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Leveraging Blockchain for Real-Time Monitoring and Optimization of Blood Supply Networks

N. Nasurudeen Ahamed[1], Tanweer Alam[2], Mohamed Benaida[3]
[1]College of Information Technology, United Arab Emirates University, Abu Dhabi, United Arab Emirates
[2,3]Faculty of Computer and Information Systems, Islamic University of Madinah, Madinah, Saudi Arabia

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ABSTRACT

Blood is one of the most vital fluids in the human body. Many existing blood donation systems lack sufficient time, reliable data, effective tracking, data integrity, visibility, monitoring, anonymity, and privacy. Centralized systems are also prone to failures due to their dependence on fixed locations. As a result, the availability of blood continues to decline while the demand steadily increases. Furthermore, current blood management frameworks face challenges due to the need for detailed data collection and the lack of consistent data transparency. Healthcare systems worldwide continue to struggle with ensuring the timely availability of safe blood, largely due to fragmented supply chains, limited visibility, and inefficient inventory management. This paper proposes a novel blood supply chain framework based on blockchain technology to address these challenges. Blockchain is an emerging technology gaining popularity across various domains, including voting systems, smart cities, and healthcare. This study explores how blockchain can enable real-time monitoring and optimization of blood supply networks by providing a decentralized and tamper-proof ledger for tracking donations, storage conditions, transportation, and transfusions. The proposed framework enhances data accessibility by incorporating generalized blood supply information into the shared ledger. The framework utilizes a permissioned blockchain, specifically Hyperledger Fabric, to ensure secure and efficient transaction management. This approach eliminates intermediaries and reduces the risk of illegal blood trade. Smart contracts are implemented within the permissioned network using Go and Java language to enforce data integrity and prevent unauthorized modifications. In the proposed blood cold chain framework, data cannot be altered once recorded, ensuring transparency and reliability, while continuously captured data is maintained in a simplified and structured manner. The effectiveness and value of the proposed solution are validated through a comprehensive evaluation process.

Corresponding Author:

Tanweer Alam
Department of Computer Science, Faculty of Computer and Information Systems, Islamic University of Madinah, Madinah, Saudi Arabia
Email: tanweer03@iu.edu.sa

1. INTRODUCTION

In today's world, blood donation is widely recognized as a life-saving act. Donating blood is not merely a gesture of goodwill; it directly contributes to saving lives. Governments and non-governmental organizations (NGOs) actively promote blood donation through awareness campaigns and outreach programs to encourage young people and volunteers to participate. Globally, blood donation for commercial purposes is strictly prohibited. Despite increased awareness, there are still significant challenges in ensuring the availability of blood during emergencies. [17]. To meet demand, blood collected from donation camps must be efficiently transported to patients through hospitals, forming a critical blood supply chain [26]. However, this supply chain faces several challenges. The centralized structure of existing blood management systems often leads to delays, inefficiencies in data management, and limited flexibility. Changes in supply locations, workforce constraints in healthcare settings, accountability issues, and rising operational costs further complicate the system.

Blood is one of the most vital fluids in the human body, responsible for delivering essential nutrients and oxygen to organs. Blood-related data typically include donor information such as blood type, health status, donation history, and other relevant medical records. While blood transfusions offer significant medical benefits, there are serious concerns about safety, including the risk of transfusing incompatible or contaminated blood. Historical incidents, such as the spread of HIV/AIDS through contaminated blood in the 1980s, highlight the importance of maintaining strict safety standards within the supply chain. Additionally, the healthcare supply chain is vulnerable to issues such as data manipulation, lack of traceability, and even counterfeiting in related domains like pharmaceuticals. These challenges emphasize the need for transparent, secure, and reliable systems to track and manage blood throughout its lifecycle. Blockchain technology has emerged as a promising solution to address these issues by enabling secure, tamper-resistant, and transparent data management. Blockchain-based systems can enhance traceability by securely recording the origin and movement of donated blood across all stages of the supply chain. Prior research has demonstrated the effectiveness of blockchain, particularly permissioned frameworks such as Hyperledger Fabric, in managing pharmaceutical supply chains and preventing counterfeit products. Unlike public blockchains, permission blockchains provide better control over data access, ensuring privacy and integrity when handling sensitive healthcare information.

Building on these advantages, this study proposes a blockchain-based framework for blood supply chain management. The system leverages the immutability and transparency of blockchain to enable continuous monitoring and secure data sharing [10]. Furthermore, smart contracts can automate processes, reduce administrative overhead, and improve operational efficiency. In emergency situations, blood transfer processes between hospitals can be executed efficiently using smart contracts.

The main contributions of this study are as follows:

- Application of blockchain technology in blood supply chain management
- Integration of secure and transparent data tracking mechanisms
- Relevance to broader supply chain domains, including food, medical, and oil industries

1.1 Blockchain

Blockchain is an emerging technology that is increasingly being integrated into various business applications. It is characterized by a decentralized, distributed, and immutable ledger. A blockchain network can be broadly divided into three main components:

- Block: Each block contains a set of transactions, and all transactions are securely recorded within the block.
- Chain: Blocks are linked together in a sequential manner using cryptographic hash values, ensuring the integrity of the data.
- Network: All blocks are interconnected through these hash links, forming a distributed network of nodes.

In a blockchain structure, the first block is known as the genesis block, which serves as the foundation for all subsequent blocks. Each new block is generated and added to the chain only after verification. Every block is cryptographically linked to the previous block, ensuring secure and tamper-resistant data storage. All transactions in a blockchain are highly secure due to the use of cryptographic techniques. Any changes made to transactions are automatically updated across the distributed ledger, maintaining consistency among all participating nodes. Additionally, data within each block are organized using a Merkle tree structure, which enhances data integrity and increases trust in the system.

