly in developing countries, reaching up to 30%, and has become a major cause of child mortality in these regions. Blockchain technology provides a good solution to address this critical issue through improving transparency and traceability of pharmaceuticals from manufacturers to end users. However, traditional blockchain applications face major challenges, particularly in terms of high costs and scalability especially when handling large volumes of data and transactions such as those found in the pharmaceutical supply chain. To address these limitations, researchers have introduced Layer 2 blockchain technologies, which operate on top of standard blockchain networks to improve scalability and reduce costs. This paper aims to design an efficient, secure, and scalable framework that can support traceability in pharmaceutical supply chains and contribute to reducing counterfeit drugs. This framework leverages Layer 2 blockchain solutions and combines Non-Fungible Tokens (NFTs) linked to Quick Response (QR) codes to provide unique identification for each drug. Furthermore, it incorporates the InterPlanetary File System (IPFS) for off-chain storage to reduce the amount of data stored directly on the blockchain. Additionally, an access control mechanism is incorporated to ensure the protection of sensitive data by limiting access based on predefined roles. This enhances privacy and reduces the risk of data leakage or misuse. In conclusion, this work provides the global scientific community with a secure and scalable framework that can be applied internationally to strengthen pharmaceutical supply chains and reduce the risks of counterfeit drugs.**

Keywords*—*Pharmaceutical supply chain; blockchain; access control; InterPlanetary File System (IPFS); Non-Fungible Token (NFT)

I. Introduction

The pharmaceutical supply chain contains many different parties, including suppliers, manufacturers, distributors, pharmacies, hospitals, and patients. Due to this complexity, it becomes difficult to ensure that all medicines are safe and authentic [1]. Moreover, poor coordination among stakeholders, limited transparency, and the reliance on centralized systems make it easier for counterfeit drugs to enter the supply chain [2]. Recent studies have also highlighted that the problem intensified during global health crises, such as the COVID-19 pandemic, when the demand for medicines surged and counterfeit drugs accounted for nearly 15% of the market. Furthermore, the lack of effective monitoring authorities and the complexity of the pharmaceutical distribution process make it increasingly difficult to prevent fake drugs from infiltrating legitimate channels [3]. Previous approaches, including artificial intelligence and IoT-based methods, have been explored for counterfeit detection, but they fall short in providing the transparency, immutability, and trust guaranteed by blockchain technology [4]. According to the World Health Organization (WHO), about 10% of drugs worldwide are counterfeit, and in some developing countries, this number increases to 30% [5]. These drugs represent a leading cause of child deaths in these countries, which leads to serious health risks. Also, it causes financial losses of over $200 billion every year [1]. These challenges show that there is a strong need for a better system that can make the pharmaceutical supply chain more secure and more transparent. Blockchain technology is seen as a strong solution.

Blockchain is a decentralized system that records all transactions of the pharmaceutical supply chain in a secure and immutable way. It allows everyone involved in the supply chain to check the history of the medicine without depending on a central authority [1]. To make blockchain even stronger for this purpose, researchers have suggested using NFTs. These NFTs can give each medicine batch a unique digital identity, which makes it much easier to check if a medicine is real or fake [6]. This combination of blockchain and NFTs can create a very strong protection system for medicines and patients.

However, blockchain systems still have some important challenges especially in terms of scalability (the ability to handle many transactions quickly) and cost (high transaction fees) [7]. When many transactions happen at the same time, traditional blockchains can become slow and expensive [8]. This makes it difficult to use blockchain for large supply chains such as those in the pharmaceutical industry.

According to Gangwal et al [7], Layer 2 solutions are being adopted to address scalability and cost challenges in blockchain systems. These solutions operate on top of the main blockchain and help process transactions faster and at a lower cost. They retain the benefits of blockchain—such as security and transparency—while making the system more efficient for real-world applications.

In addition, off-chain storage platforms such as IPFS are used to store large or sensitive data efficiently, reducing blockchain congestion and operational costs [9]. In addition, access control models such as RBAC are important to ensure that only authorized parties can access or update critical information in the system [5].

Based on these observations, our research aims to develop an integrated and efficient pharmaceutical supply chain system using blockchain Layer 2 technology. The system will utilize Polygon as a Layer 2 platform to provide faster processing and lower transaction costs while maintaining the security and decentralization of Ethereum. Each drug unit will be

