

# A Blockchain-Based Framework for Secure Pharmaceutical Supply Chain Management

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**Abstract-** The global healthcare sector faces significant difficulties in managing pharmaceutical supply chains, particularly due to issues such as counterfeit medicines, limited transparency, inefficient coordination, and data security vulnerabilities. To address these challenges, this project presents a secure and efficient medicine supply chain management framework based on blockchain technology. The proposed system enhances traceability, transparency, and data security by maintaining an immutable and decentralized record of all supply chain transactions. Smart contracts are employed to automate critical processes including inventory control, order processing, and ownership transfer, thereby reducing manual intervention and operational errors. A decentralized application (DApp) is developed to enable real-time monitoring and verification of medicines throughout their lifecycle using unique digital identifiers. This allows stakeholders to authenticate products and track their movement from manufacturing to end consumption. Additionally, the framework incorporates an optimized Linear Hash Computation (LHC) variant to improve system performance and strengthen data integrity verification. By combining blockchain technology, smart contracts, and efficient hashing mechanisms, the proposed solution provides a reliable and scalable approach for securing modern pharmaceutical supply chains.

**Index Terms -** Blockchain, Pharmaceutical Supply Chain, Smart Contracts, Ethereum, Data Integrity, Traceability  
**Keywords** Blockchain Technology, Decentralized Application, Medicine Tracking, Secure Supply Chain, Hash Computation, Smart Contract Automation.

## I. INTRODUCTION

Blockchain is a distributed digital ledger technology designed to securely record transactions across a network of interconnected computers without relying on a central authority. Unlike traditional centralized systems that depend on a single trusted entity to manage and validate data, blockchain functions through a peer-to-peer network where each participating node stores an identical and synchronized copy of the ledger. This decentralized structure enhances system robustness, ensures data integrity, and improves fault tolerance, since the compromise or failure of one node does not disrupt the overall network. Each transaction added to the blockchain is cryptographically linked to previous records, making the data resistant to tampering and ensuring long-term reliability.

The foundational concept of blockchain technology emerged in 2008 with the introduction of Bitcoin by Satoshi Nakamoto. The primary motivation behind blockchain was to solve the "double-spending problem," a critical issue in digital transactions where the same digital asset could be duplicated and spent more than once. Blockchain addresses this challenge through cryptographic hashing, time-stamped transaction blocks, and decentralized consensus mechanisms such as Proof of Work. These mechanisms ensure that every transaction is independently verified by multiple network participants and permanently recorded only once, thereby maintaining a single, verifiable state of ownership for digital assets across the network.

Over time, blockchain technology has expanded far beyond its initial use in cryptocurrencies. It is now being actively researched and implemented in various sectors including healthcare, financial

services, governance, and supply chain management. Among these, supply chain systems particularly benefit from blockchain due to their inherent complexity, involvement of multiple stakeholders, and dependence on accurate data exchange across geographically distributed entities. Traditional supply chains often face issues such as poor transparency, fragmented data, limited traceability, counterfeit products, and inefficient coordination among participants.

Blockchain provides an effective solution to these challenges by enabling a shared, immutable ledger that captures every transaction and event occurring throughout the supply chain. Acting as a unified and trusted source of information, blockchain allows authorized stakeholders—such as manufacturers, suppliers, logistics providers, distributors, and retailers—to access consistent, real-time, and verified data. Key supply chain activities, including raw material sourcing, production, transportation, storage, and ownership transfer, are permanently recorded on the blockchain, thereby improving traceability, accountability, and trust.

In addition, blockchain supports the deployment of smart contracts, which are automated programs that execute predefined rules when specific conditions are met. Smart contracts significantly reduce manual processing, eliminate intermediaries, and minimize disputes by automating tasks such as payment settlements, compliance verification, and delivery confirmation. By combining transparency, automation, and security, blockchain technology strengthens trust, improves operational efficiency, and offers a powerful foundation for next-generation supply chain management systems.