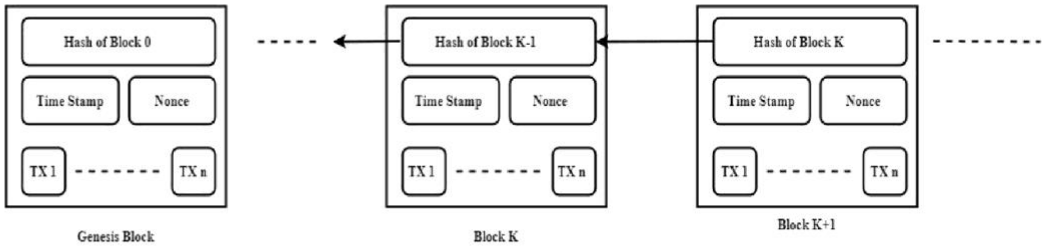

Figure. 1. Basic Blockchain Architecture

Figure 1 illustrates the structure of a Merkle tree and the data exchange process within it. In this structure, the block header contains key elements such as the timestamp and the nonce. The timestamp indicates the exact date and time at which the block is added to the blockchain, while the nonce represents the number of iterations required to validate the block during the mining or consensus process. The block body contains all the transactions associated with that block. These transactions are permanently stored once the block is added to the blockchain. In the basic blockchain structure described above, all transaction data belong to the block body and remain immutable, ensuring transparency and data integrity [18].

1.2. Medical Supply Chain Management

A supply chain is a sequential process that involves moving products from their origin to the final destination at the right time. Many industries rely on supply chain systems, including the food sector, healthcare sector, and e-commerce. In this context, we consider the healthcare supply chain as an example. In a healthcare supply chain, medicines are transported from suppliers to patients through various intermediaries such as manufacturers, distributors, and healthcare providers [9].

Figure. 2. Traditional Medical Supply Chain.

Figure 2 illustrates the traditional drug supply chain. In this model, drugs are transported from suppliers to patients through a series of intermediaries. Similarly, other healthcare products follow comparable pathways within the traditional supply chain to reach patients.

The healthcare supply chain is a complex and extensive system that includes multiple subdomains within healthcare supply chain management [13]. Examples include the drug supply chain, plasma supply chain, and blood supply chain. In this paper, we focus on the integration of blockchain technology into blood supply chain management to improve transparency, traceability, and efficiency

1.3. Research Gap

Data traceability is a critical requirement in supply chain systems, particularly in the context of blood supply chains. Compared to other supply chain operations, managing blood and plasma donation systems is significantly more complex. The processes of collection, transportation, storage, distribution, and transfusion involve multiple stakeholders and require strict coordination. Factors such as the origin of blood products, storage conditions, and transportation time make the data in blood and pharmaceutical supply chains highly sensitive. Therefore, ensuring effective distribution and maintaining confidence in the quality and safety of blood products requires a high level of data visibility.

• Decentralization is a key factor, as it enables the storage of identical data across multiple nodes, ensuring data integrity and system resilience. The analysis demonstrates that the proposed approach effectively eliminates single points of failure by operating in a decentralized manner.

• Privacy is another critical aspect that distinguishes this solution from existing approaches. Centralized systems are more vulnerable to attacks because they rely on a single point of control, whereas decentralized systems distribute data across multiple nodes, making them more secure.

• Transparency and accountability are essential features in such complex systems. The proposed solution ensures transparency by recording all activities on a permanent digital ledger. This guarantees accountability among all participants. In contrast, traditional systems often fail to record all stakeholder activities, leading to reduced traceability and weaker accountability mechanisms.

Table 1. Difference Between the Suggested Approach and the Current Non-Blockchain-Based Solutions.

References	Structures				
	Decentralization	Protection	Morality	Tracking and Tracing	Ownership
[8]	No	No	No	No	No
[25]	No	No	No	Yes	No
[6]	No	No	No	Yes	No
[16]	No	Yes	No	No	No

This research proposes a novel blockchain-based framework for the real-time monitoring and optimization of blood supply networks. Unlike traditional centralized systems, the proposed model ensures end-to-end transparency, security, and immutability of blood movement records by leveraging distributed ledger technology. Furthermore, it introduces the use of smart contracts to automate validation processes and inventory updates, thereby minimizing human errors and reducing administrative delays.

2. METHODOLOGY

2.1. Blockchain Integrated in Medical Supply Chain Management

Blockchain technology enables efficient tracking of the entire lifecycle of medicines and clinical products, from suppliers to patients. Since all transactions are recorded on a distributed ledger and each node in the blockchain network maintains a copy of these records [7], it becomes easy to verify the origin of the medication, as well as the roles of merchants and wholesalers, in real time. In addition, the distributed nature of blockchain allows healthcare authorities and medical professionals to verify and validate the credentials of suppliers. All updates and changes are automatically recorded and synchronized across the ledger, ensuring consistency and reliability. Figure 3 illustrates the integration of blockchain technology into medical supply chain management. The figure demonstrates how blockchain overcomes the limitations of traditional supply chain methods by enabling a decentralized and distributed system. As a result, transactions can be securely and efficiently updated and tracked across the entire supply chain, from suppliers to patients.

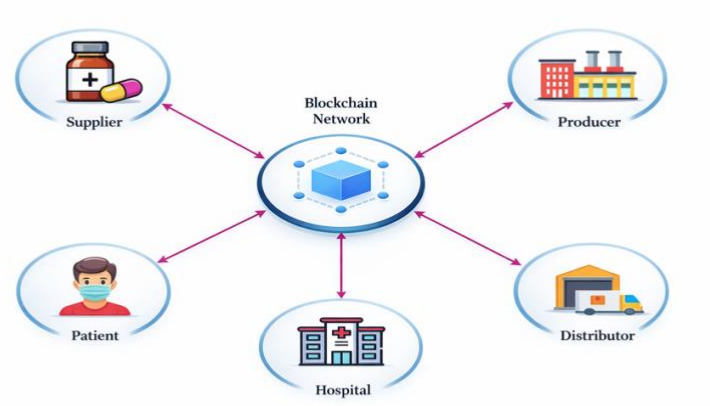

Figure. 3. Blockchain Integrated with Medical Supply Chain.

Decentralization is a fundamental characteristic of blockchain that offers significant advantages for healthcare applications, as it enables the development of distributed systems without reliance on a central authority. Moreover, the replication of data across all nodes in the blockchain network enhances transparency, allowing healthcare stakeholders, particularly patients, to understand how, when, and by whom their data is accessed and used. Importantly, because the ledger is distributed across multiple nodes, the compromise of any single node does not affect the overall integrity or current state of the system. As a result, blockchain inherently provides strong protection against accidental data loss, unauthorized manipulation, and cyberattacks such as hacking incidents.