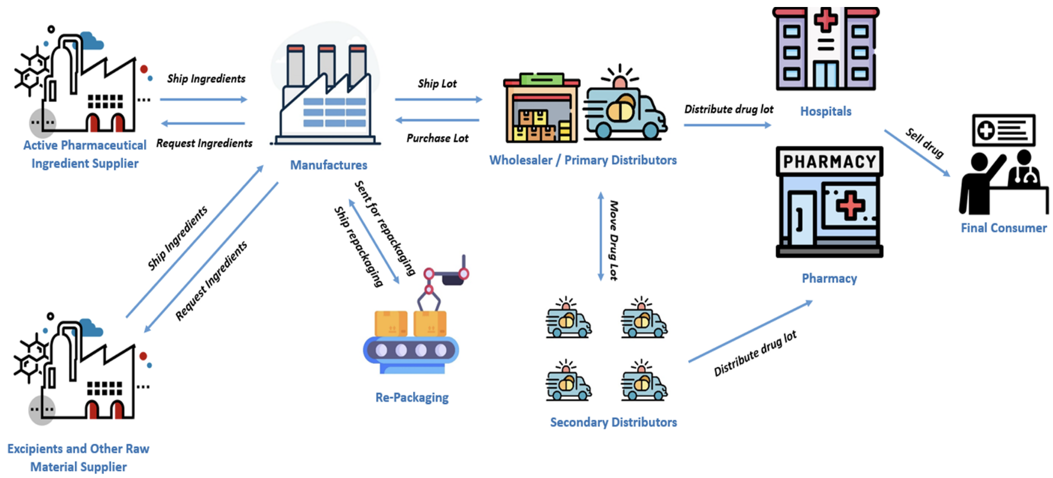

Fig. 1. Traditional pharmaceutical supply chain from raw material suppliers to end-users.

represented by a Non-Fungible Token (NFT) that is linked to a Quick Response (QR) code, allowing stakeholders such as manufacturers, distributors, pharmacies, hospitals, and patients to easily verify authenticity at every stage. To reduce storage costs and improve scalability, metadata related to drugs, such as batch numbers, expiration dates, and certificates, will be stored off-chain using the InterPlanetary File System (IPFS). Furthermore, an access control mechanism will be applied to restrict system interactions according to stakeholder roles. This integration of Layer 2 blockchain, NFTs with QR codes, IPFS, and access control is expected to enhance transparency, strengthen traceability, prevent unauthorized modifications, and contribute to reducing counterfeit drugs while ensuring high scalability and low cost across the pharmaceutical supply chain.

This paper is organized as follows. Section II introduces the background of the study, including the pharmaceutical supply chain, blockchain technology and Layer 2 solutions, as well as off-chain storage methods, NFT standards, and access control models. Section III discusses related work and compares previous approaches based on specific criteria. Section IV presents the proposed system architecture, explaining its core components and the process flow. Finally, Section V addresses the limitations of the current framework and highlights potential implementation challenges.

II. Background

This section provides the essential background required to understand the proposed framework. Focuses on five key concepts that directly address the challenges of counterfeit drugs in the pharmaceutical supply chain. First, the pharmaceutical supply chain is outlined to show how its complexity creates points of weakness. Second, blockchain and Layer 2 solutions are introduced as a way to increase scalability and reduce costs. Off-chain storage is also noted for its role in handling large drug-related data more efficiently. In addition, Non-Fungible Tokens (NFTs) with ERC standards are highlighted as tools to give each drug a unique and verifiable identity. Finally, access control models are introduced to ensure that only authorized stakeholders can interact with the system. Together, these ideas form the foundation for the rest of the paper.

A. Pharmaceutical Supply Chain

The pharmaceutical supply chain is a complex network comprising multiple independent entities, including raw material suppliers, manufacturers, distributors, pharmacies, hospitals, and patients [1]. The main goal from this chain is to ensure that medicines are delivered efficiently and safely to the end user. As we see in Fig. 1, a supply chain typically begins with raw material sourcing, which is processed and transformed into active pharmaceutical ingredients (APIs). These APIs are then used by drug manufacturers to create finished drug products. After being manufactured, drugs are packaged and sent to distribution centres, where they are stored under controlled conditions before being shipped to wholesalers, pharmacies, hospitals, or clinics [2]. Fig. 1 illustrates the complexity of the traditional pharmaceutical supply chain, providing a clear visualization of the multiple actors and interactions that create potential vulnerabilities where counterfeit medicines can infiltrate legitimate channels.

B. Blockchain Technology

Blockchain is decentralized technology that allows digital information to be recorded in a secure way to be transparent and tamper-proof [1]. Often it is described as a combination of two words (blocks and a chain). Each transaction is stored in a block, and every block is linked to the one before it, forming a continuous chain of data. Each block also has a block number, a nonce (a random number used for cryptographic purposes), transaction data, the hash of the previous block, and its own hash. This structure is very useful for ensuring that no data can be changed without affecting all the blocks that follow it, which makes blockchain very resistant to tampering. The main goal of this technology is to provide transparency, security, and trust through participants without the need for a central authority. All transactions recorded on the blockchain are time-stamped, verifiable, and publicly auditable, making the system highly resilient to fraud or unauthorized changes [4]. Fig. 2 presents the basic structure of a block in blockchain. It clearly

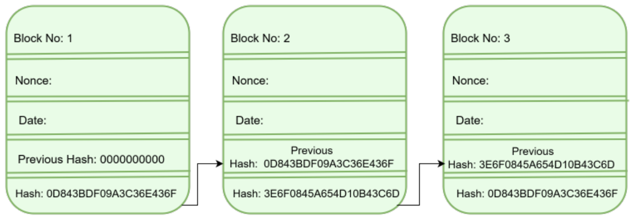

Fig. 2. Basic structure of blockchain block [4].

shows how the block elements are linked together to keep the data secure and tamper-proof.