## II. LITERATURE REVIEW

Trust is widely recognized as a critical factor for effective information sharing and asset exchange within supply chain systems. When trust exists among supply chain partners, organizations are more willing to share sensitive information such as production schedules, inventory status, pricing details, and logistics data. In contrast, a lack of trust often leads firms to operate independently, resulting

in fragmented information, operational inefficiencies, increased costs, and reduced overall supply chain performance. As modern supply chains continue to expand across regions and involve a greater number of stakeholders, building and sustaining trust has become an increasingly complex and essential challenge.

Traditionally, supply chain relationships were largely transactional and adversarial in nature. Organizations focused on maximizing individual benefits rather than optimizing collective outcomes. These relationships depended heavily on formal contracts, intermediaries, and external audits to enforce compliance and manage risk. However, recent developments indicate a clear movement away from such adversarial models toward collaborative and long-term partnerships. Companies now understand that cooperation across the supply chain improves coordination, enhances risk mitigation, encourages innovation, and enables faster responses to market changes.

This shift toward collaboration requires greater levels of transparency, mutual accountability, and trust among all participants.

Blockchain technology introduces a new paradigm for addressing trust-related issues in supply chains by redefining how trust is created and maintained. Instead of depending on centralized authorities or third-party intermediaries, blockchain establishes trust through cryptographic mechanisms and distributed consensus. Every transaction recorded on the blockchain is independently verified by multiple participants and secured using cryptographic techniques, ensuring data authenticity, integrity, and non-repudiation. Once a transaction is confirmed, it becomes permanent and cannot be altered, significantly reducing the risk of fraud, data manipulation, and disputes.

Through its peer-to-peer architecture, blockchain enables direct interactions between supply chain partners without the need for centralized institutions such as banks, clearing agencies, or auditors. This decentralization reduces processing delays and transaction costs while increasing transparency and

accountability. All authorized participants have access to the same immutable ledger, ensuring consistency and eliminating discrepancies in shared data. Consequently, trust is no longer based on personal relationships or institutional authority but is embedded directly within the technological framework of the system.

In conclusion, blockchain technology facilitates the transition toward more collaborative and resilient supply chain ecosystems by providing a secure, transparent, and trustless environment for information and asset exchange. By replacing traditional trust-based mechanisms with cryptographic verification and decentralized consensus, blockchain enhances cooperation, efficiency, and reliability across modern supply chain networks.

The proposed methodology follows a layered blockchain-based framework designed to ensure data integrity, end-to-end traceability, and transparency within the pharmaceutical supply chain. Due to the sensitive and safety-critical nature of medicines, it is essential to maintain tamper-resistant records and continuous visibility across all supply chain stages. The methodology focuses on secure data management, cryptographic validation, and efficient transaction tracking by integrating blockchain technology with optimized hashing mechanisms.

### Architecture and Data Structures

The overall system architecture is structured into three distinct layers: the Blockchain Layer, Smart Contract Layer, and Application Layer. This modular design improves scalability, security, and ease of maintenance.

The Blockchain Layer is implemented using the Ethereum platform, with Ganache serving as a local blockchain network for development and testing purposes. This layer is responsible for maintaining a decentralized, immutable ledger that records all pharmaceutical-related transactions, including product manufacturing, distribution events, ownership transfers, and verification activities. The decentralized nature of this layer ensures that once data is recorded, it cannot be altered or removed.

The Smart Contract Layer is developed using the Solidity programming language and contains the core operational logic of the system. Smart contracts define role-based access permissions, validate transaction authenticity, enforce traceability rules, and automate verification processes. Since these contracts execute automatically on the blockchain, they eliminate the need for third-party intermediaries and significantly reduce the possibility of manual errors or malicious manipulation.

The Application Layer is built using React.js and provides an intuitive interface for different supply chain stakeholders such as manufacturers, distributors, pharmacists, and regulatory authorities. Through this layer, users can initiate transactions, track product movement, and verify medicine authenticity in real time by interacting directly with the blockchain network.