2.2. Foremost Input

The risks mentioned above can be mitigated through the use of blockchain-based technologies in the blood supply chain. This emerging technology offers multiple capabilities for tracing the origin of donated blood by reliably tracking donor information across different stages of the supply chain. The main contributions of this study are as follows:

- This research proposes a private blockchain network (Hyperledger Fabric) to manage blood supply chain operations in a fully distributed, verifiable, transparent, auditable, secure, and trustworthy manner.
- We integrate the InterPlanetary File System (IPFS), a distributed storage system, with the private Hyperledger Fabric blockchain network to enhance data storage and accessibility.
- The proposed blockchain-based blood supply chain management system is evaluated through security assessments. In addition, the implemented Hyperledger Fabric framework is analyzed and compared with existing solutions.
- The proposed solution is flexible and can be easily adapted to meet the requirements of various industrial applications.

2.3. Related works

To automate blood donation management in a decentralized, transparent, traceable, auditable, private, secure, and reliable manner, several researchers have proposed blockchain-based solutions. One approach suggests a private Ethereum blockchain-based system integrated with the IPFS [12] for decentralized off-chain storage of non-critical and large-scale data. In this approach, smart contracts are used to implement system features and define rules for managing blood donations. The system automatically captures and logs events using Ethereum smart contracts. To address storage limitations, IPFS is combined with the private Ethereum blockchain. The functionality of the solution is evaluated and verified using the Remix Integrated Development Environment (IDE).

Decentralization is a key feature of blockchain that enables distributed healthcare applications [2] without relying on a central authority. This characteristic significantly benefits healthcare systems. Since blockchain data are replicated across all network nodes, transparency is enhanced, allowing stakeholders, particularly patients, to understand how, when, and by whom their data are accessed and used. Furthermore, blockchain immutability ensures that records cannot be altered once stored, which is essential for maintaining the integrity of medical records. In addition, cryptographic techniques ensure that only authorized users can access and decrypt sensitive information, thereby improving privacy and security.

Moreover, blockchain-based systems provide authenticity, immutability, traceability, and non-repudiation for telehealth transactions involving multiple participants. These systems often integrate off-chain storage solutions such as cloud storage or decentralized systems like IPFS. This is particularly important for storing large multimedia data such as images, audio, and video recordings of telehealth sessions [11]. Access control is enforced through role-based permissions, ensuring that only authorized users can access sensitive data. Smart contracts are designed to maintain data provenance and generate reliable alerts and notifications for healthcare data management.

Blockchain-based supply chain management has also been widely explored. Blood supply chain management is a critical area, as the availability of blood directly impacts human lives. Blockchain technology has been proposed as a solution to improve traceability and transparency in the blood supply chain [24], ensuring visibility from collection to end-user delivery. However, several challenges remain in blockchain adoption, particularly due to the unique nature of blood as a scarce and perishable resource. Governments and healthcare systems continuously face challenges in maintaining a stable supply of safe blood products while balancing demand and supply. Blood shortages significantly increase mortality rates and impose high social and economic costs.

Permissioned blockchain systems such as Hyperledger Fabric [23] are widely used in enterprise applications due to their controlled access and trust model. In Hyperledger Fabric, transactions must be endorsed by specific members before validation. These endorsers authenticate transactions while maintaining their identities. However, disagreements among endorsers may arise, leading to potential conflicts within the consortium. To address this issue, anonymous endorsement mechanisms based on threshold policies have been proposed to preserve privacy while maintaining consensus among participants.

Blockchain technology, as a decentralized, consensus-driven system built on peer-to-peer networks, offers transparency, security, and anonymity. In this study, private blockchain systems [3] are investigated for their suitability in healthcare applications. Various testing scenarios are developed using Hyperledger Fabric to evaluate performance, security, privacy, confidentiality, and access control. Experimental results demonstrate that private blockchain solutions provide significant advantages in terms of compliance, interoperability, adaptability, and system resilience.

Hyperledger Fabric is a permissioned distributed ledger platform that enforces access control for authorized users based on predefined roles. It supports flexible access mechanisms for reading, writing, and executing transactions. The platform is highly modular and suitable for diverse industrial applications, including healthcare, finance, insurance [19], banking, and supply chain management. It uses a Practical Byzantine Fault Tolerance (PBFT)-inspired consensus mechanism, eliminating the need for mining incentives. This ensures transaction consistency and ordered execution.

Additionally, Hyperledger Composer has been used to manage data hashing and enforce access control during data retrieval. The proposed blockchain-based architecture enhances healthcare management systems [31]. and addresses security vulnerabilities in existing smart healthcare systems. Performance evaluations using Hyperledger Caliper demonstrate improvements in security, privacy, throughput, and latency compared to traditional systems [5]. To reduce on-chain storage overhead, IPFS is used to store encrypted healthcare data off-chain. IPFS was chosen over blockchain storage for two main reasons. First, it efficiently handles large volumes of data generated by multiple devices without increasing blockchain size. Second, storing large or sensitive encrypted data directly on chain is impractical, as blockchain data is permanently accessible across all nodes, increasing the risk of exposure if compromised.

Each file uploaded to IPFS is assigned to a unique hash address for identification. Even if the same file is uploaded multiple times, it generates the same hash, ensuring data consistency and deduplication. This approach reduces redundancy in decentralized storage systems [14] and improves traceability. IPFS functions as a peer-to-peer distributed file system that uses a distributed hash table (DHT) to manage data location and ownership. It enables efficient data sharing across geographically distributed users, with all nodes maintaining synchronized copies of the hash table, ensuring data availability and consistency. IPFS is a peer-to-peer distributed file system that operates as a collection of nodes working together. It uses a distributed hash table (DHT) to store and manage information, including data location and ownership details. IPFS provides an efficient and decentralized approach for document sharing in distributed environments. The IPFS [4] stores data using cryptographic hash-based addressing rather than traditional location-based storage. Distributed systems based on DHTs are fully decentralized and do not rely on central authority. They enable seamless connectivity among users distributed across different geographic locations. As a result, each participating node maintains a copy of the latest hash table, ensuring consistency, availability, and fault tolerance across the network.

3. RESULT AND DISCUSSION

3.1. Proposed Framework

In this paper, we propose a blood supply network framework utilizing private blockchain technology. We discuss system design scenarios and models, specifically for emergency blood demand situations. One of the most critical requirements for hospitals during emergencies is immediate access to a reliable blood supply. However, if the blood donation center supplying the blood is located far from the hospital, delays and logistical challenges may occur. These challenges can be mitigated by utilizing surplus blood from nearby hospitals. Therefore, we designed a framework that enables direct and real-time emergency blood exchange between local hospitals. Using blockchain technology, all important transaction records are securely stored and shared in real time. Blockchain technology can be categorized into three main types:

Public blockchain: As the name suggests, anyone can join and participate in the network (e.g., Ethereum).

