Journal of Business, Economics and Sustainable Systems (JBESS)

Issue 1, April 22, 2026,

Research Article

Blood Bank Management System and Donation Tracking

I. Introduction

Blood is a vital biological resource that has no artificial alternative since it cannot be replaced with anything, and the efficient collection, storage, and distribution of blood are a question of life and death. But this is not true of hospitals throughout the world, especially in low- and middle-income countries, which continually experience chronic understaffing, especially in times of mass casualty incidents and natural disasters. The World Health Organisation (WHO) estimates that about 118.5 million blood donations are gathered worldwide annually; nevertheless, much of this amount ends up going to waste or does not fulfil its intended purpose since patients in need do not receive it because of logistical breakdowns [1].

The situation with the demand and supply of blood is especially acute in India. The national demand is estimated to be 15 million units per annum, with the reality collection at about 11 million units annually [2]. This ineffectiveness in structure is exacerbated by inefficiencies in operation: the vast majority of blood banks at district and sub-district levels still use paper ledgers, cross-matching logs implemented manually, and verbal communication networks. These methods are simply error-prone, slow and fail to deliver the data-driven decision-making that is needed in the current healthcare.

The effects of poor management of blood banks are well-documented. Late blood loss is one of the causes of avoidable maternal mortality, death as a result of trauma, and surgical complications. The incompatible blood transfusion is still one of the most severe and dangerous negative outcomes of clinical practice. In the meantime, when inventory is not managed well, there will be a lot of wastage on the donated units, and this will erode the confidence of the community in the donation programs and will strain the already limited resources.

Digital health interventions are a promising way out of these challenges. There has been empirical evidence of the measurable advantages of electronic health record (EHR) integration, real-time inventory dashboards, automated eligibility screening, and SMS-based donor communication in specific settings [3],[4]. But all-inclusive, end-to-end blood bank management systems incorporating all these functionalities - and subject to a stringent evaluation in the environment of Indian hospitals - are still rare in the literature.

The presented paper describes the Blood Bank Management System (BBMS), a full-stack web application, which is to digitalise and unify all phases of the blood donation lifecycle. This work has made the following contributions: (i) a resource-constrained, scalable system architecture; (ii) a real-time donation tracking engine with full audit trail; (iii) an automated compatibility matching algorithm that implements ABO and Rh cross-reference logic; and (iv) a six-month rigorous clinical pilot to provide quantitative performance benchmarks.

The rest of this paper will be structured in the following way: Section II will provide a review of related work. Part III is a system architecture and module design. The implementation is described in section IV. Section V presents findings of the clinical pilot. Findings and limitations are discussed in Section VI. Section VII closes with the guidelines to conduct the research in the future.

III. SYSTEM ARCHITECTURE AND DESIGN

A. Architectural Overview

The BBMS is based on the three-tier client-server system. The presentation level is deployed as a web-based responsive mobile app that can be used by default desktop browsers and mobile devices, so that usability is achieved across a wide range of hospital IT settings without the need to install special hardware or native apps. Business logic layer implements all the application processes, such as donor eligibility, inventory, compatibility checks, alert dispatching, and report generation as a collection of modular PHP services. The data tier is a MySQL 8.0 normalised relational database that is based on five main entities.

The entire inter-tier communication is encrypted using TLS 1.3. The system can be deployed on a commodity LAMP/WAMP infrastructure and deployed optionally in cloud platforms (AWS, Azure, or GCP) to be accessed by multiple sites. RESTful APIs are controlled endpoints that are available to integrate with an existing Hospital Information System (HIS).

B. Core Modules

The system comprises six tightly integrated modules:

1) Donor Registration and Profile Management: Stores detailed donor records with personal demographics, blood group and Rh factor, full donation history, deferral history with reinstatement dates, and encrypted medical history. Every donor has a system-generated DonorID with optional links to Aadhaar-based identity verification.

2) Eligibility Screening Engine: Checks pre-donation eligibility against set criteria such as age (1860 years), body weight (more than 50kg), haemoglobin status (12.5g/dl in females and 13.0g/dl in males), blood pressure (range), and minimum interval between donations (56 days whole blood; 14 days platelets). Ineligible donors are put into deferral with reason codes, and the reinstatement date is automatically computed.

3) Donation Tracking Engine: Keeps a real-time, time-stamped audit trail of every blood unit at all lifecycle phases: Collected → Tested → Processed → Quarantined → Available → Allocated → Transfused / Discarded. Any change in status is attributed to the member of staff in charge, who assists with the hemovigilance measures.

4) Inventory Management: Efforts to track all blood units based on ABO/Rh, component (whole blood, packed RBCs, fresh frozen plasma, platelet concentrate, cryoprecipitate), collection date, and calculated expiry. FEFO (First Expired, First Out) logic of allocation helps reduce wastage. Built-in threshold warning systems remind procurement managers through email and SMS of their stock quantities when they drop below critical points.

