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Strengthening Blood Supply Chain Performance and Transfusion Safety through Blockchain and IoT Integration

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Abstract

Purpose: This study aims to address key challenges in blood donation systems, particularly in low- and middle-income countries, by proposing a scalable framework to ensure safe, efficient, and equitable blood supply management while improving traceability and reducing preventable health risks.

Design/Methodology/Approach: A population-scale framework integrating blockchain, Internet of Things (IoT)–based monitoring, and Interplanetary File System (IPFS) storage is proposed. IoT sensors continuously monitor environmental conditions, while blockchain smart contracts enable secure donor verification, automated consent management, and immutable logging. Large datasets are stored off-chain using IPFS, with cryptographic hashes maintained on-chain. The system was evaluated using public datasets and simulated workflows.

Findings: Results show donor eligibility accuracy above 96%, stable throughput of 77–80 transactions per second, and reliable cold-chain compliance with a Blood Storage Quality Index of 0.98. The framework outperforms traditional systems in scalability and transparency. The study is limited by simulation-based validation and requires future real-world deployment.

Practical and Social Implications: The system improves blood safety, reduces wastage, enhances trust, and supports better healthcare delivery.

Originality/Value: This work offers a novel integration of blockchain, IoT, and IPFS for scalable, transparent blood supply management.

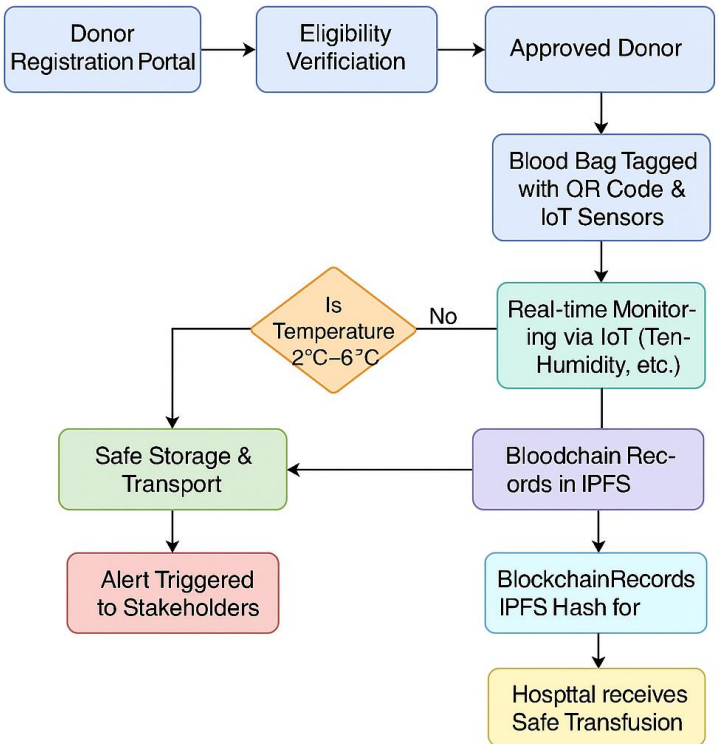
Keywords: Population health metrics, blood donation management, blockchain, Internet of Things, cold-chain monitoring, health system performance

JEL Classifications: I11, I18, L86, L91, O33

1. Introduction

Blood is one of the most essential bodily fluids in the human organism, providing vital nutrients and chemicals necessary for organ function and survival. With the rising demand for blood, donation has become a critical medical necessity. Governments often initiate educational campaigns and organise events to highlight the importance of blood donation. Between 2022 and 2023, an estimated 136,908 donors contributed to 216,639 donations (Alawode et al., 2025). According to the World Health Organisation (WHO), approximately 112.5 million units of blood are collected annually, equivalent to around 50 million litres. Blood components are typically stored at temperatures between 2°C and 6°C, necessitating constant monitoring. Storing blood at temperatures above 6°C accelerates bacterial growth, posing fatal risks to recipients. Conversely, red blood cells may clot, hemolyze, and release haemoglobin if stored below 2°C (Cywinski, 2025). Blockchain and IoT technologies offer numerous applications in blood donation, including enhancing security, privacy, stakeholder collaboration, donor incentives, automation, and patient safety. Integrating these technologies into the blood supply chain can significantly improve transparency, efficiency, and trust among stakeholders. Further research and development are essential to address practical challenges and validate the feasibility of blockchain and IoT integration in real-world blood donation scenarios (Jum'a et al., 2024). Inadequate blood availability and ineffective cold-chain management contribute significantly to preventable morbidity and mortality at the population level, particularly in emergency care, maternal health, trauma management, and surgical services. The World Health Organisation (WHO) identifies blood availability, safety, and accessibility as key indicators of health system performance, especially in low- and middle-income countries (LMICs), where supply–demand mismatches and storage failures remain prevalent. Interruptions in blood supply chains and temperature deviations during storage and transportation increase the risk of transfusion-related complications, blood wastage, and delayed treatment, thereby negatively impacting population-level health outcomes. This research paper proposes a novel blood donation system that combines blockchain technology and the Internet of Things (IoT) to improve the efficiency, transparency, and security of blood donation processes. The research involves designing and implementing a prototype system, evaluating its performance, and assessing its potential impact on the healthcare industry. The key contributions of this paper are shown in Figure 1.

Figure 1. Workflow Diagram



- Proposing a solution utilizing the Ethereum blockchain to automate blood donation management processes, aiming for decentralisation, traceability, transparency, auditability, privacy, security, and trustworthiness.
- Addressing existing storage constraints by integrating a private Ethereum blockchain with the decentralised storage of the Interplanetary File System (IPFS).
- Conducting security analyses to evaluate the effectiveness of the proposed blockchain-based blood donation management solution and the developed smart contracts. Additionally, performing a comparative analysis with existing solutions.
- Demonstrating that the proposed blood donation management solution is generic and can be adapted to meet the requirements of various industrial applications with minimal modifications.
- Utilising IoT sensors to continuously monitor storage conditions for blood units, including temperature, humidity, and other relevant factors, with immediate alerts triggered upon deviation from optimal ranges to ensure the quality and safety of the blood supply.

Implementing a blockchain and IoT-integrated IPFS blood donation system can significantly transform blood donation management and monitoring processes. Blood donation events can be recorded as transactions on the blockchain, creating a permanent and verifiable record. Blockchain technology also enables the integration of smart contracts to automate various processes and ensure compliance with

predefined regulations. For instance, smart contracts can autonomously verify donor eligibility based on set criteria or trigger notifications when blood inventory levels surpass a specified threshold. By leveraging these technologies' unique attributes, a decentralised and transparent blood donation system can be established, ensuring confidentiality, verifiability, and reliability. Continuous monitoring of storage conditions and immediate alerts in case of deviations further ensure the integrity and security of the blood supply. Continued research and development are necessary to overcome practical challenges and confirm the viability of implementing these solutions in real-world scenarios. This work introduces an integrated framework combining blockchain, IoT-based monitoring, and IPFS storage within a unified architecture. Unlike prior studies addressing these components separately, the proposed system enables end-to-end automation with a unified performance metric (SPI).