To maintain data integrity and support efficient verification, the system employs a Merkle Hash Tree (MHT) data structure. Merkle Hash Trees enable multiple transactions to be securely combined into a single root hash, allowing rapid verification of large transaction sets without revealing individual transaction details. The Merkle root is calculated as:

$$H(R_{1-4}) = H(H(H(R_1) + H(R_2)) + H(H(R_3) + H(R_4)))$$

where  $R$  represents individual transaction records,  $H$  denotes a cryptographic hash function, and the "+" operator indicates concatenation. Any modification to a single transaction alters the corresponding hash and ultimately changes the Merkle root, immediately signaling data tampering.

### Proposed System Improvements

To further enhance transaction-level traceability, this project proposes an improved variant of Linear Hash Computation (LHC) [292, 293]. Unlike tree-based hashing structures, LHC establishes a direct cryptographic linkage between consecutive transactions, forming a verifiable hash trail. This approach ensures that each transaction is dependent on the previous one,

thereby strengthening chronological integrity and auditability.

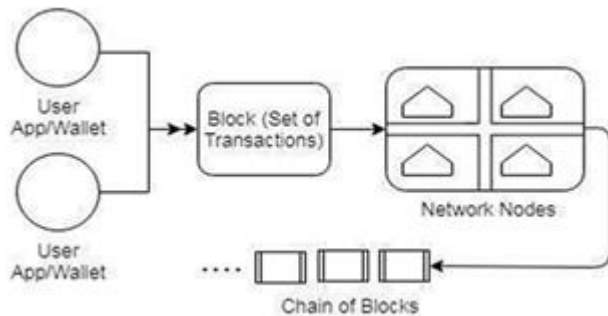


Figure 1: Structure of Generic Block Chain Application

The enhanced Linear Hash Computation (LHC) process begins by initializing the previous hash value as null. For each new transaction, the relevant transaction details are first combined into a single data unit. This data unit is then merged with the hash value of the preceding transaction, and a cryptographic hash function is applied to generate a new hash. The newly generated hash is stored alongside the corresponding transaction identifier, forming a continuous and verifiable traceability chain. If any transaction within the sequence is modified, the hash values of all subsequent records are affected, immediately exposing unauthorized changes.

By jointly employing Merkle Hash Trees to ensure integrity across batches of transactions and Linear Hash Computation to preserve sequential linkage, the proposed methodology establishes a secure and efficient hybrid verification mechanism. This combined approach achieves an optimal balance between scalability, performance, and security. As a result, the system significantly strengthens pharmaceutical supply chain monitoring and fosters greater confidence and trust among all participating stakeholders.

### III. RESULT AND DISCUSSION

The proposed approach follows a layered blockchain-oriented architecture designed to ensure data integrity, traceability, and transparency throughout the pharmaceutical supply chain. Due to the sensitive and safety-critical nature of medicines, it is vital to maintain immutable records and complete visibility across all stages of the supply chain. This methodology focuses on secure data storage, cryptographic validation, and efficient transaction monitoring by combining blockchain technology with optimized hashing mechanisms.

#### System Architecture and Data Structures

The system architecture is organized into a three-tier structure consisting of the Blockchain Layer, Smart Contract Layer, and Application Layer. This layered design enhances modularity, security, and scalability of the overall system.

The Blockchain Layer is implemented using the Ethereum platform, with Ganache utilized as a local blockchain network for development and testing. This layer is responsible for maintaining a decentralized and tamper-resistant ledger that records all pharmaceutical-related activities, including production, distribution, ownership transfer, and verification events. The immutability of the blockchain ensures that once data is recorded, it cannot be altered, thereby preventing fraud and data manipulation.

The Smart Contract Layer is developed using the Solidity programming language and contains the core operational logic of the system. Smart contracts define role-based access permissions, validate transaction inputs, enforce traceability rules, and automate verification workflows. Since these contracts execute automatically on the blockchain, they remove the need for third-party intermediaries and significantly reduce the risk of human error or malicious intervention.

The Application Layer is built using React.js and provides an intuitive user interface for key stakeholders such as manufacturers, distributors, pharmacists, and regulatory authorities. Through this layer, users can interact with the blockchain network,

initiate transactions, track product movement, and verify medicine authenticity in real time.