C. Blockchain Layer 2

While blockchain offers many advantages, it still faces some limitations in terms of scalability and cost-effectiveness, especially when handling a large number of transactions. To solve these challenges, developers have introduced Layer 2 solutions. These solutions work on top of the main blockchain and allow some processes to operate off-chain, which means that smaller transactions are handled separately and later summarized before being recorded on the main chain. This new type of blockchain helps reduce congestion, lower transaction fees, and make the system faster and more efficient [7]. Several Blockchain Layer 2 solutions have been developed:

- Polygon: A popular Layer 2 blockchain solution built on top of Ethereum. It helps improve speed and reduce transaction costs by handling many operations off the main blockchain. It keeps the benefits of Ethereum—like security and decentralization—while making it faster and more cost-efficient [5].
- zkSync: A Layer 2 scaling solution built on zero-knowledge rollups (ZK-Rollups) that enhances Ethereum's scalability while ensuring strong privacy guarantees. It uses cryptographic zero-knowledge proofs to validate transaction batches off-chain, then submits a succinct proof to the main chain [10].
- Arbitrum: A Layer 2 platform that uses optimistic rollups to speed up smart contract operations. It assumes transactions are valid by default and only performs verification [7].
- Optimism: Another Layer 2 solution based on optimistic rollups, designed to improve Ethereum's throughput and reduce gas fees. It maintains a history of state updates and allows fraud-proof mechanisms to revert invalid batches, ensuring security through delayed verification [11].

D. Off-Chain Storage

Off-chain storage refers to keeping large or non-critical data (metadata) outside the blockchain network and linking it to on-chain records through hashes or content identifiers (CIDs) [9]. This technique helps maintain blockchain performance and cost-effectiveness without compromising the integrity and accessibility of the data [11]. The integration of off-chain storage mechanisms with blockchain technology has several advantages:

- Reducing the load on the blockchain : Minimizing the size of blockchain blocks will improve transaction throughput [12].
- Lowering operational costs: Storing large datasets like medical records, certificates, or shipment logs off-chain is more cost-effective [9].
- Enhancing scalability: Off-chain storage reduces overloading on blockchain, ensuring that networks remain fast and efficient [13].

There are a number of techniques used for off-chain storage in blockchain systems, such as:

- IPFS (InterPlanetary File System): A peer-to-peer protocol that allows decentralized file storage and retrieval based on content addressing rather than location[11].
- BTFS (BitTorrent File System): A decentralized storage system built on the BitTorrent network [14].
- Cloud Storage: Some systems used cloud platforms as off-chain storage to store metadata and only saved the verification hashes on the blockchain to ensure transparency and security [13].

E. Non-Fungible Tokens (NFTs)

Non-Fungible Tokens (NFTs) are unique digital assets that are recorded on the blockchain [15]. Each NFT possesses a distinct identifier and metadata that make it individually unique and cannot be exchanged [16]. This feature enables NFTs to verify ownership, maintain traceability, and ensure the authenticity of physical or digital items in a tamper-proof manner [6].

In a blockchain system, NFTs are created and managed based on specific standards to make sure they can be used easily across different systems and apps [15]. In our proposal, we focus on explaining some important NFT standards that are widely used.

- ERC-721 is the first and most popular standard for creating NFTs which defines that each token must be unique and have its own metadata [16].
- C-1155 is a newer standard that allows creating both fungible and non-fungible tokens in one smart contract. This makes managing different types of tokens faster and easier [16].
- ERC-20 is used for fungible tokens and is often mentioned when explaining the difference between fungible and non-fungible assets[16].

F. Access Control

Access control manages and restricts permissions that are used to access specific resources such as systems, data, applications, and networks. Its main objective is to ensure security and privacy by determining and defining who can access the system and what actions they are allowed to perform [17]. In blockchain-based environments,access control is crucial because data are shared among multiple participants.

Robust mechanisms prevent unauthorized access, data leakage, and resource misuse [5]. We have different types of access control models that can be implemented in blockchain systems. The popular model is Role-Based Access Control (RBAC), where each user gets specific permissions depending on their role, such as being a supplier, manufacturer, or customer [5]. Another model is Attribute-Based Access Control (ABAC), which gives more flexibility by considering various attributes like the user's job title, location, or the time they try to access the system. In addition, smart contracts are often utilized to automate access control rules, ensuring that permissions are enforced consistently and transparently without human intervention [10].

III. Related Work

This section reviews studies that use blockchain in healthcare, focusing on pharmaceutical supply chains. We classified the studies into three categories based on the technologies used.