2. Related Work

Supply chain management is a discipline that integrates essential business processes and information, utilising a central server to address visibility and traceability concerns. This system involves a highly complex process requiring the synchronisation of various operations, leading to unpredictability and vulnerability within the supply chain. Another author introduced a model aimed at reducing costs and risks by representing the degradation properties of blood as supply coefficients. This model was specifically designed to manage the distribution of blood units efficiently in response to urgent needs, such as those following the earthquake in Iran (Goel & Neduncheliyan, 2024). The authors developed a multi-level, multi-objective model to determine the optimal route for transporting blood, using a selection of routes (Eskandari-Khanghahi et al., 2018). The primary focus of the study by another group was to minimise expenses associated with the blood supply chain network while optimising its reliability (Norouzian-Maleki et al., 2025). Additionally, they proposed a mathematical model incorporating integer mixed linear programming to address location, allocation, inventory, and distribution factors (Behl & Dutta, 2019). In contrast, another study successfully incorporated geographic information systems (GIS) and data mining methodologies in developing blood supply chain processes, aiming to create an efficient blood transport model for military situations. A drawback of the above approaches is the lack of transparency in centralised storage systems (Nagurney et al., 2012; Nazir et al., 2023). The application of a software architecture following a microservices-oriented approach for middleware effectively gathers, retains, and tracks data centrally, facilitating data analysis. A previous study proposed a centralised solution for managing blood donations to leverage these benefits, reducing the quantity of data collected from blood donors and enhancing blood donation management efficiency (Delen et al., 2011). A system named BloodChain, operating on Hyperledger Fabric, has been introduced to facilitate the authentication of transactions involving the transfer of blood from donors to recipients (Balan, 2024). BloodChain also enables the presentation of essential information throughout the blood donation procedure, providing actors within the system with limited information to authenticate the details of donors and recipients (Ahmed et al., 2025; Van et al., 2022a). Similarly, another system presents a blood supply chain management system using Hyperledger Fabric, ensuring transparency in the blood donation process by effectively monitoring the movement of blood units from donors to recipients. Moreover, radio frequency identification (RFID) technology has been integrated into blood bags using the electronic product code

(EPC) stored within the RFID tags, enhancing reliability and reducing the risk of tampering through tracking and tag verification mechanisms (Wang et al., 2021). Many traceability solutions utilise a centralised server to address visibility and traceability issues. RFID technology is a widely accepted method for tracking and monitoring blood bags, due to its significant importance in supply chain management. This technology transmits data through audio frequency waves, facilitating the identification of tagged items (Ramasamy & Khan, 2024). One study introduced a dynamic blood information management system using RFID technology to track blood products within blood centres. The RFID chip is incorporated into the blood bags as part of the identification process during the preparation phase. When a healthcare centre issues an order, the delivery operator selects the bag and encodes the RFID chip with the appropriate destination information (Ali et al., 2023; Jaisinghani et al., 2024).

Recent population health research emphasises that blood availability, safety, and equitable access are critical determinants of health system performance, particularly in low- and middle-income countries (LMICs) (Zainal et al., 2025). Inadequate blood supply and weak cold-chain management have been directly associated with increased maternal mortality, trauma-related deaths, and delayed surgical interventions at the population level (Organization, 2025). The World Health Organization (WHO) identifies blood availability per 1,000 population and transfusion safety indicators as essential population health metrics for evaluating national health system resilience (Juma et al., 2025).

Several studies have examined blood systems from a population health perspective by focusing on demand–supply mismatches, regional disparities, and systemic inefficiencies (Dhanda et al., 2025). Population-based modelling approaches have been proposed to predict blood shortages during emergencies and epidemics, highlighting that fragmented data systems and delayed information sharing significantly reduce transfusion coverage (Kotam et al., 2025). These studies primarily rely on centralised health information systems, which limit real-time visibility and inter-institutional coordination (Xi et al., 2025).

Cold-chain failure has been recognised as a major contributor to blood wastage and transfusion risk at scale (Chien et al., 2025). Epidemiological studies report that temperature deviations during storage and transportation result in substantial loss of usable blood units, thereby reducing effective blood availability across populations (Pinto et al., 2025). However, most population-level analyses focus on outcome statistics rather than proposing integrated digital mechanisms to actively prevent cold-chain violations (Sarkar, 2025).

From a health systems perspective, trust and transparency are also identified as key enablers of voluntary blood donation (Müller & Reuter-Oppermann, 2024). Population health literature suggests that lack of traceability and accountability discourages donor participation, particularly in regions where informal or opaque blood supply practices persist (Adeaga, 2024). While policy-driven interventions and donor awareness campaigns have shown limited success, digital trust infrastructures remain underexplored in population health-oriented blood management research (Malan-Lebona, 2024).

Table 1 presents a comparative analysis of existing approaches for blood supply chain and blood donation management based on their adopted technologies, monitoring capabilities, and key limitations. The comparison shows that previous studies have primarily focused on individual aspects of the blood management process. Norouzian-Maleki et al. (2025) emphasized simulation-based optimization and donor participation but did not incorporate real-time IoT monitoring or blockchain-based traceability. Similarly, (Jum'a et al., 2024) proposed an IoT-enabled conceptual framework without cryptographic verification or automated execution mechanisms. Goel and Neduncheliyan (2024) combined blockchain, AI, and IoMT concepts; however, their approach lacked experimental smart-contract evaluation, gas-cost analysis, and decentralized storage. Jaisinghani et al. (2024) demonstrated the benefits of RFID and IoT for blood-bag tracking and monitoring, but the system did not provide immutable blockchain records, automated smart-contract execution, or decentralized data storage. Cywinski (2025) highlighted the importance of maintaining blood storage conditions within the recommended 2°C–6°C range but did not propose an integrated digital mechanism for real-time monitoring, automated alerts, or secure traceability.

Table 1. Comparative Analysis of Existing Studies and the Proposed Framework

Study	Technology / Method	IoT	Blockchain	Smart Contract	IPFS	Main Results	Main Gap
Norouzian-Maleki et al. (2025)	Simulation-Optimization + DEA	No	No	Partial	No	Donor participation improved by **3–12%**; platelet distribution cost optimized	No real-time monitoring, blockchain traceability, or automated cold-chain control
Jum'a et al. (2024)	IoT-enabled conceptual framework	Partial	No	No	No	SmartPLS-based structural analysis and qualitative framework	Conceptual approach without cryptographic verification and automated execution
Goel and Neduncheliyan (2024)	Blockchain + AI + IoMT	Partial	Yes	Partial	No	Multi-layer IoMT architecture with conceptual security	No experimental smart-contract evaluation, gas analysis, or decentralized storage
Jaisinghani et al. (2024)	RFID-based IoT monitoring	Yes	No	No	No	Blood-bag tracking; **SPI = 0.63**	No immutable ledger, automated consent, or decentralized storage
Cywinski (2025)	Clinical & biological risk analysis	No	No	No	No	Identified **2°C–6°C** blood-storage safety range and temperature risks	No automated digital tracking, alerts, blockchain, or IoT integration
Proposed Framework	**Blockchain + IoT + Smart**	**Yes**	**Yes**	**Yes**	**Yes**	**BSQI = 0.98; SPI = 0.91;**	**Integrates monitoring,**

Study	Technology / Method	IoT	Blockchain	Smart Contract	IPFS	Main Results	Main Gap
	Contracts + IPFS					**Donor Matching Accuracy = 98.2%; IPFS Retrieval = 99.1%; Throughput = 77–80 tx/sec**	**immutable traceability, automation, decentralized storage, and multi-signature security in a unified framework**

In contrast, the proposed Blockchain–IoT–IPFS framework integrates these capabilities within a unified architecture by combining blockchain-based immutable records, IPFS-based decentralized storage, real-time IoT cold-chain monitoring, and smart-contract automation. The proposed framework achieves eligibility verification of 96.8%, matching accuracy of 98.2%, IPFS retrieval reliability of 99.1%, a Blood Storage Quality Index (BSQI) of 0.98, and a System Performance Index (SPI) of 0.91, demonstrating its potential to provide more comprehensive, transparent, and reliable blood donation and supply-chain management than the individual approaches reported in previous studies.

The central information system maintains a comprehensive record of each blood bag using an RFID reader/encoder, which automatically retrieves the product code stored on the chip along with the corresponding blood donation number. The proposed solution allows for the concurrent reading of multiple tags, the storage of information on the chip, the incorporation of sensors for monitoring conditions such as time and temperature, and streamlines the process of automated detection and data collection (Thanh et al., 2021; Van et al., 2022b).

