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Sustainable Blood Supply Chain Modeling with Government Intervention: A Three-Level Stackelberg Approach under Two-Sided Supply–Demand Uncertainty and Explicit FEFO Implementation

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Abstract

This study aimed to develop and validate an integrated three-level Stackelberg optimization model for a sustainable blood supply chain incorporating government subsidies, simultaneous supply and demand uncertainty, independent age dynamics for red blood cells, platelets, and plasma, explicit First-Expired–First-Out allocation, and transportation-related carbon emissions. A three-level Stackelberg game was formulated in which the government acted as the leader, the Iranian Blood Transfusion Organization and provincial processing centers constituted the first-level followers, and distribution centers represented the second-level followers. Four combined supply–demand scenarios were constructed using five years of historical data. The follower problem was transformed using Karush–Kuhn–Tucker conditions after verifying the linear independence constraint qualification and was subsequently linearized as a mixed-integer linear programming model. Product aging and FEFO allocation were modeled through age-indexed inventory and allocation variables. The model was solved using CPLEX and validated against five months of operational platelet data from the Isfahan blood supply network. Government intervention increased the collection of O-negative blood by 760%, although marginal benefits declined beyond a subsidy budget of 60 units. Implementation of the model reduced immediate-fresh demand shortages from 30% ± 4.2% to 5% ± 1.4%, representing an 83% reduction. The proposed three-product model achieved 14% lower total cost and a 17-percentage-point higher service level than the single-product benchmark. Extending platelet shelf life from three to five days reduced platelet wastage by 61% and generated monthly carbon-emission savings of 12.4 kg. Optimized Big-M values reduced solution time by more than fifteenfold compared with the conventional value of one million. Model predictions showed a mean validation error of 4.1%. The proposed framework provides an effective decision-support mechanism for coordinating government subsidies, blood-product allocation, perishability, uncertainty, service priorities, and environmental objectives while improving cost efficiency, service levels, and operational resilience.

Keywords: *Blood supply chain; Stackelberg game; Government subsidy; Supply–demand uncertainty; FEFO; Blood products; Carbon emissions; Mixed-integer linear programming.*

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1. Introduction

Blood supply chains are among the most critical and operationally demanding components of healthcare systems because they must ensure the continuous availability of lifesaving products despite perishability, uncertain demand, variable donation rates, strict compatibility requirements, and limited processing and storage capacities. Unlike conventional supply chains, blood systems cannot rely on ordinary procurement practices because blood is donated rather than manufactured, its supply is strongly affected by social behavior and emergency conditions, and its products have markedly different shelf lives. Red blood cells, platelets, and plasma require distinct storage conditions, processing procedures, and allocation rules, while shortages may immediately threaten patient safety. These characteristics make blood supply chain planning a multidimensional decision problem involving collection, processing, inventory control, transportation, allocation, wastage prevention, and service prioritization. Recent healthcare supply chain research has consequently emphasized the need to improve efficiency, resilience, and patient safety simultaneously rather than treating cost minimization as the only objective [1-3].

A central difficulty in blood supply chain management is the simultaneous presence of supply-side and demand-side uncertainty. Donation levels may fluctuate because of seasonal patterns, epidemics, public perceptions, transportation barriers, adverse weather, or disruptions to donor recruitment programs. At the same time, hospital demand is uncertain because of emergencies, surgeries, trauma cases, outbreaks, and changes in clinical activity. The mismatch between unpredictable demand and unstable supply can lead either to shortages or to excessive inventory and expiration. Scenario-based modeling has therefore become an important approach for representing multiple possible operational conditions and assessing the performance of integrated blood inventory systems. Earlier blood supply chain research has shown the relevance of scenario-based simulation for coordinating inventory decisions across interconnected facilities, while robust modeling has been introduced to reduce the vulnerability of blood systems during pandemic-related disruptions [4, 5]. Nevertheless, many available models emphasize uncertainty on only one side of the system and do not fully capture the simultaneous occurrence of reduced donations and increased hospital demand.

The consequences of disruption became particularly visible during and after the COVID-19 pandemic, which exposed structural weaknesses in healthcare and industrial supply chains. Pandemic conditions disrupted transportation, workforce availability, supplier relationships, procurement processes, inventory policies, and access to essential medical products. Studies of post-pandemic supply chain risk management indicate that organizations increasingly recognize preparedness, adaptive capacity, and risk visibility as essential operational capabilities. Resilience involves not merely recovering from a disruption but anticipating vulnerabilities, maintaining critical service levels, and rapidly reconfiguring resources under changing conditions [6, 7]. In blood systems, these requirements are particularly important because delayed replenishment cannot always be compensated through commercial purchasing and because shortages of compatible blood products may have immediate clinical consequences.