A. Blockchain Without Access Control

In this subsection, we reviewed research that used blockchain in pharmaceutical supply chains. All studies in this section do not explicitly implement access control mechanisms.

Musamih et al. presented a framework based on Ethereum blockchain technology, with smart contracts and off-chain storage through IPFS, to improve the traceability of drugs in the pharmaceutical supply chain [18]. However, their study has some limitations. Using the Ethereum network can be costly due to high gas fees. To overcome these challenges, they suggest using Layer 2 solutions or private blockchain platforms.

Gebreab et al. developed a blockchain solution for the traceability and certification of refurbished medical devices [19]. The study focused on solving issues related to the safety, quality, and potential fraud in the reuse of medical equipment. In the model authors used dynamic and composable NFTs to digitally represent medical devices and their replacement parts. Also, to ensure each device's refurbishment is verified and tamper-proof, they used non-transferable NFTs, known as soulbound tokens, which serve as certificates. To avoid the high cost of storing data on the blockchain, device information is storage on IPFS. The study highlights the limitation of high gas fees on public blockchains, recommending the use of private networks for more cost-effective deployment.

Srinivas and Pradhan introduced TokenPharma framework based on the Ethereum blockchain [15]. They used ERC-721 standard of NFTs to improve pharmaceutical asset ownership and management in the healthcare sector. The system achieved strong performance metrics, with average latencies of 5.04s (create), 4.68s (buy), and 4.27s (resell) and respective throughputs of 223.83 TPS, 262.7 TPS, and 268.76 TPS. Memory usage remained between 645 and 780 MB. However, the study has not evaluated the framework under real-world, large-scale deployment conditions.

Gao et al. developed a blockchain-based safeguard mechanism and incorporated it into a Smart Relief Manufacturing System (SRMS) to improve transparency in relief supply chains (RSCs) during long-term disasters such as pandemics [13]. The framework uses Smart Connected Products (SCPs) to enable the large-scale customization of medical supplies like PPEs and MREs. Also, it introduces a multi-phase, bi-directional collaboration process involving customers in ordering, production, and delivery stages. Although the system restricts data submission through cryptographic signatures, it does not explicitly implement or discuss any formal access control models. Also, it lacks real-world deployment and omits aspects such as financial and material flows, indicating directions for future research.

Datta and Namasudra proposed a blockchain-based drug supply chain system using Ethereum smart contracts and decentralized IPFS storage to prevent counterfeit drugs [20]. The approach uses Schnorr signatures for off-chain production and transaction encryption in IPFS, while ECDSA is used for signing on-chain transactions. Performance analyses demonstrate improvements in throughput, computational efficiency, and communication costs compared to earlier models. However, the authors also highlight that relying on Ethereum's Proof-of-Work (PoW) mechanism introduces energy inefficiency and exposes the system to potential 51% attacks.

B. Blockchain with Access Control

This subsection presents studies that used blockchain with some form of access control in medical and pharmaceutical supply chains. These systems not only focus on improving traceability and security but also add ways to control who can access or use the system. Some studies use account based permissions, digital signatures, or smart contract rules to limit access to authorized users.

Subramanian et al. introduced a creative solution to the growing problem of counterfeit and low-quality medicines in the pharmaceutical supply chain [21]. Their work focused on the development of a mobile app, called "Crypto Pharmacy," which combines hybrid blockchain technology (using the NEM platform) with cryptocurrency and QR code tracking to make medicine purchases more secure and transparent. One of the best advantages of their system is that it allows patients, doctors, and pharmacists to trace each drug's trip from the manufacturer to the end user, reducing the risk of fake products entering the market. They also included real-time IoT monitoring to ensure that sensitive drugs are stored under proper conditions, such as temperature control. While their prototype worked well, the study pointed out a gap in current research—most systems lack large-scale deployment and don't yet take full advantage of advanced tokenization methods like NFTs.

Rehman et al. introduced transparent, immutable and secure vaccine supply chain (TISVSchain), an Ethereum blockchain-based architecture that can be utilized to improve the transparency, traceability, and security of vaccine supply chain management [22]. The system employs Ethereum smart contracts to record each stage of vaccine handling, from manufacturing authorization to final distribution. Access to the system is controlled through unique account addresses (UAs) issued by a regulatory authority to ensure that only approved entities can participate. Also, the customers can check the authenticity of the vaccine by scanning the QR code, which will be connected to on-chain data. It is necessary to mention that the framework was designed to be deployable on both public and private Ethereum blockchains. Although the model demonstrated low gas cost and efficient performance, it did not integrate off-chain storage, which limits scalability and increases the overload on the blockchain network.

Aslam et al. addressed the issue of counterfeit and low-quality medicines in the pharmaceutical supply chain by developing a framework called MSMAChain based on a private Ethereum blockchain [23]. The authors aimed to improve drug traceability through the use of smart contracts, IPFS for off-chain storage, and tracking technologies such as QR codes and RFID. Also, they demonstrated that MSMAChain can reduce transaction costs and enhance transparency, security, and data integrity within the supply chain. However, the authors also identified several limitations, including challenges related to scalability, high computational requirements, and difficulties in integrating with other blockchain systems. They suggested that future work should focus on improving the performance of consensus mechanisms and exploring the use of edge or cloud computing to support larger-scale implementations.