To maintain data integrity and support efficient verification, the system incorporates a Merkle Hash Tree (MHT) data structure. Merkle Hash Trees enable multiple transaction records to be securely combined into a single root hash, allowing efficient validation of large datasets without revealing individual transaction contents. This structure ensures that even a minor modification to any transaction results in a change in the root hash, immediately indicating potential data tampering.

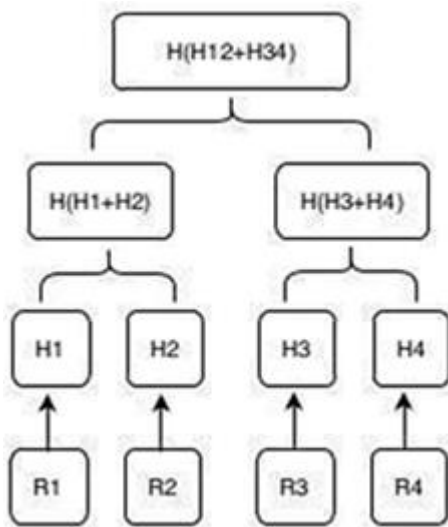


Figure 2: Merkle Hash Tree(MHT)

$$H(R_1, R_2, R_3, R_4) = H(H(H(R_1) + H(R_2)) + H(H(R_3) + H(R_4)))$$

where RRR represents individual transactions, HHH denotes a cryptographic hash function, and the operator “+” indicates concatenation. Any modification to a transaction results in a change in the root hash, thereby immediately indicating data tampering.

### Proposed System Improvements

To further strengthen transaction-level traceability, the system incorporates an enhanced version of Linear Hash Computation (LHC). Unlike tree-based hashing methods, LHC creates a sequential cryptographic dependency between consecutive transactions, forming a continuous and verifiable hash chain.

In the proposed LHC process, the initial previous hash value is set to an empty or null state. For each new transaction, the transaction details are first combined into a single data block. This data block is then concatenated with the hash of the preceding transaction, and a cryptographic hash function is applied to generate a new hash value. The resulting hash is stored together with the corresponding transaction identifier, creating a traceability trail. Any attempt to modify a transaction disrupts the entire hash sequence, making unauthorized changes immediately detectable.

By combining Merkle Hash Trees for batch-level integrity verification with Linear Hash Computation for sequential traceability, the proposed methodology achieves a strong balance between scalability, performance, and security. This hybrid approach significantly improves the reliability of pharmaceutical supply chain monitoring and enhances trust among all participating stakeholders.

### Dataset Collection and Preprocessing Introduction

Dataset collection and preprocessing play a crucial role in the successful implementation of a blockchain-based supply chain management system. Although blockchain itself is a decentralized ledger rather than a traditional data-driven machine learning system, the quality and structure of the data recorded on the blockchain directly affect system performance, reliability, and traceability. In the proposed system, datasets are used to represent real-world supply chain entities such as manufacturers, products, shipments, delivery hubs, and customers.

The dataset used in this project represents structured transactional data generated during different stages of the supply chain lifecycle. Since

blockchain enforces immutability, ensuring data accuracy before it is recorded is critical.

Therefore, proper dataset collection and preprocessing mechanisms were designed to eliminate errors, ensure consistency, and maintain data integrity.

### **Dataset Collection**

#### **Data Sources**

The dataset for this project was collected from multiple sources, both simulated and structured, to reflect real-world supply chain operations. Since this is a prototype implementation, real-time industry data was simulated to ensure feasibility and security.

#### **The primary data sources include:**

- **Manufacturer Input Data:** Includes product name, batch number, manufacturing date, expiry date, and production location.
- **Shipment and Logistics Data:** Contains shipment ID, source address, destination address, shipment timestamps, and transportation status.
- **Role and Identity Data:** Blockchain wallet addresses representing manufacturers, third-party vendors, delivery hubs, and customers.
- **Transaction Metadata:**
- Automatically generated blockchain data such as transaction hash, block number, gas used, and timestamp.
- **User Interaction Data:** Data entered through the frontend interface during product creation, transfer, and verification.