Healthcare supply chains also differ from many commercial networks because their performance must be evaluated through patient-centered criteria. Cost reduction remains important, but it cannot be separated from safety, timeliness, equity, availability, and the continuity of clinical services. Evidence from intensive care supply chains underscores the importance of evidence-based inventory policies, coordinated procurement, reliable distribution, and risk-sensitive planning for improving patient safety and operational efficiency [1]. Similar principles apply to immunization supply chains, where resource centers, coordination structures, training, information systems, and regional support mechanisms contribute to stronger availability and distribution performance [8]. These findings suggest that blood supply systems require coordinated decision structures that connect policy-level interventions with organizational planning and operational allocation.

Another challenge concerns the perishability of blood products. Perishable supply chains must continuously balance product availability against deterioration, expiration, and waste. Blood products are especially complex because each component has a different maximum shelf life: platelets expire rapidly, red blood cells can be stored for several weeks, and frozen plasma may remain usable for considerably longer periods. A single inventory policy is therefore inadequate for all components. Research on perishable and closed-loop supply chains has highlighted the importance of integrating deterioration, recovery, waste reduction, return flows, and product-specific lifecycle characteristics into network design [9]. Reviews of hub facility location for perishable products similarly show that location, transportation, storage, uncertainty mitigation, and sustainability must be jointly considered because delayed movement can directly reduce usable inventory and increase disposal [10]. These insights are highly relevant to blood supply chains, where inventory age is not merely an economic variable but a determinant of clinical usability.

Effective inventory management is therefore fundamental to the sustainability of blood supply systems. Inventory decisions determine whether hospitals receive appropriate products at the required time, whether older units are used before expiration, and whether emergency reserves remain available. Sustainable inventory management seeks to reduce waste without increasing the probability of shortages, a balance that becomes difficult when demand is volatile and replenishment depends on donations [11]. In perishable systems, age-sensitive allocation policies such as First-Expired–First-Out are necessary because conventional aggregate inventory measures do not reveal which units are closest to expiration. If product age is ignored, apparently adequate stock levels may conceal a high risk of near-term wastage or an insufficient supply of clinically acceptable units. Explicitly incorporating age into allocation decisions can therefore improve inventory turnover, reduce expiration, and support more accurate service-level evaluation.

Waste reduction is also a broader sustainability concern. Research on food waste demonstrates that reducing the disposal of perishable products requires coordinated forecasting, storage, processing, transportation, inventory rotation, and demand management rather than isolated operational adjustments [12]. Although blood differs fundamentally from food, both systems involve time-sensitive products whose value deteriorates when logistics are poorly coordinated. In blood supply chains, wastage is particularly consequential because each expired unit represents not only a financial loss but also a lost donation, unused processing capacity, avoidable transportation, and a missed opportunity to treat a patient. Therefore, minimizing expiration should be integrated into the system objective rather than treated as a secondary operational indicator.

Sustainability in healthcare supply chains requires simultaneous attention to economic, social, and environmental performance. Sustainable supply chain management in the medical industry includes responsible sourcing, resource efficiency, risk reduction, waste management, service continuity, and the consideration of environmental consequences across the product lifecycle [3]. More broadly, sustainable supply chain practices have been associated with improved financial sustainability and organizational performance when they are aligned with strategic objectives and implemented consistently [13, 14]. In a blood supply chain, the economic dimension includes collection, processing, transportation, shortage, storage, and disposal costs; the social dimension concerns equitable and timely access to lifesaving products; and the environmental dimension includes transportation emissions, energy-intensive storage, and waste generation.

The environmental component is increasingly important because healthcare logistics may involve frequent refrigerated transportation, specialized storage, and geographically dispersed facilities. Sustainable supply chain network design research has shown that optimization models are increasingly expected to integrate economic, environmental, and social objectives rather than focusing exclusively on cost [15]. In blood networks, transportation decisions influence not only delivery times and product quality but also carbon emissions. Frequent small shipments may improve responsiveness but raise transportation-related emissions, whereas consolidated shipments may reduce environmental impacts but increase waiting time or expiration risk. An integrated model must therefore balance cost, emissions, inventory age, and service requirements across multiple echelons.

Operational excellence also depends on the ability to sustain performance under disruption. Research in other sectors has shown that sustainability and post-crisis mitigation strategies can reinforce operational excellence when resilience practices are embedded in supply chain design [16]. Similarly, resilience-enhancing technologies and generative artificial intelligence have been discussed as tools for supporting decision-making, scenario analysis, communication, and adaptive planning across business sectors [17]. In healthcare supply chains, these technologies may improve forecasting and coordination, but their usefulness depends on reliable data, appropriate governance, and the ability of decision-makers to interpret model outputs. Thus, optimization remains essential for converting information into actionable allocation and network decisions.