Das et al. proposed a Ethereum blockchain system aiming to address the main problems associated with traditional drug supply chains, such as an increase of counterfeit medications, poor traceability, and a lack of transparency [24]. Their solution offers a safe and affordable method of tracking medications through the supply chain by using smart contracts, QR code scanning, and inventory tracking. A main part of the system is the "Buy-Sell-Verify-Ack" process, which is used to confirm and record each transaction, along with a red-flagging feature to stop suspicious drugs from being sold. Also, the security and cost-efficiency were tested using smart contract tools like Slither and Aderyn, showing that the system is safe and uses gas efficiently. However, the authors referred to the fact that public blockchains can have problems with scalability. To solve this, they suggest using private blockchains or Layer 2 technologies in future improvements.

Padma and Ramaiah introduced a blockchain-based pharmaceutical supply chain management framework (BPSCM) using a private Ethereum blockchain [17]. The system leverages smart contracts to manage stakeholder interactions, enforce access restrictions using Ethereum account-based modifiers, and ensure secure product traceability. For user authentication and to protect the provenance of pharmaceutical products, EdDSA digital signatures and symmetric encryption are employed, while transaction validation is carried out using the Proof of Stake (PoS) consensus mechanism. Additionally, off-chain storage through IPFS is utilized to reduce blockchain storage overhead. Despite its strengths in security and performance, the study does not incorporate a formal access control model within the system architecture, and it lacks evaluation under real-world, large-scale deployment scenarios.

Musamih et al. suggested a blockchain-based framework that used NFTs for product management, digital certification, trading, and delivery within the medical supply chain [6]. They used smart contracts deployed on the Ethereum blockchain, following the ERC-721 standard to tokenize healthcare products as unique digital assets, while IPFS was used for storing the metadata for each product to reduce blockchain storage costs. For access control , the study relies on ownership-based authorization, where only the NFT holder can perform certain actions. While the solution is fully implemented and tested through a decentralized application (DApp), it has yet to be deployed or assessed in real-world conditions. The high and unpredictable transaction fees on the Ethereum network remain a key limitation to practical use.

Samantray and Reddy introduced the novel Blockchain-enabled Healthcare Supply Chain Management (BeHSCM) system to enhance the security, traceability, and data integrity [10]. The system is built on a private Ethereum blockchain and utilizes Solidity smart contracts to handle key supply chain tasks. To ensure data protection, the model integrates the Keccak-256 hash function with zero-knowledge proofs (ZK-SNARKs), implemented using the ZoKrates tool, enabling transaction verification without disclosing sensitive information. Additionally, IPFS is employed for off-chain storage. However, the model has certain limitations. It may face scalability issues under high volumes of healthcare transactions. Furthermore, integrating the system into existing infrastructure can be technologically challenging and may require additional resources.

Chiacchio et al. introduced a blockchain-based solution to improve drug traceability by using NFTs as digital twins for serialized pharmaceutical packages [25]. Each drug unit is labelled with a QR code that follows GS1 standards, containing key information such as GTIN, serial number, batch number, and expiration date. Each NFT is directly linked to the QR code, creating a unique and traceable digital record for every package. Instead of using standard NFT formats like ERC-721, the system uses custom smart contracts on a permissioned blockchain. Access control also depends on the NFT owner, who is identified by their blockchain address and is the only one authorized to update the token's data. Additionally, the system was mainly designed to operate within a single manufacturing facility, making it difficult and costly to apply as a universal solution across multiple organizations.

Gebreab et al. focused on improving the traceability and ownership management of medical devices by using NFTs on the Ethereum blockchain [16]. Their system applies the ERC-721 standard to represent each device as a unique digital asset, with certificates of authenticity and metadata stored using IPFS. Verify ownership transfer through QR code scanning and passphrase confirmation to ensure secure delivery. The study includes both cost and security analyses, demonstrating that the NFT-based approach provides a secure, transparent, and cost-effective solution for tracking medical devices and preventing counterfeiting.

C. Blockchain Layer 2

The studies in this section do not focus directly on pharmaceutical supply chains, but they show how Layer 2 blockchain technologies can improve system performance, reduce costs, and enhance data privacy. Although used in different contexts, the methods presented can be adapted to support secure and efficient pharmaceutical supply chain systems in future research.