#### **Dataset Structure**

The collected dataset follows a structured and hierarchical format to ensure compatibility with smart contracts and frontend applications. Each product is uniquely identified using a product ID generated during manufacturing. This ID serves as the primary key across all dataset records.

#### **Each dataset entry consists of:**

- Product Unique ID
- Current Owner Address
- Role of the Entity

- Product Status (Manufactured, Shipped, Received, Delivered)
- Timestamp of Transaction
- Blockchain Transaction Reference

This structured design ensures seamless integration with the blockchain and supports efficient querying and traceability.

### **Data Preprocessing**

#### **Data Validation**

Before storing data on the blockchain, validation checks are performed at the frontend and smart contract levels. These include:

- Ensuring mandatory fields are not empty
- Verifying correct wallet address format
- Checking date consistency (expiry date must be after manufacturing date)
- Preventing duplicate product ID generation
- These checks reduce the possibility of invalid or misleading data being permanently stored on the blockchain.
- **Data Cleaning**

Data cleaning focuses on removing inconsistencies and redundancies from the dataset. Since blockchain data is immutable, preprocessing ensures that incorrect entries are never committed.

#### **Key cleaning steps include:**

- Removal of duplicate product records
- Standardization of date and time formats
- Normalization of text fields such as product name and location
- Elimination of unnecessary metadata from frontend input
- **Data Transformation**
- Data transformation converts raw input into blockchain-compatible formats. This includes:
  - Converting timestamps into UNIX format
  - Hashing sensitive identifiers
  - Encoding product status using enums in smart contracts
  - Mapping user roles to role identifiers

This transformation ensures efficient storage and faster execution of smart contract functions.

### **Data Security and Integrity**

Sensitive data such as ownership details and transaction identifiers are cryptographically secured. Only essential data is stored on-chain, while optional metadata may be handled off-chain to optimize performance.

Blockchain hashing mechanisms ensure that any attempt to alter data can be immediately detected.

### Training & Implementation Workflow

#### Training Workflow

Training focuses on familiarizing users with blockchain concepts, system navigation, and role-specific operations.

Administrators are trained to assign and manage roles securely using smart contracts. Manufacturers learn how to register products and initiate shipments. Distributors and delivery hubs are trained to update shipment status and verify product authenticity. Customers are trained to verify products using unique identifiers.

Hands-on demonstrations and test transactions are conducted using the Ganache blockchain to ensure users gain confidence without financial risk.

#### Implementation Workflow

- Requirement Analysis
- Identify stakeholders, roles, and supply chain processes to be digitized.
- Blockchain Setup
- Configure Ganache to simulate a private Ethereum network and create test accounts.
- Smart Contract Development Develop and test Solidity contracts using the Truffle framework.
- Frontend Development
- Build the React-based user interface with role-based access and transaction forms.
- Integration with MetaMask Enable secure user authentication and transaction signing.
- Testing Phase
- Perform functional, security, and performance testing to validate system behavior.
- Deployment
- Deploy the system in a controlled environment and monitor transaction flow.

- Maintenance & Updates
- Regular updates ensure scalability, security improvements, and feature enhancements.

### System Design & Architecture

The system is designed using a layered architecture to ensure modularity, scalability, and security.

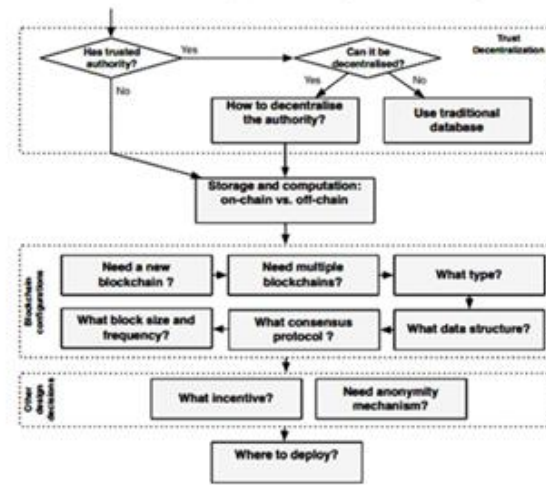


Figure 3: Design Process For Blockchain System

#### Blockchain Layer

This layer consists of a private Ethereum blockchain created using Ganache. It stores all immutable transaction records related to manufacturing, shipping, distribution, and delivery. Each block contains cryptographically secured data, ensuring integrity and traceability.