Private blockchain: Only authorized participants are allowed to join and operate within the network (e.g., Hyperledger Fabric).

Consortium blockchain: A hybrid model that combines features of both public and private blockchains, where a group of organizations jointly manages the network.

In our proposed work, we focus on a private blockchain implementation using Hyperledger Fabric. In this context, public blockchains are permissionless, whereas private and consortium blockchains are permissioned. The detailed differences between permissioned and permissionless blockchains are summarized in Table 2.

Table 2. Difference between Permissioned and Permissionless.

Permissioned	Permissionless
Prohibitive admittance to the Organization	Open admittance to the organization
Light agreement calculations	Complex agreement calculations
Agreement with restricted adaptability	Versatile agreement
No need for motivational components	Motivating force instruments

1.2. Hyperledger Fabric

Hyperledger Fabric is an open-source blockchain platform hosted by The Linux Foundation and supported by IBM as "Blockchain as a Service." It is primarily designed for enterprise and organizational use. Hyperledger Fabric supports smart contracts by enabling interaction among all relevant parties within a network. It is a type of private or permissioned blockchain in which organizations or government entities own and manage the nodes, and allow authorized nodes to communicate with each other. In this system, the identities and roles of participants are known to other authorized members [28].

Hyperledger Fabric follows a modular architecture that allows the integration of pluggable components for different infrastructure elements, such as consensus mechanisms. It also supports customizable consensus algorithms that can be configured and deployed as needed. Fabric supports chaincode, which is equivalent to smart contracts in Ethereum.

Hyperledger Fabric follows an Execute–Order–Validate (or Submit) model, in which transactions are first executed, then ordered, and finally validated before being committed to the ledger.

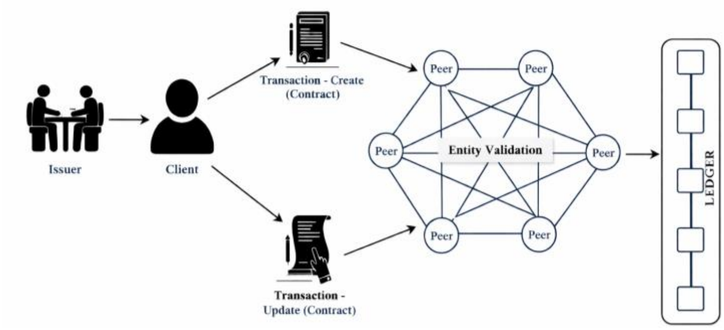

Figure. 4. Hyperledger Fabric Architecture.

Based on the arrangement of validators defined in the endorsement policy shown in Figure 4. [1], [15]. This approach improves scalability by reducing congestion, preventing non-determinism in consensus execution, and enabling private execution of transactions among a selected group of participants. The scalability of Hyperledger Fabric also depends on how efficiently the hardware resources of participating entities execute the transaction validation pipeline [29]. Since Hyperledger Fabric does not rely on computationally expensive mining processes to validate transactions, it supports the development of scalable blockchain systems with lower latency. The key components of a typical Hyperledger Fabric network are as follows:

• Ledger: The ledger maintains a chain of blocks that store immutable historical records of all state changes.

• Nodes: Nodes are the logical entities in the blockchain network and are categorized into three types:

1. Clients: Applications that act on behalf of users to submit transactions to the network.
2. Peers: Nodes that execute transactions and maintain the state of the ledger.
3. Orderers: Nodes that establish communication between clients and peers by ordering transactions, grouping them into blocks, and delivering them to peer nodes for commitment..

1.3. Components of Hyperledger Fabric

The main components of Hyperledger Fabric are as follows:

- Chaincode: Chaincode is similar to a smart contract in other blockchain platforms such as Ethereum. It is a program written in a high-level programming language that runs against the current state of the ledger database. In this work, the chaincode is implemented using the Go programming language. Figure 5(a) illustrates how two different organizations can share data using chaincode.
- Peer: A peer in the network refers to a node that maintains a local copy of the ledger for each channel it participates in, as shown in Figure 5(b). Peers may also execute chaincode locally. Therefore, peers provide client applications with access to both the ledger and the chaincode within their respective channels.
- Channel: A channel is a private communication pathway between a set of peer nodes. It is a logical structure formed by a subset of participants, where each channel maintains its own independent ledger and blockchain state, as depicted in Figure 5(c). As a result, a single

Hyperledger Fabric network can support multiple separate blockchains through different channels. If a peer participates in multiple channels, it maintains a separate ledger for each one.

- Orderers: Orderer nodes provide the ordering service that establishes a common communication layer between clients and peers. They are responsible for receiving transaction messages, ordering them, and packaging them into blocks, as illustrated in Figure 5 (d). Orderers ensure the consistent, atomic, and sequential delivery of transactions within each channel.

(a) Chain Code (b) Peer

(c) Channel (d) Orderers

Figure. 5. Hyperledger Fabric Components.

1.4. Decentralized Version

Blockchain provides a distributed ledger or database that is shared among all participants in the network based on a consensus mechanism. The need for a third-party verifier is eliminated, making the system more secure and decentralized. Any transaction that results in a change to the blockchain ledger is digitally signed, verified, and validated by validator nodes, each of which maintains a copy of the ledger. This ensures the creation of decentralized, secure, time-stamped, and tamper-resistant records. Blockchain technology has been widely applied in various industries, including finance, healthcare, supply chain, logistics, record management, and accounting [27]. Due to its robust and decentralized architecture, blockchain is used to address challenges related to trust, transparency, security, and data sharing. It removes the requirement for intermediaries by leveraging cryptographic techniques to provide reliable and verifiable solutions for all participating entities. One example of such a platform is Hyperledger Fabric. Hyperledger Fabric supports decentralized applications (DApps), where smart contracts (chaincode) can be written in programming languages such as Go or Java and executed within secure container environments. In Hyperledger Fabric, decentralized application logic written in Go is similar to Ethereum smart contracts. This allows the implementation of automated agreements between suppliers and consumers without the involvement of third parties. In the proposed blood supply chain management system, chaincode (smart contracts) is developed to manage and regulate the transfer of blood from donation centers to hospitals. This approach helps eliminate intermediaries and reduces the risk of black-market involvement in blood distribution.

```
Pseudocode 1: Create Smart Contract (ChainCode) for
BloodDoantion
      Procedure contract Blood camp
      string public patient name;
      function Blood camp() public
      patient name =” XXXX”;
      function set (string name) public
      patient name =name;
      function patient() constant returns (string)
      return patient name;
      End Procedure
```