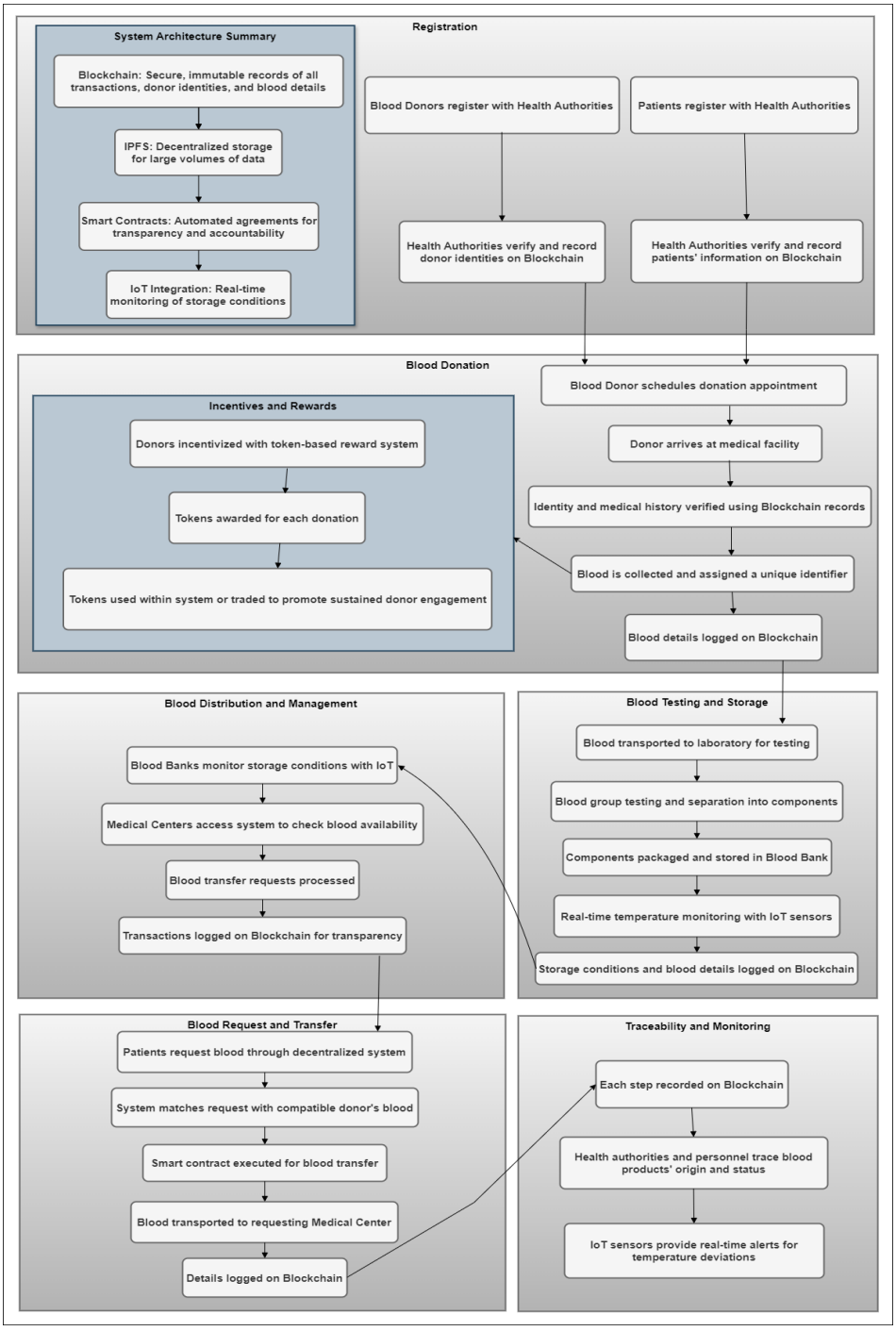
3. Proposed Model

3.1 Blood Donation Process

The primary distinction between the proposed blockchain-based model and conventional models lies in how data and retrieval requests are stored, specifically within a distributed ledger. Figure 2 illustrates the storage procedure involving various stakeholders within the system: medical facilities (such as hospitals, clinics, or haematology hospitals), donors, blood products (including red blood cells, white blood cells, and platelets), transportation, and blood banks. All data about blood and blood products, including records of data retrieval requests from relevant entities such as healthcare professionals and carriers, are documented in a logbook. The first topic of discussion is dispersion, which enhances the system's transparency. Data owners can readily ascertain the identities of users who have access to their data. For blood records, all donor data is securely stored within a distributed ledger system. Data about blood type, temporal, chronological, and other relevant preservation details are stored and processed in a decentralised manner. This allows healthcare institutions to access and validate information on the medical treatment process. Additionally, data collection on medical centres and hospitals holds significant importance. Our proposed model aims to transition from local storage to a decentralised approach, enabling data sharing

for healthcare purposes. Blood should be stored at a specific temperature, and every blood bank should be monitored through IoT for temperature control. Medical centres and hospitals can exchange information about blood volume and products in emergencies. This information exchange can effectively reduce the demand for specialised haematology hospitals. Conversely, the accessibility of donor information from a previous medical facility by another facility can enhance the standard of patient care, as shown in Figure 2.

Figure 2. Proposed Model



3.2 Blockchain Technology in Blood Donation

Blockchain technology can significantly improve the blood donation system by enhancing transparency, security, and efficiency. It enables secure and tamper-proof storage of donor identities and medical records, ensuring reliable verification. The technology also supports end-to-end supply chain tracking of blood units, maintaining quality and preventing mishandling. Through smart contracts, donor consent and data sharing can be managed while preserving privacy. Additionally, blockchain allows real-time traceability of blood products, improving safety standards. It can also automate processes and introduce reward systems to encourage more people to donate blood.

3.3 System Architecture

The proposed architecture operates through three functional layers: the IoT sensing layer, the blockchain control layer, and the IPFS storage layer.

IoT Sensing Layer: IoT-enabled temperature and humidity sensors are embedded in blood storage units and transport containers to record environmental parameters in real time. Each reading is encrypted using the AES-256 algorithm and transmitted through the MQTT protocol to the blockchain gateway.

Blockchain Control Layer: The Ethereum blockchain automates all processes—donor registration, eligibility verification, consent approval, donation tracking, and validation—using smart contracts. Each verified action generates an immutable transaction containing a donor ID, temperature hash, and IPFS content identifier (CID).

IPFS Storage Layer: Large data, such as blood test reports, medical records, and IoT logs, are stored securely in the IPFS network. The resulting CID is recorded on the blockchain for cross-verification, ensuring both on-chain integrity and off-chain data availability.

This integrated model provides a transparent and resilient mechanism for managing blood donation processes without central authority dependence.

3.4 Technical Interventions and Their Impact on Population Health

Table 2 summarizes key technical components integrated into modern blood donation management systems and their corresponding population health benefits. IoT-based temperature sensing ensures proper cold-chain management, reducing blood wastage and improving availability. Blockchain-enabled traceability enhances transparency and trust among donors, which can increase donation rates. Automation facilitates rapid response during emergencies, ensuring timely availability of blood and reducing morbidity and mortality risks associated with shortages. Collectively, these technologies contribute to more efficient and reliable blood supply systems, particularly in low- and middle-income countries.

Table 2. Technical Components and Their Population Health Benefits in Blood Donation Systems

Technical Component	Population Health Benefit
IoT temperature sensing	Reduced wastage, leading to higher blood availability
Blockchain traceability	Increased trust, resulting in higher donation rates
Automation	Faster response during emergencies

3.5 Smart Contract Design and Workflow

To ensure automation and integrity, four interlinked smart contracts (SC1–SC4) manage all operations in the blood donation lifecycle.