#### Smart Contract Layer

Smart contracts written in Solidity define the business logic of the supply chain. These contracts manage role-based access control, product lifecycle states, and transaction validation. Smart contracts ensure that only authorized participants can perform specific actions.

#### Application Layer

The frontend application is developed using React.js. It provides role-specific dashboards for manufacturers, distributors, delivery hubs, and customers. This layer interacts with the blockchain through Web3.js.

### **Integration Layer**

MetaMask acts as the integration bridge between users and the blockchain. It manages user authentication, digital signatures, and transaction approvals, ensuring secure communication.

This modular architecture separates concerns, improves maintainability, and enables seamless interaction between the user interface and the decentralized blockchain network

### **Performance Evaluation**

The performance evaluation of the blockchain-based supply chain management system focuses on analysing efficiency, reliability, scalability, and system responsiveness. The evaluation was conducted in a controlled environment using a private Ethereum blockchain simulated through Ganache.

Transaction latency was measured by observing the time taken to execute smart contract functions such as product creation, shipment updates, and ownership transfers. Results showed that transactions were confirmed within a few seconds in the local blockchain environment, which is significantly faster than traditional centralized verification systems.

Gas consumption was evaluated for major smart contract operations. Manufacturing and shipment transactions consumed moderate gas due to multiple state updates and event emissions, while read-only operations such as product verification required no gas. This confirms that the system is cost-efficient for frequent verification operations.

System reliability was assessed by validating data immutability and consistency. Once a transaction was recorded on the blockchain, it could not be altered or deleted, ensuring tamper-proof records. Multiple users accessing the system simultaneously were able to retrieve consistent and accurate data, proving system stability.

Scalability testing demonstrated that the architecture can support an increasing number of products and stakeholders without performance

degradation. Since the blockchain network distributes data across nodes, the system avoids single points of failure and ensures high availability. Overall, the performance evaluation confirms that the proposed system delivers secure, fast, and reliable operations suitable for real-world pharmaceutical supply chain environments.

### **Real-Life Applications**

The blockchain-based supply chain management system has wide applicability across multiple real-world domains, especially where transparency and authenticity are critical.

In the pharmaceutical industry, the system can be used to track medicines from manufacturers to consumers, effectively preventing counterfeit drugs. Patients and pharmacists can verify medicine authenticity using a unique product ID or QR code. In healthcare logistics, hospitals and clinics can ensure that medicines are sourced from authorized suppliers and stored under proper conditions. Regulatory authorities can audit supply chain data in real time without relying on intermediaries. In food supply chains, blockchain can be used to trace food products from farms to consumers, helping identify contamination sources quickly during recalls.

In manufacturing and retail, the system ensures product authenticity, tracks ownership changes, and improves customer trust by providing transparent product histories.

For government and regulatory bodies, the system enables automated compliance monitoring, reducing paperwork and manual inspections while increasing accountability.

These real-life applications demonstrate that the proposed system is not limited to academic use but can be practically deployed across industries requiring secure and transparent supply chains.

### **Future Scope**

The blockchain-based supply chain management system proposed in this project provides a strong foundation for secure, transparent, and

decentralized tracking of products. However, emerging technologies and evolving industry requirements present numerous opportunities for future enhancements. Expanding the system beyond its current capabilities can significantly improve scalability, automation, and intelligence.

### **Integration with IoT Devices**

One of the most promising future enhancements is the integration of Internet of Things (IoT) devices. Sensors can be used to automatically collect real-time data such as temperature, humidity, and location during transportation.