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The above Pseudocode 1 (Contract) establishes a dedicated blood donation camp for hospitals. In case of an emergency for a particular patient, this contract is executed through the hospital to ensure timely availability of blood for the appropriate recipient. In this way, the involvement of third parties can be eliminated. Moreover, all transactions occur in a decentralized manner, making them visible to all participants in the network. An additional advantage of this permissioned blockchain-based supply chain system is the ability to monitor critical parameters such as blood type and storage temperature. These factors can be tracked effectively throughout the supply chain. Furthermore, all relevant data can be securely stored in a distributed manner, ensuring transparency, integrity, and traceability.

```
Pseudocode 2: Smart Contract (Chain Code) for Blood Temperature
        Procedure class Blood
        "blood id": "Blood123"
        "blood type": "B Positive"
        "unit": "350"
        temperature
        "transaction-id" : "123456"
        "centigrade": "4"
        "timestamp" : "2021-03-07 13:10 IST"
        End Procedure
```

The above Pseudocode 2 (Contract) is designed for blood storage management. Human blood must be stored under controlled temperature conditions and preserved within a specific time period. However, patients and end users are generally unaware of the storage temperature and the duration for which blood is preserved. To address this issue, all relevant information is stored in a permissioned blockchain in a decentralized manner through chaincode (smart contract) implementation. This ensures transparency, traceability, and reliable monitoring of blood storage conditions throughout the supply chain.

1.5. Blood Supply Chain Using Blockchain Through Decentralized IPFS Storage

Completely decentralized blockchain systems ideally rely on decentralized storage frameworks such as the IPFS. IPFS stores files across a distributed network of public nodes and provides content-based addressing using the file's SHA-256 hash, making it easy to integrate storage with blockchain systems. IPFS is a distributed storage system that returns a unique hash for each uploaded file [33].

The IPFS system is also supported and maintained by healthcare stakeholders, such as hospitals and medical organizations. It uses a content-addressing mechanism in which the address is derived from the content of the file itself. Each file is converted into a unique hash string, which serves as its identifier. Anyone can retrieve the complete file stored in IPFS using its corresponding hash stored on the blockchain. IPFS enables efficient distribution and storage of large volumes of data [20].

IPFS is a peer-to-peer system in which no node has priority over another. IPFS nodes store objects in local storage and communicate with each other to exchange data. These objects represent files and other data structures. The IPFS protocol is composed of several sub-protocols responsible for different functions:

- Identity: Manages node identity generation and authentication.
- Network: Manages connections with other peers using underlying networking protocols.
- Routing: Maintains information to locate specific peers and objects and responds to both local and remote queries.
- Exchange (BitSwap): A block exchange protocol that ensures efficient data distribution. It operates as a market-based mechanism that incentivizes data replication.
- Objects: A Merkle Directed Acyclic Graph (DAG) of content-addressed immutable objects used to represent data structures such as file hierarchies and communication data.
- Files: A versioned file system inspired by Git.
- Naming: A self-certifying naming system.

Figure 6 illustrates the proposed blockchain-based blood supply chain framework. In this system, Hyperledger Fabric is used as a permissioned blockchain network, where only authorized participants are allowed to join and interact. Doctors are able to access patients' blood type and required blood units. In the proposed framework, all data are stored in decentralized storage, ensuring transparency for all participants in the permissioned network. Doctors can view available blood types and, after verification and approval, request blood from donation centers for the intended patient. This approach ensures that all requirements, such as blood type compatibility, storage temperature, and preservation duration, are properly monitored and satisfied [32], [22].

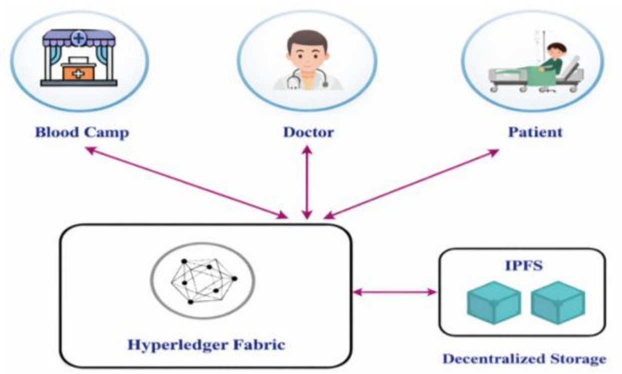

Figure.6. Blood Supply Chain Using Hyperledger Fabric through Decentralized Application

The sequence diagram in Figure 7 illustrates the process of accessing blood from a blood donation camp to the appropriate patient. In this modern healthcare system, blockchain technology is utilized to ensure transparency, traceability, and decentralization in the blood supply chain. Initially, the blood donation camp uploads relevant information such as blood type and storage temperature to decentralized storage. When required, doctors or hospitals access this information through a decentralized system such as IPFS to retrieve blood availability details. If the available blood matches the patient's requirements, the doctor directly submits a request to the blood donation camp. The camp then approves the request and initiates the distribution process to the concerned hospital. Finally, the patient receives the appropriate blood in a timely and secure manner [34], [35].