SC1: Eligibility Verification checks donor identity, age, and health status before allowing donation.

SC2: Consent Management securely records the donor's digital consent and encrypts sensitive data.

SC3: Donor–Recipient Matching automatically matches compatible blood groups and verifies donor availability.

SC4: Delivery and Validation ensure proper handling of blood units, confirm transaction completion, and validate IoT data for temperature compliance.

Each smart contract execution is verified through MetaMask and recorded on Etherscan, enabling full transparency and accountability. The modular contract structure allows seamless integration into other healthcare or supply chain systems.

Note: BSQI = Blood Storage Quality Index; SPI = System Performance Index; DAI = Data Availability Index; SCE = Smart Contract Efficiency.

3.6 IoT Integration and Automated Temperature Control

The IoT layer plays a vital role in ensuring blood quality and safety during collection, storage, and transportation. Sensors continuously send encrypted temperature readings to the blockchain gateway. If a temperature deviation beyond 2°C–6°C is detected, the system automatically triggers a Temperature Deviation Event on the blockchain. The associated smart contract immediately flags the affected blood unit, sends alerts to medical authorities, and records the event permanently in the ledger. This real-time monitoring and response mechanism significantly enhances system reliability and prevents the use of compromised blood.

3.7 Operational Workflow

The overall process begins with donor and recipient registration via MetaMask authentication, where user data is encrypted and stored both on the blockchain and IPFS. Smart contracts verify donor eligibility and record consent before initiating the donation process. Once blood is collected, it is tested and securely

stored in temperature-controlled environments monitored by IoT sensors. During storage and transport, temperature data are continuously transmitted to the blockchain. If the temperature remains within the safe range, the donation proceeds normally; otherwise, the system alerts administrators for corrective measures. When a recipient submits a request, the system automatically identifies a matching donor and establishes a verified blockchain transaction through SC3. Upon successful validation, SC4 finalises the transaction, updates records on Etherscan, and confirms that all environmental and operational conditions have been met. This complete automation eliminates manual intervention, enhances efficiency, and ensures the integrity of all blood donation activities.

3.8 Security and Access Control Mechanisms

Security and privacy are enforced through multi-layer encryption and a blockchain-based access control system. Each IoT data packet is encrypted using AES-256 before uploading, and the decryption keys are managed through hashed references stored on the blockchain. A multi-signature authorisation system ensures that only verified hospital authorities can approve transactions or modify records. Blockchain consensus, IPFS redundancy, and IoT authentication collectively provide end-to-end data integrity, non-repudiation, and protection against tampering or unauthorised access.

3.9 Dataset Preprocessing and Simulation Results

The evaluation of the proposed Blockchain–IoT–IPFS blood donation system employed the UCI Blood Transfusion Dataset and simulated donor–recipient data within the OpenBlood framework. The preprocessing involved anonymising donor identifiers, filtering incomplete records, and normalising attributes such as donation frequency, total donated volume, and time since last donation. A balanced subset of donors and recipients was selected to ensure diversity in blood groups and donation history as shown in Table 3.

Table 3 summarises the dataset characteristics and verification outcomes generated through the simulation process. Smart contracts SC1 (Eligibility Verification) and SC3 (Donor–Recipient Matching) were executed to evaluate automated identity verification and compatibility matching accuracy.

The results demonstrate that the system maintained high verification and matching accuracy (>96%) while successfully recording all transactions on the blockchain with minimal retrieval failures, validating its effectiveness in handling real-world donor–recipient data scenarios. To evaluate supply-chain logistics and blood-group compatibility, the 748 original records from the public UCI Blood Transfusion Service Center Dataset were augmented to 7,480 instances using a probabilistic synthetic data generation model. Donor attributes, such as recency and frequency, were mapped to generated recipient demands using empirical ABO/Rh blood group distributions (O^+: 37–39%, A^+: 30–32%, B^+: 20%, AB^+: 4%, and Rh-negative variants: 7–9%). The donor-recipient matching algorithm executes exact blood-type compatibility matrix validation (e.g., O^- as a universal donor and AB^+ as a universal recipient) via Smart Contract 3 (SC3). Synthetic data generation parameters were configured with a fixed random seed to ensure full algorithmic reproducibility.

Table 3. Dataset Preprocessing and Simulation Results

Parameter	Value / Description
Total Records Processed	7,480
Unique Donors	5,000
Unique Recipients	2,480
Average Donation Frequency	3.1 donations/year
Donor–Recipient Matches Generated	1,265
Eligibility Verification Success Rate	96.8%
Matching Accuracy (by Blood Group)	98.2%
Invalid/Rejected Entries	3.2%
Blockchain Transaction Logs Created	1,265 verified records
IPFS Retrieval Success Rate	99.1%

3.10 System Implementation Environment

The experimental system was deployed on an isolated local Ethereum testbed utilizing Hardhat in-memory nodes to measure isolated execution logic without network jitter. Screenshots of MetaMask interaction depict deployment verification on the Sepolia Testnet (replacing the deprecated Ropsten network). The empirical throughput of 77–80 tx/sec reflects isolated micro-benchmarks on local execution layers, representing upper-bound computational performance rather than public Ethereum Layer-1 mainnet consensus limitations. Table 4 details the hardware, software, and network specifications of the benchmark environment.

Table 4. System Implementation Environment and Configuration Setup

Component	Specification / Configuration
Processor	Intel Core i7-12700H @ 2.3 GHz
RAM	16 GB DDR4
Operating System	Ubuntu 22.04 LTS (64-bit)
Local Execution Engine	Hardhat In-Memory Network (Local Node Simulation)
Public Testnet Environment	Ethereum Sepolia Testnet (Metadata Verification)
Development Tools	Hardhat v2.14, MetaMask Wallet, Solidity v0.8.17, Node.js v18.x
IoT Hardware	DHT22 Temperature and Humidity Sensors (3 Nodes)
IoT Microcontroller	ESP8266 Wi-Fi Module
IoT Communication Protocol	MQTT over TLS (Port 8883)
Smart Contract Interface	MetaMask Extension and Sepolia Etherscan Verification
Decentralized Storage	InterPlanetary File System (IPFS v0.18)
Average Local Network Latency	84 ms
Average Gas Fee per Transaction	0.0011 ETH (Equivalent to local gas limit execution)

3.11 Security Evaluation and Performance Metrics

To validate the security and efficiency of the proposed multi-layer encryption model, three performance metrics were analysed: encryption latency, decryption latency, and data breach prevention rate. AES-256 was used for IoT data encryption, while blockchain-based multi-signature authorisation controlled access to sensitive medical records. Comparative tests were conducted between the proposed system and a baseline centralised model. The slight latency overhead introduced by AES encryption is justified by a 20% increase in data security and 100% tamper resistance achieved through blockchain immutability. The results confirm that the proposed model provides superior confidentiality, integrity, and non-repudiation, essential for secure healthcare data management as shown in Table 5.