Singla et al. developed the Immutable and Decentralized Pharma (IDP) model to improve the security and transparency of pharmaceutical supply chains[26]. Their approach uses blockchain (Polygon) and smart contracts to track medicines from raw materials to the final consumer. The system creates smart contracts for each stage, including raw materials, medicines, and transactions, and links them using a PreviousTransactionHash to ensure immutability and traceability. The prototype was implemented in Solidity and tested on the Polygon testnet, achieving around 43 transactions per second with a latency of 2.5 seconds. A cost analysis showed an estimated 502 USD per day under assumed workloads. The study demonstrates how blockchain can reduce counterfeit drugs by providing a reliable and tamper-resistant supply chain management system. However, the authors noted challenges such as the high operational cost due to frequent contract deployments, scalability concerns, and balancing transparency with data privacy.

Ma and Zhang introduced a new framework that uses blockchain to manage electronic health records more securely and efficiently[11]. Their approach combines Ethereum's Layer 2 ZK-Rollups with decentralized storage through IPFS, allowing sensitive medical information to be stored off-chain and access to the data is protected using cryptographic keys . Also, the system uses zero-knowledge proofs—Zero-Knowledge Succinct Non-Interactive Arguments of Knowledge (ZK-SNARKs)—to verify transactions without exposing private information. This method helps lower transaction costs and speeds up processing. Tests showed that the system responded faster and used less gas than traditional cloud-based or blockchain-only solutions.

Pongallu et al. introduced SecureMedZK, a system built on the Polygon Layer 2 blockchain to make managing electronic health records (EHRs) more secure and scalable [12]. The system uses zero-knowledge rollups to protect patient privacy, allowing sensitive data to be processed off the blockchain while still keeping transactions verifiable. It also applies NTRU lattice-based encryption, a quantum-resistant method that ensures long-term data security. For faster and more reliable transactions, the system uses the Practical Byzantine Fault Tolerance (PBFT) consensus algorithm. The encrypted medical files are stored using AWS S3, and the key encryption is managed through AWS services to meet HIPAA compliance. The results showed that SecureMedZK performs better in terms of speed, scalability, and security. However, the authors refer that PBFT might not scale well in larger networks.

Krishnan and Ganesan introduced a blockchain-based framework to enhance cattle healthcare and dairy production, focusing on small-scale farmers [8]. The solution is built on Polygon, which is a Layer 2 blockchain that runs on Ethereum and uses ZK-Rollups to make transactions faster and more cost-effective. Each cow is linked to a unique ERC-721 NFT, which refers to its health data stored through IPFS. To protect private information, the system includes ZK-SNARKs, which allow data to be verified without revealing the actual content. However, one important limitation is that many farmers may not have the digital skills needed to use the system. Even so, the solution offers a useful, scalable, and secure way to support modern livestock management.

Table I presents a comparison of the studies that applied blockchain technology to pharmaceutical supply chains. The comparison was based on the most significant features employed by each study, including the use of Layer 2 blockchain solutions, NFTs, QR code integration, IPFS, access control, and whether they followed the ERC-721 standard. This table aims to identify existing technological gaps and discover opportunities where the proposed system can add value by integrating various secure and scalable elements.

TABLE I. COMPARATIVE SUMMARY OF BLOCKCHAIN-BASED APPROACHES IN PHARMACEUTICAL SUPPLY CHAIN

Ref	BC	L2	NFT	QR	QR-L	IPFS	ERC721	AC	Med
[8]	✓	✓	✓	×	×	✓	✓	✓	×
[12]	✓	✓	×	×	×	✓	✓	✓	×
[10]	✓	×	×	×	×	✓	×	✓	✓
[26]	✓	✓	×	×	×	✓	×	✓	✓
[11]	✓	✓	×	×	×	✓	×	✓	×
[20]	✓	×	×	×	×	✓	×	×	✓
[24]	✓	×	×	✓	×	×	×	✓	✓
[6]	✓	×	✓	×	×	✓	✓	✓	✓
[17]	✓	×	×	×	×	✓	✓	✓	✓
[13]	✓	×	×	×	×	×	✓	✓	✓
[15]	✓	×	×	×	×	✓	×	✓	✓
[23]	✓	×	✓	×	✓	✓	✓	✓	✓
[19]	✓	×	✓	✓	✓	✓	×	✓	✓
[22]	✓	×	✓	✓	✓	×	✓	✓	✓
[16]	✓	×	✓	✓	✓	✓	×	✓	✓
[25]	✓	×	✓	✓	✓	✓	✓	✓	×
[21]	✓	×	✓	✓	✓	✓	✓	✓	✓
[18]	✓	×	×	×	×	✓	×	✓	✓

From Table I, all studies used blockchain as a core component, while only four studies [12], [11], [26], and [8] employed Layer 2 blockchain technologies such as Polygon. Among them, only one study [26] applied Layer 2 in the pharmaceutical domain, whereas the others focused on different areas such as cattle health monitoring and electronic health records. This indicates that Layer 2 solutions are still not well explored in the context of drug traceability.

NFTs were used in six studies [8], [6], [15], [19], [25], and [16] to represent medical products. However, just two of them,[16] and [25], used NFTs linked by QR codes to make it easy and safe to authenticate. This shows that linking physical products with their digital counterparts using QR is not given much use. Furthermore, ERC-721 standards are used by [8], [6], [15], [19] and [16]. The others either had custom contracts or none specified as to what standard was being employed.