5) Compatibility Matching and Request Management: Clinicians make blood requests by including recipient blood group, component type, volume, and level of urgency (Routine / Urgent / Emergency). The compatibility engine matches the units available to a precalculated ABO/Rh compatibility table (Table I), ranks the matches based on propinquity to expiry, and provides a shortlist to the blood bank officer to verify and physically crossmatch.

6) Reporting and Analytics Dashboard: Produces customisable reports that include donation trends, inventory utilisation, component wastage rates, donor demographics, and transfusion results. Visualisations will include time-series charts of daily collection volumes and heatmaps on the blood group distribution.

C. ABO/Rh Compatibility Matrix

Table I shows the compatibility lookup table applied in the BBMS compatibility engine. A tick (✓) is a pairing of donors and recipients that is compatible with red blood cell transfusion.

TABLE I

ABO/Rh Red Blood Cell Compatibility Matrix

Donor \ Recipient	O-	O+	A-	A+	B-	B+	AB-	AB+
O-	✓	✓	✓	✓	✓	✓	✓	✓
O+		✓		✓		✓		✓
A-			✓	✓			✓	✓
A+				✓				✓
B-					✓	✓	✓	✓
B+						✓		✓
AB-							✓	✓
AB+								✓

D. Database Schema

The relational schema is made to Third Normal Form (3NF) to avoid redundancy and referential integrity. The five main entities and their main characteristics are summarised in Table II.

TABLE II

Core Database Entities and Attributes

Entity	Key Attributes
Donor	DonorID (PK), Name, DOB, Gender, BloodGroup, RhFactor, ContactInfo, DeferralStatus, LastDonationDate
BloodUnit	UnitID (PK), DonorID (FK), Component, CollectionDate, ExpiryDate, Status, Volume_mL, StorageLocation
Recipient	RecipientID (PK), Name, BloodGroup, RhFactor, HospitalID, WardNo, AttendingPhysician
Request	RequestID (PK), RecipientID (FK), Component, Units, Priority, RequestDate, ApprovedBy, Status
Transfusion	TransfusionID (PK), RequestID (FK), UnitID (FK), TransfDate, Outcome, AdverseEvent, NurseID

II. Literature Review

Studies of blood bank information systems cover web-based systems, mobile applications, traceability based on blockchain and demand prediction based on machine learning. All strategies focus on particular areas of pain, yet they usually have significant gaps.

Kumari et al. [3] have created an initial web-based blood bank management system that has substituted the paper ledgers and provided real-time blood group availability search facilities. Their system showed quantifiable benefits of a decrease in manual workload without tracking donors, automatic notifications, and compatible features, which are essential in safe transfusion practice. On the same note, Okonkwo et al. [5] created a normalised relational database schema of a blood bank in a hospital in Nigeria, but made some valuable contributions to data integrity; they did not go any further and implement a full-stack application.

There have been mobile-based methods of donor recruitment. Patel and Sharma [4] created a GPS-based donor registration application enabling recipients to find nearby potential donors within a radius that was set to the application. Whereas it showed promise in terms of emergency donor mobilisation, the inventory control and post-donation MO Monitoring were not discussed. Bhatt and Mehta [8] further elaborated on the same with a lifecycle-based mobile app that is a blood bank in India with donation alerts and blood request reminders, but they only evaluated the work with a usability study and not clinical application data.

Distributed ledger solutions came to the fore because of concerns over the integrity and accountability of data. Ramteke and Dhore [6] used blockchain technology to provide a tamper-proof audit trail on blood donation to meet regulatory compliance and traceability requirements. Their prototype showed that the approach was feasible, but they had scalability problems with large volumes of transactions associated with large urban hospitals. The time-critical transfusion environments have also been practically limited by the computational overhead of consensus mechanisms.

Machine learning has proven to be successful in blood demand forecasting. Garg et al. [7] used ARIMA time-series models and feedforward neural networks to estimate daily blood component requirements, noting that about 18 per cent inventory wastage was reduced. Nevertheless, these models have a high requirement of historical data on which they are trained- a condition that a small or new blood bank can hardly satisfy.

Krishnamurthy and Rao [9] studied the role-based access control (RBAC) in a medical information system and were able to prove that with access policies being granular, the number of unauthorized access of data was significantly decreased in a blood bank setting. The present system security architecture was informed by their structure.

The current work is an integration of the merits of previous studies: structured relational data management, real-time donor tracking, and automated alert systems, as well as compatibility matching into one clinically validated system to be deployed in Indian tertiary care hospitals.