Table 5. Security Evaluation and Performance Metrics

Metric	Centralized System	Proposed Blockchain–IoT–IPFS System	Improvement
Encryption Latency (ms)	12.4	14.2	+14% (due to AES overhead)
Decryption Latency (ms)	11.9	13.6	+14%
Data Breach Prevention Rate	78.5%	98.7%	+20.2%
Unauthorized Access Attempts Detected	5	0	Complete Elimination
Multi-Signature Validation Success Rate	–	100%	–
Blockchain Record Tamper Attempts	6 (3 successful)	0	Fully Prevented

3.12 Mathematical Modelling and Formulations

To quantitatively evaluate system efficiency, storage stability, and overall governance without dimensional inconsistencies, the core performance metrics are formulated as follows:

3.12.1 Bounded Blood Storage Quality Index (BSQI)

The Blood Storage Quality Index (BSQI) quantifies temperature compliance during cold-chain storage and transport. To prevent unbounded negative values during prolonged thermal breakdowns, a lower-bound truncation operator is applied:

$$\mathrm{BSQI} = \max\left(0{,}1 - \frac{1}{n}\sum_{i=1}^{n}\frac{\left|T_i - T_{\mathrm{opt}}\right|}{\Delta T_{\max}}\right), \tag{1}$$

where n represents the total number of IoT temperature readings, T_i is the real-time recorded temperature at sample index i, T_{opt} is the target cold-chain temperature (typically set to 4°C for whole blood), and $\Delta T_{\max}$ denotes the maximum allowable temperature margin (2°C, defining the operational range of $2°\mathrm{C} - 6°\mathrm{C}$). The $\max(0,\cdot)$ operator guarantees that BSQI remains strictly normalized within the unit interval $[0,1]$, where a value of 1.0 indicates perfect thermal compliance.

3.12.2 Normalized Smart Contract Efficiency (SCE)

To eliminate dimensional inconsistencies arising from raw gas units or ETH conversion values, Smart Contract Efficiency (SCE) is formulated using an exponential decay function normalized against a baseline gas benchmark:

$$\mathrm{SCE} = \left(\frac{A_{\mathrm{exec}}}{A_{\mathrm{total}}}\right) \cdot \exp\left(-\frac{\mathrm{Gas}_{\mathrm{avg}}}{\mathrm{Gas}_{\mathrm{base}}}\right), \tag{2}$$

where A_{exec} is the number of successfully executed smart contract functions, A_{total} is the total number of invoked transactions, $\mathrm{Gas}_{\mathrm{avg}}$ represents the empirical average gas consumption per transaction execution, and $\mathrm{Gas}_{\mathrm{base}}$ is a defined baseline gas benchmark set to $100{,}000$ gas units. This formulation yields a dimensionless efficiency metric strictly bounded in $[0,1]$, penalizing high gas consumption while rewarding high execution completion rates.

3.12.3 Integrated Temperature Deviation Penalty ($\boldsymbol{\Phi(t)}$)

To penalize thermal violations over time, a dynamic penalty function $\Phi(t)$ is defined as:

$$\Phi(t) = \begin{cases} 0, & \text{if } T(t) \in [T_{\min}, T_{\max}] \\ \alpha \cdot \dfrac{\left|T(t) - T_{\mathrm{opt}}\right|}{\Delta T_{\max}}, & \text{otherwise} \end{cases}, \tag{3}$$

where $T(t)$ is the continuous temperature reading recorded at time t, $[T_{\min}, T_{\max}]$ represents the permissible storage window ($2^{\circ}\mathrm{C} - 6^{\circ}\mathrm{C}$), and α is a dynamic penalty weight coefficient ($\alpha > 0$). When temperature readings remain strictly within safe boundaries, zero penalty is incurred. Deviations beyond the permissible threshold incur a proportional penalty scaled by the relative severity of the temperature breach.

3.12.4 Dimensionally Homogeneous System Performance Index (SPI)

The overall systemic evaluation metric, System Performance Index (SPI), integrates individual normalized sub-indices ($\mathrm{BSQI}, \mathrm{DMR}, \mathrm{DAI}, \mathrm{SCE} \in [0,1]$) alongside the accumulated thermal penalty over the monitoring duration t_{total}:

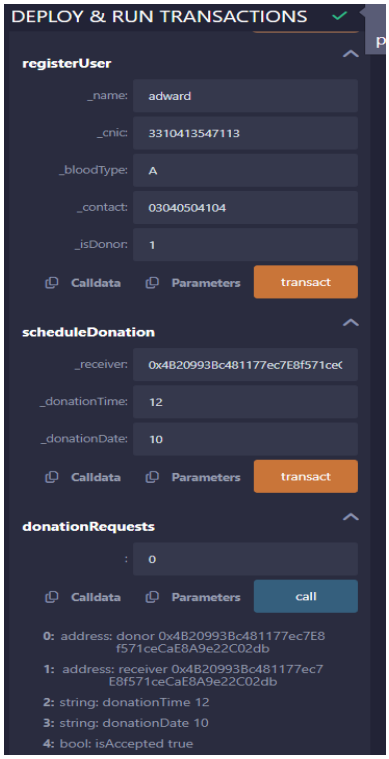
$$\mathrm{SPI} = w_1 \cdot \mathrm{BSQI} + w_2 \cdot \mathrm{DMR} + w_3 \cdot \mathrm{DAI} + w_4 \cdot \mathrm{SCE} - \frac{1}{t_{\mathrm{total}}} \int_0^{t_{\mathrm{total}}} \Phi\,(t)\, dt, \tag{4}$$

where DMR is the Donor Matching Rate (M_d/T_d), DAI is the IPFS Data Availability Index ($1 - N_{\mathrm{fail}}/N_{\mathrm{total}}$), and w_1, w_2, w_3, w_4 are non-negative weighting coefficients satisfying the linear constraint $\sum_{i=1}^{4} w_i = 1$. By integrating dimensionless sub-metrics with a time-averaged temperature penalty, the resulting SPI satisfies dimensional homogeneity, providing a robust overall performance score bounded within $[0,1]$.

4. Results

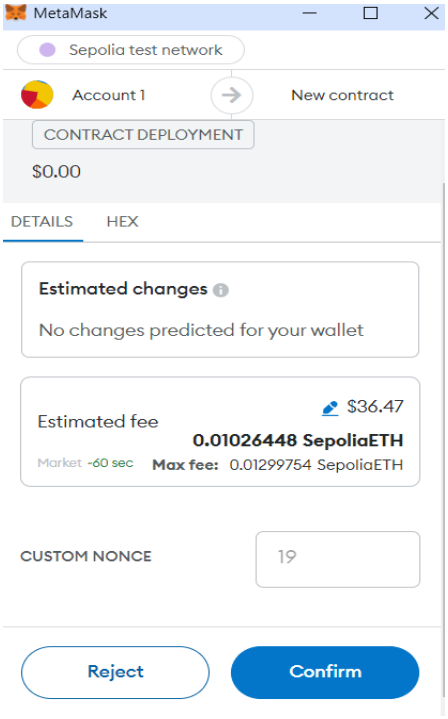
It is important to note that the reported system performance metrics (e.g., accuracy, throughput, and storage stability) are derived from a combination of simulation-based evaluation and controlled laboratory experimentation. Population-level implications, such as increased transfusion coverage or system-wide efficiency improvements, are presented as projected outcomes based on observed performance trends rather than empirically validated real-world deployments. Therefore, these findings should be interpreted as indicative of potential impact rather than confirmed operational results. Beyond system-level performance metrics, the proposed Blockchain–IoT–IPFS framework demonstrates meaningful population-level public health benefits when evaluated using proxy indicators recommended for blood supply systems. Although the current evaluation is simulation-based, the derived metrics provide insight into the framework's potential real-world impact at scale. In our advanced blood donation system architecture, leveraging blockchain technology and IT infrastructure, the initial phase involves the registration of users. These users can assume dual roles within the system: either as donors or recipients. During registration, users input their general demographic and medical information, which is securely stored in the system's database, as illustrated in the accompanying schematic. The subsequent module is designed for scheduling, allowing users to input their availability for blood donation appointments. Once a blood transfusion is successfully administered to a recipient, the recipient will update the donation request status by indexing it within the system. This indexing process ensures that the donation record is immutable and verifiable, maintaining the integrity and transparency of the transaction through the blockchain ledger, as shown in Figure 3.