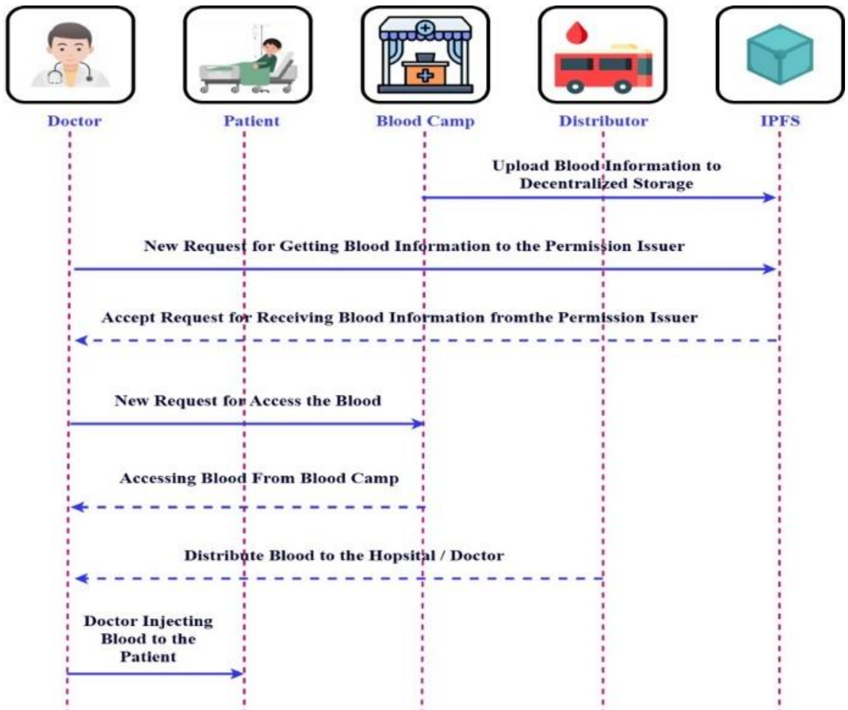

Figure.7. Sequence Diagram of Accessing Blood

4. RESULT

In this section, we implement Hyperledger Fabric (private channel) for managing patient-related data within the blockchain system. All blood types, blood units, and other related information are stored in separate blocks. These records are maintained and shared in a decentralized manner, ensuring transparency and traceability throughout the blood supply pipeline. The flow of the blood supply process is straightforward and easy to track. Additionally, once recorded, data cannot be altered by any participant. This is achieved through the use of a private channel in Hyperledger Fabric, which secures the blood supply chain. A channel is a private communication subnet between two or more organizations that enables confidential and secure data exchange. The messages transmitted through a channel are accessible only to authorized participants within that channel, ensuring privacy and security of information, as shown in Figure 8.

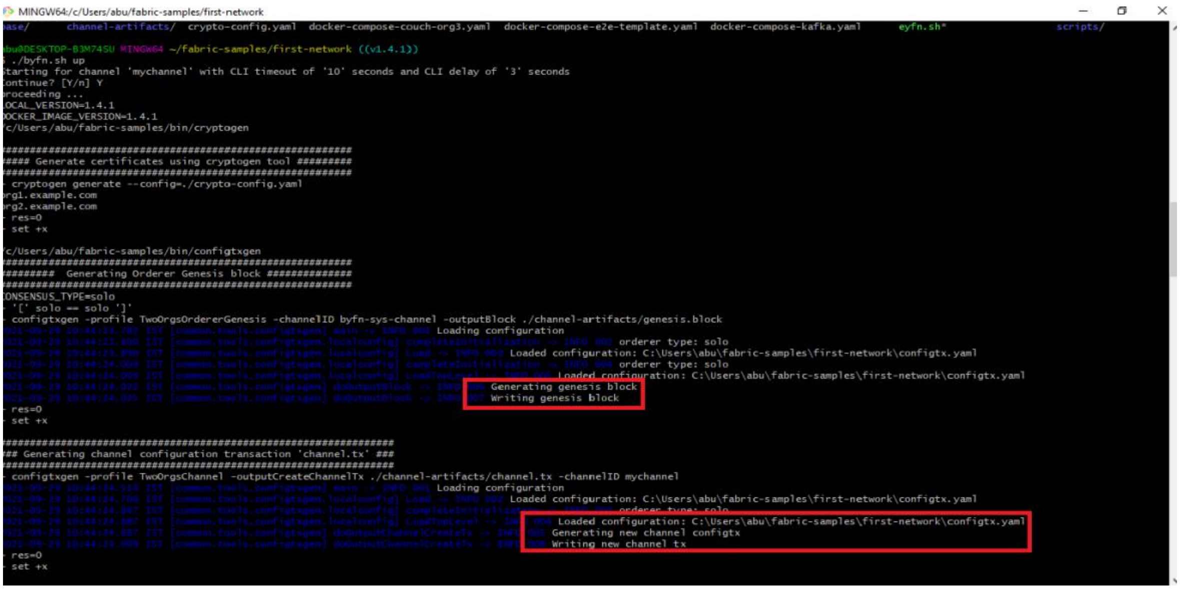

Figure.8. Generating New Channel for Patients

Once a channel is created, all records remain private and can be retrieved whenever required. After setting up the channel, doctors or patients can monitor relevant information such as hospital and blood camp locations, ambulance (vehicle) location, blood type availability, and the number of patients waiting for transfusion. Figure 9 illustrates the navigation and interaction among the patient, hospital, and blood supplier (blood donation camp), showing how location and status information are shared within the system.

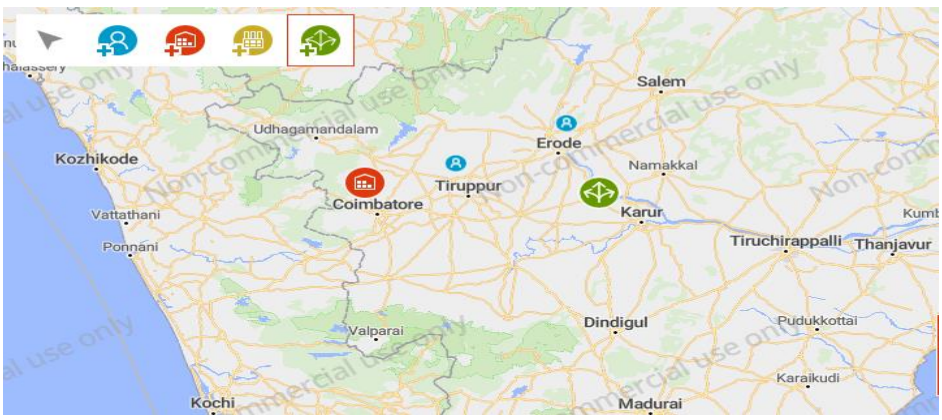

Figure.9. Navigation Map for Flow of Blood Supply Chain.

Figure 10 describes the schedule allocation of the blood supply chain, including the source of blood, destination, type of vehicle used, priority level, total number of orders, and other relevant parameters. All this information is stored in separate blocks within the blockchain to ensure proper organization and traceability. Whenever required, this data can be securely retrieved and utilized for decision-making and coordination within the blood supply chain system.