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IV. Implementation

A. Technology Stack

A LAMP stack was used to construct the BBMS: Apache 2.4, MySQL 8.0, and PHP 8.1 to provide server-side logic. The front-end uses HTML5, CSS3, JavaScript (ES6) and Bootstrap 5.2 to make responsive layouts that are mobile-first. AJAX calls support the asynchronous retrieval of data, hence providing the user with a fluid user experience without complete page reloads. PHPMailer and Twilio SMS API offer auto-delivery of notifications. It is containerised with the help of Docker and deployed similarly on on-premise and cloud environments.

B. Donor Registration and Eligibility Workflow

Once a donor is at a collection centre, the profile of the donor is accessed by a staff member by DonorID, name, or mobile number. According to the latest deferral record and the latest donation date, the system automatically sets the eligibility of the donor.With qualification, the operator continues to record the donation; with deferral, the system indicates the cause of the deferral and the latest allowable date of return. In the case of a first-time donor, a registration form is used where all the required fields are captured using inline validation. Once donated, the collected unit goes through the processing pipeline and passes through its status line. Lab staff enter serology results (HIV, HBsAg, HCV, Syphilis, Malaria) and units with reactive results are quarantined and flagged to be disposed of, and a confidential notification is sent to the donor to receive counselling. The units that are not reactive are labelled as Available in the inventory.

C. Inventory Management and FEFO Allocation

The expiry date of each unit of blood is automatically determined at the time of collection: 42 days of whole blood in CPDA-1 anticoagulant, 5 days of platelet concentrates, and 12 months of fresh frozen plasma. The inventory dashboard gives a real-time view arranged by the blood group, component, and shelf-life status

(>14 days, 814 days, <7 days, Expired). The amber colour indicates units that fall under the critical shelf-life window; red colour indicates those for which the expiry date has passed, and they are not allocated.

When filling a blood request, the FEFO allocation engine initially filters units based on compatibility, then ranks the candidate units based on their remaining shelf life (oldest first), ignoring the remaining shelf life of units that are not compatible with the request. This approach was discovered to have been the most effective single implementation during the pilot to reduce wastage.

D. Alert and Notification System

There are three types of automated alerts: (i) Donor reminders - sent 56 days after whole blood donation, which reminds the donor to donate again; (ii) Inventory low-stock alerts - sent to blood bank officers when any of the blood group/components reach a predefined low level; (iii) Expiry alerts - sent when 7 days and 3 days to the expiry date of blood units Twilio REST API is used in all SMS alerts, PHPMailer with SMTP authentication in email alerts.

E. Security Architecture

Role-based access control (RBAC) implements the least-privilege access control on four roles: Administrator (full system access), Blood Bank Officer (inventory, donation tracking, request processing), Clinician (blood request submission, recipient management), and Auditor (read-only access to all records and logs). All PII and medical history of the donors are encrypted with AES-256 at rest; all data in transit is secured with TLS 1.3. Each log-in, change in data, and export of reports is logged in a non-alterable audit trail, which allows adherence to the Information Technology Act, 2000 and the National Blood Policy.

V. Results and Performance Evaluation

A. Pilot Deployment

Between January and June 2024, the BBMS was implemented in a 500-bed tertiary care hospital in New Delhi. Over six months of operation, the system handled 3,847 donor registrations, 3,412 completed donation events, 2,956 transfusion requests and 18,240 state transitions of individual inventories. The system was 99.6% in uptime (without scheduled maintenance windows). Performance data were prospectively gathered and compared with a matched six-month baseline period where the hospital was using its former manual system.

B. Operational Performance

The core performance of the manual system and the BBMS have been compared in Table III in six major operational measures.

TABLE III

Operational Performance: Manual System vs. BBMS

Metric	Manual	BBMS
Avg. Request Fulfillment Time	47 min	8 min
Inventory Accuracy Rate	79.0%	98.3%
Blood Unit Wastage Rate	11.4%	3.7%
Donor Return Rate (6 months)	38%	61%
Emergency Response Time	62 min	14 min
Data Retrieval Time	~12 min	< 5 sec
Adverse Transfusion Events	4 events	1 event

Staff Manual Workload (hrs/day) ~5.2 hrs ~1.4 hrs

The greatest changes were in request fulfilment time (reduction of 83%) and emergency response time (reduction of 77%). The accuracy of inventory improved by 79 to 98.3%, and this was mostly due to the fact that real-time electronic updates removed the transcription errors and lost entries that plagued paper-based systems. There was a reduction in blood wastage of 67.5% (11.4% to 3.7% FEFO allocation and proactive expiry alerts), and this was related to FEFO allocation and proactive expiry alerts.