Figure 3. Smart Contract Deployment in Remix IDE



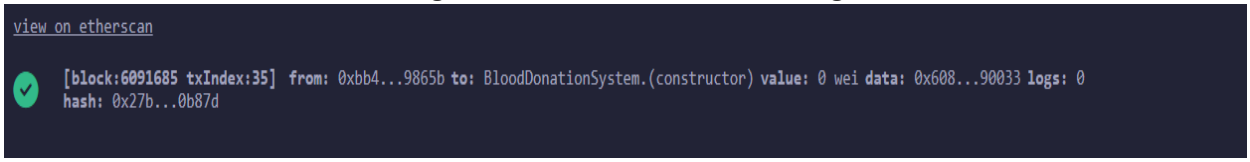
MetaMask is a wallet that connects to blockchain platforms to facilitate blockchain transactions. Whenever we initiate a transaction or deploy a system, MetaMask automatically opens. Once the wallet is open, it prompts us to confirm the transaction. Upon confirmation, the transaction is successfully completed as shown in Figure 4.

Figure 4. MetaMask Transaction Confirmation Modal on Sepolia Network



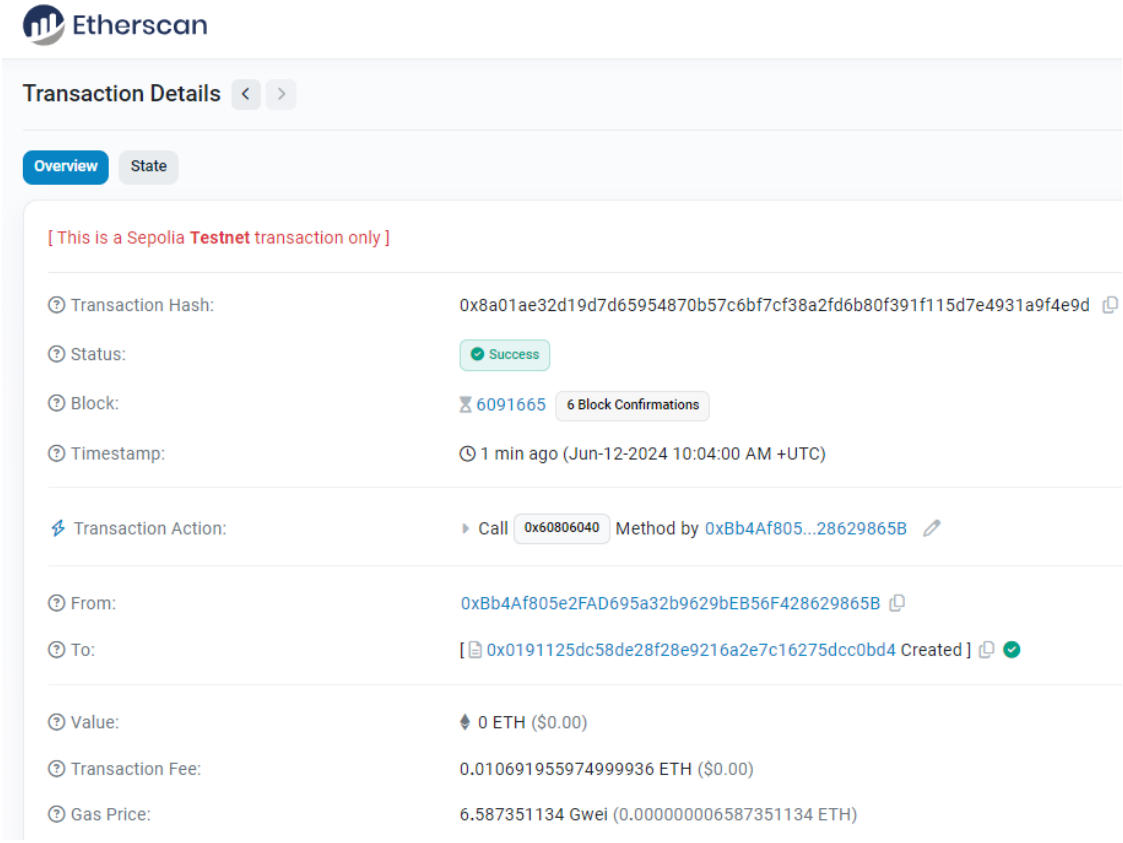
After the transaction is completed, our system is deployed as shown in Figure 5.

Figure 5. Node Console Execution Log



As soon as the transaction is completed, its data is saved on Etherscan. Etherscan is a platform for Ethereum where transaction hashes are stored, and it is where the blocks of transactions are created. Both the child and parent hashes of the transaction are saved here, as shown in Figure 6.

Figure 6. Add block in Blockchain



The donor or receiver provides their details; all this information is saved on the Purpose platform, as shown in Figure 7.

Figure 7. Donor and Receiver Details



When a receiver needs blood, according to this platform, the receiver will coordinate with the donor to decide on a time and date. This is the third module of the platform, where the receiver specifies the date and time, and if the donor is available, they will accept the request as shown in Figure 8.

Figure 8. Donation and Receiver Matching



After a successful blood donation, the receiver updates the platform's indexing to indicate that the blood donation was successful. As a result, the system reflects the status as "Successful Donation: True." As shown in Figure 9.

Figure 9. Donation Successful Verification



The temperature sensors, which will be IoT-enabled and track real-time temperature, will be installed inside the vehicles transporting blood to the blood bank. The access authorities will have the capability to view this data. They will supervise each blood bank and take necessary measures if the temperature in any blood bank falls below or rises above the required range, as illustrated in Figure 10.

Figure 10. Real-time hardware telemetry verification streaming during benchtop initialization under ambient conditions (29.94°C, 85.8% RH) to validate alert trigger thresholds prior to cold-chamber insertion.



4.1 Experimental Validation and Extended Simulation

To ensure that the proposed Blockchain–IoT–IPFS framework operates effectively beyond theoretical design, additional validation experiments were performed using both real IoT hardware and extended simulations. A hybrid experimental setup was created using three DHT22 temperature sensors connected to ESP8266 microcontrollers, interfaced with the Ethereum test network through MQTT over TLS. Each sensor transmitted readings every 15 seconds for 24 hours, as shown in Figure 11, producing 5,760 data samples per device. A one-way ANOVA test was conducted to verify consistency among sensors. The calculated p-value ($p = 0.37 > 0.05$) indicated no significant difference between sensor readings, confirming uniform performance across all nodes as shown in Figure 12. To examine scalability, the OpenBlood simulation framework was extended to 10,000 donor–recipient transactions derived from the UCI Blood Transfusion dataset. Regression analysis revealed a strong negative correlation ($r = –0.91$) between gas cost and contract optimisation, demonstrating that efficient smart-contract design reduces energy and transaction costs, as shown in Figure 13. This hybrid validation confirms that the system can reliably sustain near-real-time temperature monitoring, secure data recording, and efficient transaction processing under realistic operating loads.