All the papers [8],[10],[11], [20],[26], [6], [17], [15], [23],[19],[16] and [18] utilized IPFS for off-chain storage as a cost-saving measure and also to avoid blockchain congestion. Other researches like [12], [24],[22] and [13] that did not utilize IPFS used other types of storage, such as local databases or centralized cloud storage. This may weaken the data integrity and decentralisation that blockchain aims to provide.

In security, most studies, such as [19], [11], [16], and [21] utilized access control mechanisms within them, although how it was being implemented was different and not always clearly explained.

Finally, most of the studies in the table focused directly on the pharmaceutical supply chain. This shows that there is strong interest in using blockchain to improve drug traceability and fight counterfeiting. However, even though the domain is well covered, some important technologies, such as Layer 2

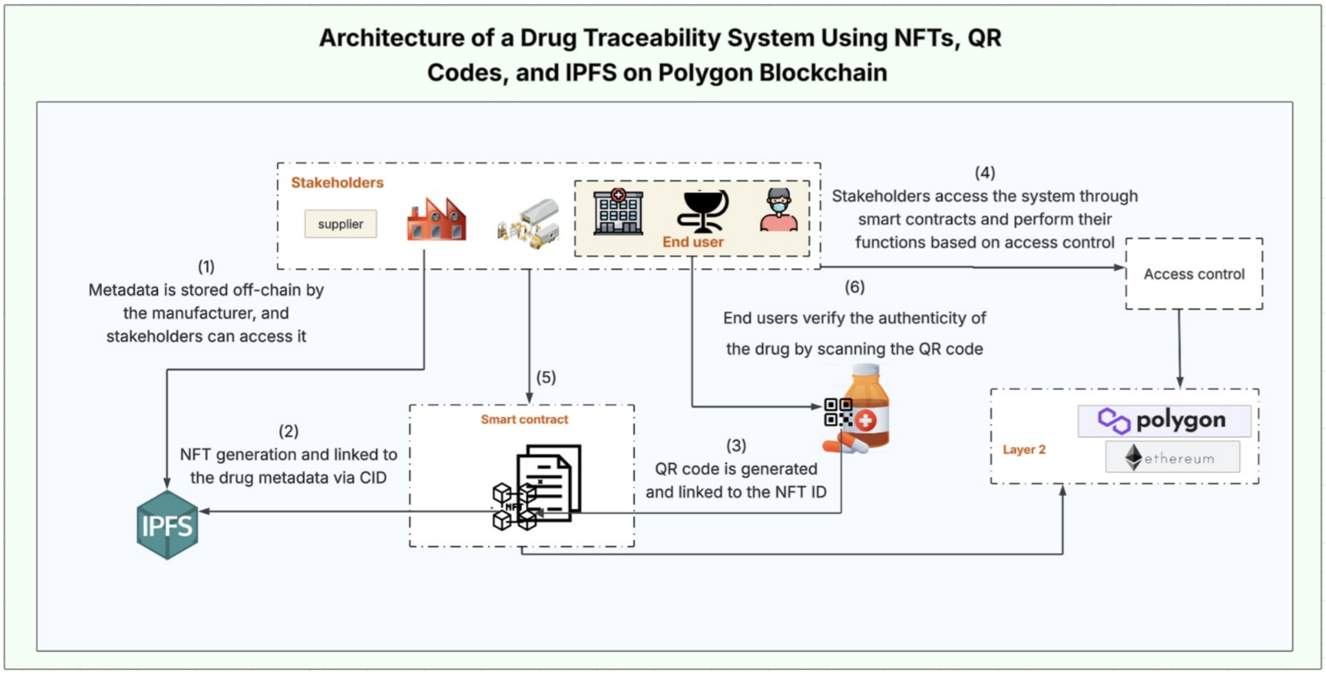

Fig. 3. Proposed system architecture for secure and traceable pharmaceutical supply chain.

blockchain, linking NFTs with QR codes, and decentralized storage using IPFS are still not widely used together in one system. This means that there is still a gap in how these technologies are combined to enhance scalability and reduce the cost in the pharmaceutical supply chain to reduce the spread of fake drugs. The proposed system in this paper aims to close this gap by bringing these tools together in a secure, scalable, and cost-effective way for managing pharmaceutical supply chains.

IV. Proposed Architecture

This proposed framework addresses the above gap by integrating all the technologies mentioned in Table I (Polygon blockchain, NFTs, QR codes, and IPFS). Fig. 3 illustrates the system architecture. For clarity, this section is classified into two parts: system components and system processes.

A. System Components

This system includes several main components that work together to track and verify drugs: Stakeholders:

The main participants in the drug supply chain who interact with the system. They include:

- Supplier: Provides raw materials for drug manufacturing.
- Manufacturer: Produces the drug and initiates the traceability process. The manufacturer operates under the supervision of the health authority (e.g., FDA) to ensure safety and compliance.
- Distributor: Transfers drugs from the manufacturer to healthcare entities.
- Hospital: Receives the drugs and ensures their authenticity before use.
- Pharmacy: Dispenses drugs to patients and performs verification using QR codes.
- Patient: The final user who scans the QR code to verify drug authenticity.