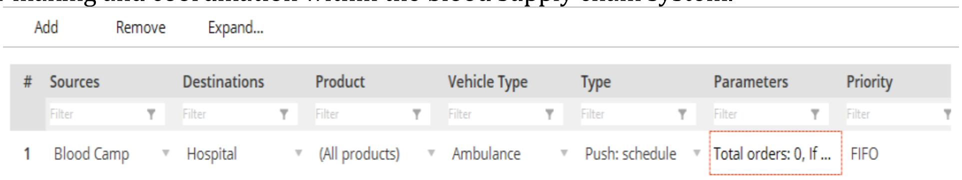

Figure.10. Schedule Allocation for Blood Supply.

When an organization joins a blockchain network, it can create and maintain a private channel with selected participants. Organizations define and establish channels to allow specific nodes to perform private and confidential transactions that are not visible or accessible to other members of the same network. Each channel consists of participating nodes, a shared ledger, chaincode deployed on the channel, and one or more ordering services.

Figure.11. Fabric Channel Execution Completed.

Figure 11 illustrates private communication within the blood supply chain using Hyperledger Fabric. Through this system, information related to the appropriate patient and blood transfer is securely shared via a private channel. Once the blood is delivered to the correct destination, the execution process within Hyperledger Fabric is completed. However, all transaction data remains permanently stored in the blockchain ledger. Hyperledger Fabric has evolved significantly in recent years and now supports a wide range of features that enterprises can rely on. It is designed primarily for enterprise applications from the outset. Among all Hyperledger projects, it is the most actively developed, with a continuously growing community. As a result, it has been successfully applied to blood supply chain management systems.

5. DISCUSSION

In this study, we model the blood supply chain from the blood bank to the appropriate hospital using blockchain technology. The proposed system integrates a private blockchain framework with decentralized storage. For this purpose, we propose a permissioned blockchain system using Hyperledger Fabric, which is decentralized, transparent, verifiable, auditable, secure, and reliable for managing the blood supply chain.

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The proposed approach utilizes the IPFS for decentralized off-chain storage of non-critical and large-scale data. We also provide a brief description of the algorithms, sequence diagrams, and system architecture to illustrate how the proposed blood supply chain management system operates. Furthermore, we evaluate the efficiency and performance of the solution through a comprehensive security analysis.

5.1. *Proposed Private Blockchain Network (Hyperledger Fabric)*

The proposed approach is built on a private blockchain network, which organizations typically use to enhance data privacy and control. Nodes can access the blockchain only if they have the required authorization. These nodes operate within a restricted environment and are not openly accessible from the public network. Sensitive information, such as blood management records, must be stored securely, as only authorized individuals and organizations should have access to patient data and related medical information. A private blockchain network is therefore more suitable for the proposed system, as it ensures privacy, confidentiality, and controlled access through authorization mechanisms.

5.2. *Decentralized Storage Systems- IPFS*

Large-scale data that would be expensive to store directly on Hyperledger Fabric can instead be managed using external storage systems. In this approach, only a hash of the data is stored on the blockchain ledger, while the actual files are stored in a decentralized storage system such as IPFS, which supports efficient and distributed storage of large files. The proposed blockchain-based approach demonstrates that blockchain technology can effectively be used to track blood units during transportation and distribution. The Hyperledger Fabric code developed in this study is designed for managing donated blood delivery; however, it can also be extended to other supply chain systems, such as food logistics. The movement of donated blood through the supply chain differs from other products due to its sensitive nature. One key requirement is a cold chain system to maintain product quality. Similarly, certain pharmaceuticals and medical products require controlled conditions, including specific temperature, humidity levels, and storage requirements during transportation and distribution. This research focuses on traceability, which involves tracking the origin and movement of items such as blood, pharmaceuticals, and medicines. This is achieved by using unique identification numbers assigned to each product, enabling secure and efficient tracking throughout the supply chain.

5.3. *Safety Examination*

- Honesty (Transparency): The proposed private blockchain-based solution enables the healthcare supply chain to monitor donated blood units effectively. By recording all transactions on the ledger, information related to blood donations becomes transparent and accessible. Additionally, the use of barcode scanners to assign a unique identification number to each blood bag helps ensure data accuracy and integrity.
- Responsibility (Accountability): Each participant is assigned a specific role through the access control features of Hyperledger Fabric. If any errors occur during the transportation or distribution of donated blood units, the designated and authorized distributor is held accountable. This ensures that all participants are responsible for their actions within the system.
- Authorization (Access Control): Ensuring the integrity of ledger information in the medical supply chain is essential. Since blockchain records are immutable, once data is written, it cannot be altered or deleted. As a result, only authorized members are granted access to critical operations based on their roles within the supply chain, enforced through access control mechanisms.
- Availability (Fault Tolerance): The private blockchain operates on a distributed and decentralized architecture. Transaction data is replicated across all participating nodes, ensuring that information is not lost even if one node fails. This feature guarantees high availability and reliability, which is essential for critical domains such as healthcare.

- Protection Against Man-in-the-Middle (MIM) Attacks: Every transaction recorded in the ledger is digitally signed using the sender's cryptographic key. This prevents unauthorized interception or modification of data during transmission. As a result, man-in-the-middle attacks are effectively mitigated, enhancing the security of the blood donation system and the overall medical supply chain. This also reduces the risk of forgery, as only trusted and authorized entities can access and execute transactions.

5.4. Comparison of the proposed solution with existing blockchain solution

Based on key factors such as the blockchain platform, programming language, mode of operation, transaction cost, transparency, and storage system, Table 3 compares the proposed solution with an existing blockchain-based solution. The proposed system operates on a private blockchain network, ensuring controlled access, enhanced privacy, and improved security.

Table 3. Comparison of the proposed solution with existing blockchain solution

References	**Structures**				
	Blockchain Policy	**Program**	**Types of Blockchain Network**	**Traceability**	**Off-Chain Storage**
[17]	HyperLedger	Chain Code	Private	Yes	No
[21]	HyperLedger	Chain Code	Private	Yes	No
[30]	Ethereum	Smart Contract	Public	Yes	Yes
[12]	Ethereum	Smart Contract	Private	Yes	Yes
Our Result	HyperLedger Fabric	Chain Code	Private	Yes	Yes

5.5. Performance Estimation

Block size

When comparing the scalability and number of operations between on-chain and off-chain models, performance evaluation considers patient data (blood) transactions. The assessment benchmark is based on 100 blocks containing patient data transactions, while the number of nodes is increased to simulate scalability up to 1000 blocks.