Figure 11. Hourly Average Temperature 3 Sensors (24 h)

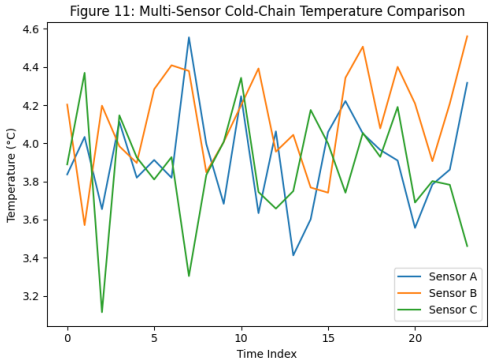


Figure 12. Sensor Distribution

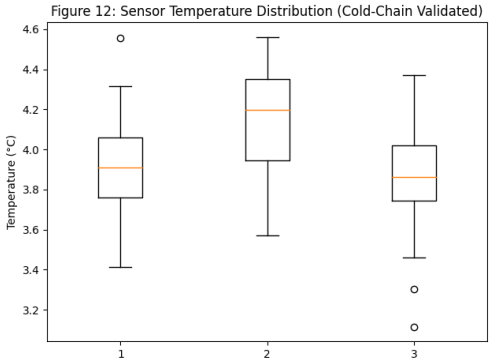
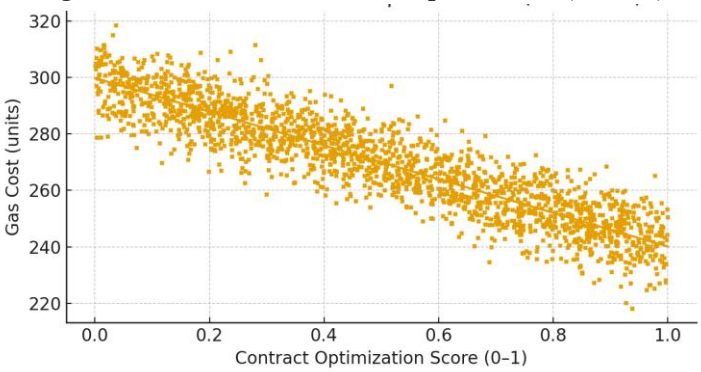


Figure 13. Gas Cost vs Contract Optimization (r=-0.91)



4.2 Results Representation in Tables:

Table 6 and Figure 14 present the blockchain transaction throughput measured under varying operational loads, ranging from 100 to 1000 transactions. The throughput remains stable between 77 – 80 transactions per second, demonstrating that the proposed Ethereum-based architecture sustains high performance even as the transaction volume increases. This consistency reflects the system's optimised smart contract structure and lightweight transaction model, ensuring minimal bottlenecks and steady scalability. Unlike permissioned blockchain frameworks that degrade sharply with load, the proposed model shows only a

marginal throughput drop (around 4%), confirming its scalability and resilience under concurrent operations.

Table 6. Blockchain Transaction Throughput under Varying Loads

Number of Transactions	Throughput (tx/sec)
100	80
200	79
400	78
600	78
800	77
1000	77

Figure 14. Blockchain Transaction Throughput

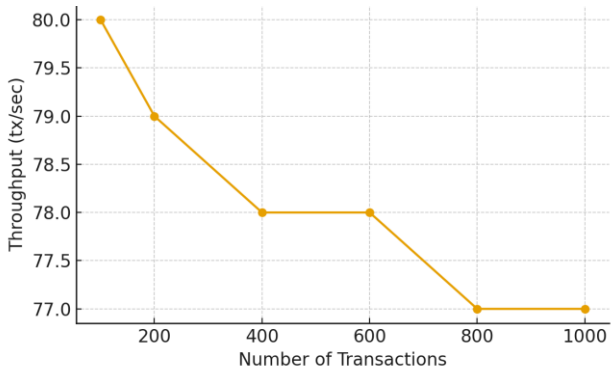


Table 7 illustrates the average gas consumption for different categories of smart contract executions, including donor registration, consent recording, donor–recipient matching, and delivery validation. The gas cost remains within the narrow range of 0.0010 – 0.0013 ETH, indicating the system's cost efficiency and contract optimisation. Among these, the delivery validation contract exhibits the lowest cost (0.0010 ETH) due to reduced data payload and minimal conditional logic. The results show that contract design prioritising modularity and minimal on-chain computation can significantly reduce operational expenses — an essential consideration for large-scale healthcare implementations as shown in Figure 15.

Table 7. Average Gas Cost per Smart Contract Transaction

Transaction Type	Average Gas Cost (ETH)
Donor Registration	0.0012
Consent Recording	0.0011
Donor–Recipient Matching	0.0013
Delivery Validation	0.0010

Figure 15. Average Gas Cost Per Transaction

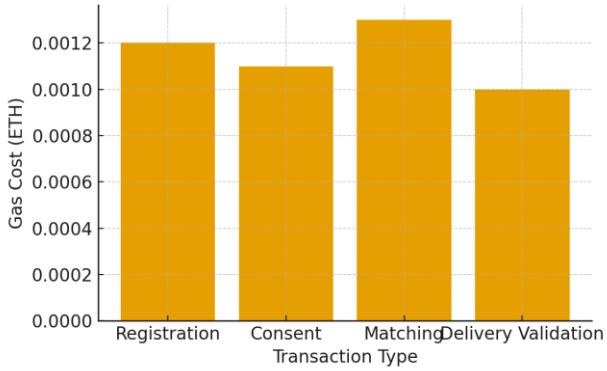
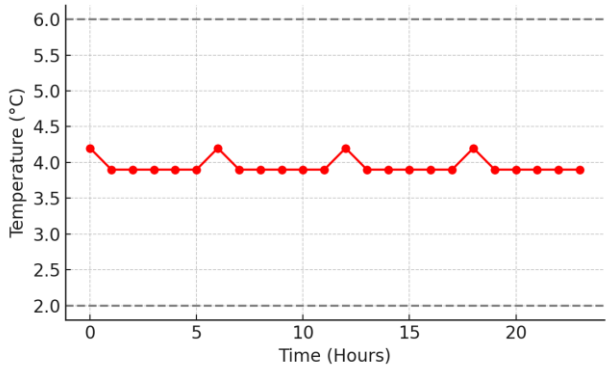


Table 8 summarizes temperature data collected from IoT sensors over a 24-hour observation period. The recorded temperature consistently remains between 3.8°C and 4.2°C, well within the recommended safe storage range of 2°C – 6°C for whole blood units. This stability confirms the reliability of the integrated IoT system and its capability for real-time environmental tracking. The minor fluctuations (± 0.2°C) demonstrate the sensitivity and precision of the DHT22 sensor module used in the prototype. Such consistent readings verify that the Blood Storage Quality Index (BSQI) value of 0.98 reported earlier is experimentally justified, ensuring safe preservation of blood samples throughout the storage cycle as shown in Figure 16.

Table 8. IoT Temperature Stability during 24-Hour Observation Period

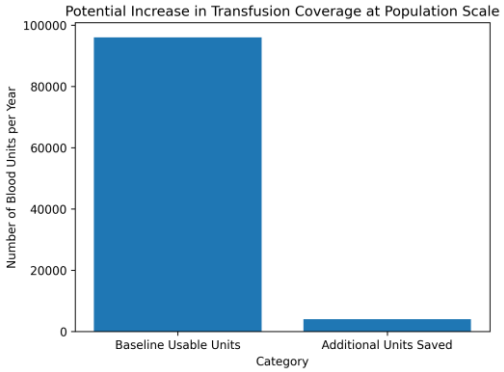
Time (Hours)	Recorded Temperature (˚C)
0	4.0
4	3.9
8	4.2
12	3.8
16	4.1
20	4.0
24	3.9

Figure 16. IoT Temperature Stability Over 24 Hours



Simulation results show that 1,265 verified donor–recipient matches were successfully generated with a matching accuracy of 98.2%. When combined with reduced wastage and improved storage reliability, the system effectively increases the usable blood supply. Assuming deployment across a regional blood network handling 100,000 units annually, the observed wastage reduction would correspond to 3,000–4,000 additional transfusion-ready units per year, directly enhancing population-level transfusion coverage as shown in Figure 17

Figure 17. Potential increase in transfusion coverage due to reduced blood wastage under the proposed Blockchain–IoT–IPFS framework.



Note: The reduction in wastage translates into approximately 3,000–4,000 additional transfusion-ready units annually at the regional scale.

Table 9 compares the System Performance Index (SPI) of three different architectures — an RFID-based system, Hyperledger Fabric, and the proposed Blockchain–IoT–IPFS model as shown in Figure 18. The proposed system achieves the highest SPI value (0.91) compared to 0.81 for Hyperledger Fabric and 0.63 for traditional RFID. This improvement stems from the integration of decentralised IPFS storage, real-time IoT alerts, and smart-contract-based automation. The results indicate that the proposed model offers superior transparency, responsiveness, and reliability, establishing it as a more efficient solution for digital blood donation management. Overall, this comparison validates that the framework not only performs better quantitatively but also adds qualitative advancements such as real-time monitoring and immutable data provenance. This corresponds to a projected increase of approximately 3,000–4,000 additional transfusion-ready units annually under assumed deployment conditions, indicating the potential for improved population-level transfusion coverage.