C. Donation and Donor Retention Analysis

SMS acknowledgements (automated), health advice (personalised), and reinstatement reminders led to a 23-percentage-point rise in the six-month donor return rate (38% to 61%). Survey of donor feedback surveys (n=312) revealed that shorter waiting time in the collection centre (mean reduction: 28 minutes) and issuance of digital donation certificates were the two most frequently reported reasons as to why they would repeat the donation.

The deferral tracking module detected 142 inadvertently accepted donors by the previous manual system within their required deferral window. With BBMS, there were automatic deferral flags that did not allow re-entry into the donation pool prematurely, enhancing safety compliance.

D. Adverse Event Analysis

In the manual baseline phase, 4 adverse events were documented in transfusion matters, with two being attributed to the ABO group misidentification as a result of errors in the manual transcription. The occurrence of a febrile non-haemolytic transfusion reaction, which was not associated with compatibility, occurred in one instance under the operation of the BBMS, but no adverse events associated with compatibility were documented. This improvement is thought to stem primarily from the compatibility matching module mandated system-level crosscheck before unit allocation.

E. System Response and Scalability

Apache JMeter was used to load test as many as 150 active users (running concurrently) doing inventory queries and blood request submissions. Average page response time did not exceed 850 milliseconds with 100 simultaneous users and gracefully deteriorated to 2.3 seconds with 150 simultaneous users, which is well within acceptable clinical usability limits. The central ideas of performance under load maintenance were database query optimisation with the help of compound indexes on Blood Group, Rh Factor and Expiry Date fields.

VI. Discussion

VI. DISCUSSION

The six-month pilot showed that the developed, integrated BBMS can provide clinically and operationally significant improvements in all the measured dimensions. The four-to-one ratio of adverse transfusion occurring events is perhaps the most significant finding, as a haemolytic transfusion reaction has a case fatality rate of about 1 in 600,000 transfused units [10].

Economic and ethical implications of the 67.5% relative decrease in blood wastage include economic and ethical aspects. With an average cost of processing 1,100 per unit in Indian government hospitals, the wastage reduction in the pilot period (between 389 and 126 units wasted) is a potential saving of 2.89 lakhs in six months - a number that is sufficiently larger than the total cost of implementing and maintaining the system within the initial year of operation.

Strategically, donor retention is a crucial aspect. Safe blood supply relies upon voluntary non-remunerated blood donation, but the problem of attrition of donors following the initial donation continues to pose a challenge. This 23-percentage-point increase in return rates in this pilot is consistent with the results of similar digital intervention trials and indicates that inexpensive SMS-based engagement can have a significant impact on donor behaviour.

A. Limitations

A few restrictions can be observed. First, the pilot involved only one well-resourced tertiary care hospital; exploring the generalisability to other district hospitals with less robust IT infrastructure and staff digital literacy is necessary. Second, the compatibility engine only carries out ABO and Rh-D matching, and no extended phenotype matching (e.g., patients with chronic transfusion policy, e.g. thalassemia, sickle cell disease, etc.) has been implemented yet. Third, this version did not have an inter-bank network to share emergency blood across geographically distinct facilities, which is also a major missing feature.

B. Future Work

Planned enhancements include: (i) machine learning-based demand forecasting using LSTM networks trained on historical collection and consumption data; (ii) inter-bank network integration enabling real-time blood sharing across facilities in a regional cluster; (iii) extended compatibility profiling for patients with alloantibodies; (iv) Aadhaar-linked donor identity verification to eliminate duplicate donor records across facilities; and (v) a native mobile application for donor self-registration and appointment scheduling.

VII. Conclusion

The paper has introduced the overall design, implementation, and clinical trial of a Blood Bank Management System that incorporates real-time donation tracking. The BBMS overcame the major weaknesses that were inherent in the traditional manual blood bank operations by digitalising and integrating donor management, inventory control, compatibility matching, and transfusion auditing into a single platform.

The six-month deployment of pilots at a 500-bed hospital showed an 83-per cent change in request fulfilment time, a 19.3-percentage-point increase in inventory accuracy, a 67.5-per cent relative decrease in blood wastage, and a 23-percentage-point increase in donor retention rates. The system operation eradicated adverse transfusion events that could be attributed to errors in compatibility. These are the results that support the clinical, safety, and cost-effectiveness of an integrated blood bank digitalisation.

Its open-standards technology stack, modular and scalable architecture, places the BBMS in a position to be adopted in a wide range of healthcare environments in India and other resource-constrained settings. The system will also be expanded in the future by adding predictive demand forecasting, inter-bank network connection and profiling of extended compatibility, which will further contribute to blood supply chain safety and reliability.

Acknowledgment

The authors acknowledge and appreciate the assistance and hard work of the medical, nursing and administrative staff of the pilot hospital during the period of deployment. The authors should also credit the blood bank donors whose cooperation is what enabled this assessment. No outside funding was provided in this study.

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