- Duration of Block = 80 Bytes.
- Duration of Information Exchange (Off Chain Storage) = 132 Bytes.
- Median size for Blood (Patient) Information = 18 KB. (For Assumption)
- Block's Total Volume= 1 MB.

Dataset Quantity

The amount of information processed in the blockchain is compared between off-chain and on-chain models by considering 1,000 transactions to construct the comparison graph. The evaluation starts with a baseline of 1,000 transactions and is incrementally increased in steps of 1,000 for further analysis.

- Median size for Blood (Patient) Information = 18 KB. (For Assumption)
- On-Chain Storage for 1000 Exchanges = 18432000 [18 KB Convert to Bytes= 18432 Then, 18432*1000 = 18432000]
- Off-Chain Storage for 1000 Exchanges = 132000. [132 *1000]

It is abundantly obvious from the contrast that an off-chain architecture for storing health (Blood)information is a strong and flexible model.

Speed and Capacity Compression Ratio

This storage approach provides the blockchain network with a significant advantage in addressing capacity and memory limitations. Consider a healthcare (blood supply chain) blockchain network without IPFS that relies on an on-chain storage approach. In such a scenario, the storage requirement increases with the number of nodes, as it includes the cumulative size of all block headers and the total data stored across the blockchain network.

- Duration of Block = 80 Bytes.
- Duration of Information Exchange (Off Chain Storage) = 132 Bytes.
- Median size for Blood (Patient) Information = 18 KB. (For Assumption)

- A Total Transaction Duration for On-Chain Storage (ttd_{on}) =18432 Bytes.
- A Total Transaction Duration for On-Chain Storage (ttd_{off}) =132 Bytes.

Percentage of Memory Compression (PMC)

PMC = (q_{off} * h_{mass}) + $\sum_{1}^{q\ off}(ttd\ off)$ / (q_{on} * h_{mass}) + $\sum_{1}^{q\ on}(ttd\ on)$

Where,

- q_{off} = quantity of blocks (Off-Chain Storage).
- q_{on} = quantity of blocks (On-Chain Storage).
- h_{mass} = mass of block header (80 Bytes).

Now let us estimate the memory efficiency using the assumption that there are only 500 transactions including patient health (blood) records. In our concept, 1000 processes require 18 blocks of on-chain storage, whereas 1 block is necessary for off-chain storage. Consequently,

PMC = ((1 * 80) + 66000) / ((18*80) + 9171000) [Assume, 500 Transaction]
PMC = (80+66000) / (1440 + 9171000)
PMC = 66080 / 9172440
PMC = 0.00720

By comparing the off-chain model's blockchain storage space savings to the on-chain model's uncompressed size, as shown below, it is possible to calculate the amount of reduction.

Amount of Reduction (AR) = $\sum_{1}^{q\ on}(ttd\ on)$ - $\sum_{1}^{q\ off}(ttd\ off)$ / $\sum_{1}^{q\ on}(ttd\ on)$ *100.
(AR) = 9172440-66080 / 9172440 *100
(AR) = 9106360 / 9172440 *100
(AR) = 0.99279 *100
(AR) = 99.279%

The previous calculations of the percentage of memory compression and amount of reduction rate for 500 transactions involving patient health (blood) records reveal significant space savings on the blockchain.

Evaluation of memory access rates

The memory recovery times using centralized and decentralized storage are evaluated for various file sizes, as shown in Figure 14 (15, 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, and 300 KB). Using IPFS storage in the proposed "Blood Supply Chain Management Using Blockchain Technology" framework, the system retrieves patient blood information significantly faster than the centralized approach.

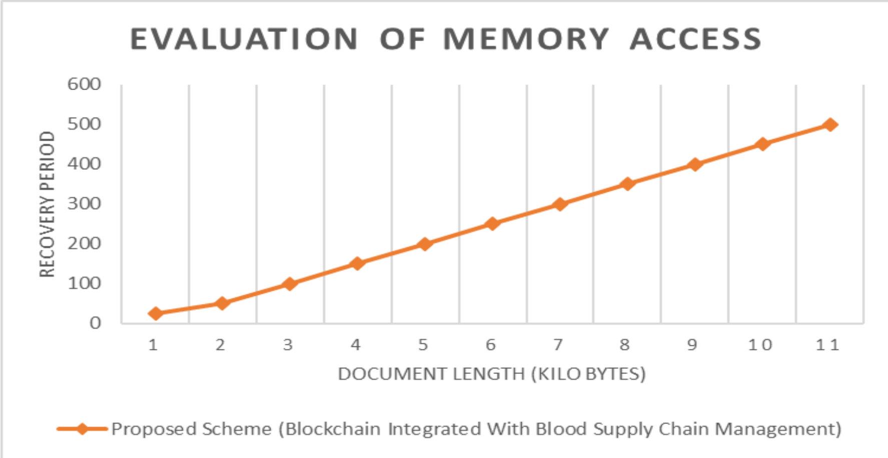

Figure.14. Evaluation of Memory Access for the Proposed Scheme.

6. CONCLUSION

This study demonstrates the transformative potential of blockchain technology in addressing critical inefficiencies and transparency gaps within traditional blood supply networks. The proposed framework is decentralized, secure, and robust, eliminating the need for a trusted third party. Since both blockchain and IPFS are decentralized technologies, blood-related data and associated information are stored in distributed storage systems, ensuring efficiency and reliability. Access to blood resources is controlled through authorized permissions in Hyperledger Fabric. After approval by authorized personnel, doctors can easily access and retrieve blood from the donation center. In this system, it is essential to continuously track key blood-related data such as blood type, storage temperature, and preservation duration. By enabling real-time monitoring, secure data sharing, and automated validation through smart contracts, the proposed blockchain-based framework significantly improves the traceability, reliability, and responsiveness of blood logistics systems.

In the future, research can focus on large-scale real-world implementations across diverse healthcare environments to evaluate scalability and adaptability. Integration with national health information systems, AI-based demand prediction models, and mobile donor engagement platforms can further enhance system intelligence and outreach. Additionally, addressing legal, ethical, and privacy considerations in healthcare blockchain adoption will be essential for ensuring regulatory compliance and widespread acceptance. This work establishes a foundation for developing secure, resilient, and patient-centric blood supply networks using next-generation technologies.

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