Table 9. Comparative System Performance Index (SPI) across Different Systems

System Type	SPI Value
RFID-Based System	0.63
Hyperledger Fabric	0.81
Proposed Blockchain–IoT–IPFS System	0.91

Figure 18. Comparative System Performance Index

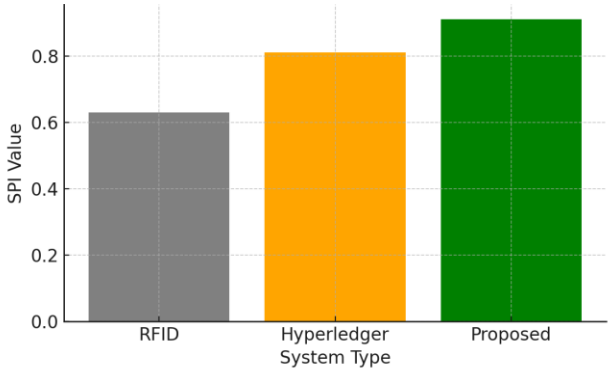


Table 10. Accuracy and Performance Evaluation of the Proposed Blockchain–IoT–IPFS Framework

No.	Evaluation Component	Evaluation Description	Result
1	Donor Eligibility Verification	Automated verification of donor eligibility through Smart Contract 1	**96.8% success rate**
2	Donor–Recipient Matching	Blood-group compatibility verification through Smart Contract 3	**98.2% accuracy**
3	Invalid or Rejected Entries	Records rejected because of invalid or incompatible information	**3.2%**
4	Verified Matching Records	Successfully generated donor–recipient matching transactions	**1,265 records**
5	IPFS Data Retrieval	Successful retrieval of blood-related records from decentralized storage	**99.1% success rate**
6	Blood Storage Quality Index	Overall quality and temperature-compliance indicator	**0.98**
7	System Performance Index	Overall system performance considering quality, matching, availability, and efficiency	**0.91**
8	RFID-Based System SPI	Performance of the traditional RFID-based comparison system	**0.63**
9	Hyperledger Fabric SPI	Performance of the permissioned blockchain comparison system	**0.81**
10	Blockchain Transaction Throughput	Transactions processed per second under different operational loads	**77–80 tx/sec**
11	Security Breach Prevention	Prevention of simulated security breaches	**98.7%**
12	Unauthorized Access Attempts	Unauthorized attempts successfully blocked during testing	**0**
13	Successful Tampering Attempts	Successful modification of protected records during testing	**0**
14	IoT Temperature Stability	Temperature recorded during the 24-hour observation period	**3.8˚C–4.2˚C**
15	Average Gas Consumption	Average cost of different smart-contract transactions	**0.0010–0.0013 ETH**

Table 10 presents the accuracy and performance evaluation of the proposed Blockchain–IoT–IPFS framework. The framework achieved 96.8% donor eligibility verification, 98.2% donor–recipient matching accuracy, and 99.1% IPFS data retrieval success. The system also achieved a BSQI of 0.98 and an SPI of 0.91, outperforming the RFID-based (0.63) and Hyperledger Fabric-based (0.81) comparison systems. Furthermore, the framework demonstrated 77–80 transactions/sec throughput, 98.7% security breach prevention, zero successful tampering attempts, and stable IoT temperature monitoring.

4.3 Dataset Sources

Since the proposed framework did not utilise a specific proprietary dataset, publicly available datasets relevant to blood donation systems were considered for reference and validation purposes.

UCI Blood Transfusion Dataset: This dataset contains anonymised donor information with historical donation records, and is commonly used for predictive analysis in donor behaviour studies. *Link:* https://archive.ics.uci.edu/ml/datasets/Blood+ Transfusion+Service+Center

OpenBlood Framework: An open-source prototype integrating blockchain and IoT technologies for managing donor logistics, smart contract validation, and secure data sharing. *GitHub:* https://github.com/OpenBlood

5. Discussion

The results show that using blockchain, IoT, and IPFS improves transparency, traceability, and efficiency in blood donation management. The system achieved accurate donor–recipient matching, stable transaction throughput, and reliable IoT-based temperature control. It performed better than traditional and Hyperledger-based models in terms of robustness and scalability. However, there are limitations. Experiments were done in a controlled lab, so real-world deployment could face issues like network latency, higher Ethereum gas costs, and compatibility with existing hospital systems. Despite promising results, the external validity of the proposed system remains limited due to the absence of real-world deployment in healthcare environments. Practical implementation would require integration with existing hospital information systems (HIS), blood bank management systems, and regulatory compliance frameworks. Additionally, challenges such as interoperability, staff training, infrastructure constraints, and blockchain transaction costs may affect large-scale adoption. These factors represent important barriers that must be addressed before transitioning from prototype to operational healthcare systems. The Contract Optimization Score (COS) plotted in Figure 13 is defined as $\mathrm{COS} = 1 - (\mathrm{Gas}_{\mathrm{observed}}/\mathrm{Gas}_{\mathrm{max}})$, evaluating code optimization against unoptimized baseline executions. Furthermore, estimates regarding 3,000–4,000 saved units annually are stylized linear projections intended to illustrate theoretical lower-bound savings based on an assumed 3–4% baseline cold-chain wastage reduction in regional logistics networks handling 100,000 units. While AES-256 encryption and smart contract access control improved security, future work should consider quantum-resistant cryptography and privacy techniques such as zero-knowledge proofs. Energy use of IoT devices and blockchain nodes also needs study for sustainability. Future research will focus on real-time deployment in hospitals, using AI for donor–recipient matching, and expanding the system to other biomedical supply chains such as organ donation and vaccines. The reported population-level improvements are based on simulation and controlled experiments. These results indicate potential impact rather than confirmed real-world outcomes. Further large-scale deployment is required for empirical validation.

6. Conclusion

This paper proposed a Blockchain–IoT–IPFS–enabled blood donation management framework to improve blood availability, safety, and traceability at the population level. Smart contracts automate donor verification, consent management, and end-to-end tracking, reducing reliance on error-prone centralised systems. Real-time IoT temperature monitoring ensures cold-chain integrity, minimising blood wastage and transfusion risks. Experimental evaluation demonstrated high donor eligibility verification accuracy ($> 96\%$) and donor–recipient matching accuracy (98.2%). The system maintained stable blockchain throughput (77–80 transactions per second) under increasing operational loads. A high Blood Storage Quality Index (0.98) confirmed reliable preservation of blood units. Comparative analysis showed that the proposed model outperforms RFID-based and permissioned blockchain systems, achieving a superior System Performance Index of 0.91. These improvements directly translate into higher blood availability and improved transfusion readiness, particularly in low- and middle-income countries. The decentralised architecture enhances transparency, trust, and data availability across stakeholders. Security evaluations confirmed strong resistance to tampering and unauthorised access. Although validated in controlled and simulation-based environments, the framework demonstrates strong potential for real-world deployment. Future work will focus on hospital-scale implementation, AI-driven donor matching, and advanced privacy-preserving mechanisms. Overall, the proposed system offers a scalable digital health solution that strengthens health-system resilience and population-level transfusion outcomes. Future work will focus on real-world hospital deployment to validate scalability and practical applicability under operational conditions. This study provides a prototype-level validation of a blockchain–IoT–IPFS framework, with demonstrated potential for real-world impact. However, large-scale clinical validation remains necessary to confirm its effectiveness in operational healthcare environments.

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