Access control: Ensures that each stakeholder can only access and interact with the system based on their role and permissions. In this system, Role-Based Access Control (RBAC) is used so that every participant on the blockchain has a specific role and can perform actions based on permissions. The manufacturer is the only one who can produce and upload drugs to the network. The distributor receives the drugs from the manufacturer and delivers them to hospitals and pharmacies. Hospitals and pharmacies can verify the drugs and are responsible for dispensing them to patients. The patient can only check the drug using the QR code. This access control prevents unauthorized actions and keeps all operations secure and transparent.

InterPlanetary File System (IPFS): A decentralized storage system used to store drug metadata off-chain to reduce the amount of data stored on the blockchain.

Non-Fungible Token (NFT): Represents a unique digital identity for each drug unit. It links to the metadata stored in IPFS via a content identifier (CID).

QR Code:The encrypted QR code is linked to the NFT and attached to the drug package. It allows stakeholders to verify that the drug is authentic. The QR code follows the GS1 standard, which includes four main parameters:

- (01) Global Trade Item Number (GTIN),
- (17) Expiration date,

- (10) Batch or lot number, and
- (21) Serial number

These parameters make the system compatible with international pharmaceutical traceability systems and support serialization for each drug unit. Serialization helps trace every package and detect any copied or fake drugs, improving transparency and safety through the whole process.

Smart Contract: The smart contract contains the NFT, which is stored on-chain, and allows stakeholders to interact with the system and perform their roles based on access control.

Polygon Blockchain: Polygon is a Layer 2 solution [7]. We selected Polygon for our system because it maintains Ethereum's security and decentralization while offering better performance and lower gas fees. It also supports NFTs and smart contracts, which are essential for our design. Compared to other Layer 2 solutions like Optimism and Arbitrum, Polygon is more user-friendly, well-documented, and has already been used in similar fields such as healthcare.

B. System Processes

This subsection describes the main processes of the proposed system and explains how its components interact to guarantee secure and transparent drug traceability across the supply chain.

1) Metadata storage: The process begins with the manufacturer, who prepares detailed metadata for each drug unit. This includes the batch number plus production and expiration dates. The manufacturer uploads this information to IPFS, which generates a unique Content Identifier (CID). The CID acts as a cryptographic reference. It permanently links the on-chain record to the off-chain data and ensures integrity while reducing blockchain storage overhead.

2) NFT generation and linking: After the metadata is secured, the manufacturer mints a unique ERC-721 token (NFT) on the Polygon network for each drug unit. This NFT acts as the drug's digital identity by linking the physical product to its verified digital counterpart.

3) QR code encryption, generation, and storage: A QR code is generated and securely encrypted with the NFT ID. This QR code is stored digitally and also printed on the drug package. It serves as the access point to retrieve the drug's information and verify its authenticity.

4) Supply chain transfer and updates: As the drug moves through the supply chain, each transaction is recorded, such as transfers between manufacturers, distributors, hospitals, and pharmacies. Stakeholders sign these interactions with their blockchain addresses.

5) Smart contracts and on-chain recording: All interactions and updates are handled by smart contracts and recorded on-chain using the Polygon blockchain. These contracts verify each action and enforce role-based permissions, ensuring that only authorized entities can update or approve records. This approach reduces the risk of tampering or fraud while guaranteeing traceability, transparency, and tamper-proof records.

6) End-user verification process: The patient receives the drug and scans the QR code using a mobile device. After that, the system uses the scanned QR code to retrieve the associated NFT ID of the drug. The NFT ID is applied to fetch the drug's linked metadata from the IPFS. Once obtained, the system displays the drug data on the platform and allows the patient to verify the authenticity of the drug and ensures that it has not been tampered with.

V. Conclusion and Future Work

This paper presented a blockchain-based framework to improve the traceability of the pharmaceutical supply chain and reduce the circulation of counterfeit drugs. The proposed system integrates Layer 2 blockchain (Polygon), NFTs connected to QR codes, IPFS, and access control to provide a secure and scalable solution. These components collectively enhance transparency, reduce storage costs, and protect sensitive information throughout the supply chain.

Currently, the research focuses on designing and developing the system architecture. The implementation and testing phase is ongoing, and the experimental results with performance evaluation will be included in a future work. The next stage will involve a complete end-to-end deployment of the proposed framework on the Polygon test network. The evaluation will include quantitative metrics such as transaction latency, gas cost, throughput, and storage efficiency. In addition, a comprehensive security assessment will be conducted to analyze signature verification accuracy, QR code robustness against duplication, and access control enforcement. These results will provide a deeper understanding of the system's scalability, reliability, and real-world applicability.

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