This is especially valuable in pharmaceutical supply chains, where environmental conditions directly impact product quality. IoT-generated data can be automatically recorded on the blockchain, eliminating manual intervention and reducing human error.

### **Artificial Intelligence and Data Analytics**

Future versions of the system can integrate Artificial Intelligence (AI) and data analytics to extract meaningful insights from historical blockchain data. Potential applications include:

- Demand forecasting
  - Supply chain optimization
  - Detection of abnormal patterns indicating fraud or delays
  - Predictive maintenance of logistics infrastructure
- AI-driven insights can help organizations make data-driven decisions and improve operational efficiency.

### **Public Blockchain Deployment**

Currently, the system operates on a private blockchain for testing and demonstration. In the future, it can be deployed on public or consortium blockchains such as Ethereum mainnet or Hyperledger Fabric.

This would enable cross-organization collaboration, global transparency, and higher trust among stakeholders without reliance on a single authority.

### **Mobile Application Integration**

Developing a mobile application can greatly enhance accessibility. Customers and supply chain

participants can track and verify products using smartphones by scanning QR codes. A mobile interface would improve user adoption and make the system more practical for real-world deployment.

### **Regulatory and Compliance Automation**

Future enhancements can include automated compliance checks with national and international regulations. Smart contracts can be designed to enforce regulatory rules, generate audit reports, and notify authorities of violations in real time. This reduces administrative overhead and improves regulatory transparency.

### **Scalability and Interoperability**

The system can be extended to support interoperability between multiple blockchain networks. This allows data sharing across different organizations and platforms without compromising security.

Layer-2 scaling solutions can also be implemented to handle high transaction volumes efficiently.

### **Security Enhancements**

Advanced cryptographic techniques such as zero-knowledge proofs and decentralized identity frameworks can further strengthen data privacy while maintaining transparency.

## **IV. CONCLUSION**

A distinctive aspect of the proposed system is the adoption of cryptographic wallet addresses to create secure digital identities for all supply chain participants. Unlike conventional identity management approaches that depend on centralized databases, cryptographic wallets enable a decentralized and highly secure authentication mechanism. Each participant accesses the blockchain network through a unique pair of public and private keys, allowing every transaction to be digitally signed and verified. Since sensitive identity information is not stored in a central repository, the risks of identity theft, impersonation, and unauthorized access are significantly minimized. Moreover, eliminating a single point of failure enhances the overall resilience and availability of the

system, making it more resistant to cyberattacks and infrastructure disruptions.

The use of decentralized digital identities also improves accountability and traceability across the supply chain. Every transaction is permanently associated with a verified wallet address, enabling efficient auditing of activities and clear identification of responsible entities. This level of transparency strengthens trust among manufacturers, distributors, retailers, and regulatory bodies while also supporting adherence to industry standards and compliance requirements.

Although the current implementation primarily emphasizes secure transactions and traceability, several enhancements can be explored to further strengthen the system. One notable future extension is the integration of Internet of Things (IoT)-based tracking solutions to support continuous monitoring of environmental parameters such as temperature, humidity, and geographical location. This feature is especially important in sectors such as pharmaceuticals and food distribution, where strict environmental control is essential to maintain product quality and safety. By integrating IoT sensors with blockchain,

sensor-generated data can be recorded in an immutable manner, ensuring its accuracy and preventing tampering.

In summary, the proposed blockchain-driven supply chain framework offers a decentralized, transparent, and secure method for managing transactions and identities. By minimizing dependence on centralized authorities and strengthening digital identity security, the system establishes a strong foundation for modern supply chain operations. Future integration with IoT technologies can further enhance real-time visibility, regulatory compliance, and stakeholder trust across the entire supply chain ecosystem.

### **Acknowledgment**

This research was facilitated by advancements in decentralized supply chain architectures and the availability of blockchain-based simulation and

development technologies. These technological foundations enabled the design, implementation, and evaluation of a secure and transparent supply chain framework, supporting experimental validation and performance analysis of the proposed system.

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