Digitalization has transformed supply chain planning through electronic procurement, data integration, artificial intelligence, machine learning, and real-time monitoring. E-procurement can improve transaction transparency, reduce processing time, strengthen supplier coordination, and enhance supply chain performance when implementation barriers are managed effectively [18]. E-commerce and digital technologies have likewise altered inventory visibility, order processing, demand responsiveness, and customer-service expectations in retail supply chains [19]. Industry 4.0 technologies have been associated with improved supply chain performance through automation, connectivity, analytics, and operational visibility [20]. Although blood is not procured through ordinary commercial markets, the underlying benefits of real-time information exchange, integrated databases, automated inventory monitoring, and digital decision support are directly relevant to blood collection and distribution systems.

Artificial intelligence and machine learning offer further opportunities for forecasting demand, identifying disruption patterns, optimizing routing, and supporting inventory decisions. Research in emerging-market supply chains suggests that artificial intelligence can improve forecasting accuracy, resource allocation, process efficiency, and responsiveness when adequate data and technical capacity are available [21]. However, healthcare organizations often face adoption barriers related to infrastructure, workforce literacy, governance, trust, interoperability, and institutional readiness [22]. Consequently, advanced forecasting tools should complement rather than replace transparent optimization models. In blood supply chains, interpretable mathematical programming remains valuable because it makes constraints, priorities, trade-offs, and policy consequences explicit.

The design of blood networks also requires careful coordination of transportation and distribution. Logistics efficiency depends on facility locations, routing structures, shipment frequencies, capacity allocation, and the timely movement of products between collection centers, processing facilities, distribution centers, and hospitals. Research on logistics distribution in operationally sensitive settings emphasizes that distribution efficiency is shaped by coordination, infrastructure, information availability, and the alignment of logistics resources with mission requirements [23]. Blood supply networks face comparable challenges because facilities must operate across different geographic areas and deliver time-sensitive products under capacity limitations. Poor coordination can produce simultaneous shortages at one location and excess inventory at another.

Supplier and stakeholder relationships are also important, even where the supply source consists of voluntary donors rather than commercial vendors. Supply chain relationship research indicates that trust, communication, responsiveness, and coordination influence operational continuity and service quality [24]. In blood systems, analogous relationships exist among government agencies, blood transfusion organizations, collection centers, processing facilities, hospitals, transportation providers, healthcare professionals, and donor communities. A model that treats each actor as an isolated cost-minimizing unit may fail to represent the strategic interactions that shape real decisions. Game-theoretic methods are therefore appropriate for examining hierarchical systems in which government policies influence organizational behavior and downstream allocation.

Government intervention may be especially important when market incentives are insufficient to ensure the availability of socially critical products. Rare blood groups provide a clear example because their collection is difficult, their demand may be urgent, and maintaining adequate reserves may impose costs that are not reflected in conventional operational objectives. Government subsidies can influence donation campaigns, collection priorities, reserve policies, and organizational capacity. However, unlimited subsidy spending is neither realistic nor necessarily efficient. Public decision-makers must identify the level at which additional expenditure produces diminishing marginal benefits. This requires a model in which the government acts strategically, anticipates the response of operational organizations, and allocates a constrained budget to maximize social benefit.

Financial considerations also affect supply chain resilience and sustainability. Supply chain finance perspectives emphasize that liquidity, financing structures, cost allocation, and financial risk shape operational decisions and interorganizational relationships [25]. In blood systems, although products are not traded conventionally, financial constraints still affect collection capacity, staffing, transportation, storage technology, and emergency preparedness. Government subsidies can therefore be interpreted as a financing mechanism for correcting underinvestment in socially necessary collection activities, particularly for rare blood groups. A well-designed subsidy model should connect public expenditure with measurable improvements in collection, shortage reduction, service levels, and waste prevention.

Legal and regulatory compliance further complicates supply chain coordination. Cross-border and multi-jurisdictional supply chains must address regulatory differences, documentation requirements, standards, liability, and compliance monitoring [26]. Blood supply chains are typically governed by strict national standards concerning collection, testing, processing, storage, traceability, transportation, and clinical use. Even when the studied network is domestic, the broader lesson is that optimization models must remain consistent with operational and regulatory constraints rather than treating the movement of products as unrestricted. Compatibility requirements, age limits, processing rules, and capacity restrictions must therefore be explicitly represented.

Research on humanitarian and food bank supply chains provides another useful parallel. These systems must allocate scarce, donated, and often perishable resources to uncertain demand while balancing efficiency, equity, and service objectives. Reviews of food bank optimization have identified recurring problems related to facility location, inventory, routing, allocation, fairness, and uncertainty [27]. Blood supply chains share these characteristics but face even stricter compatibility and shelf-life constraints. The comparison reinforces the importance of incorporating priority categories so that scarce products are directed toward the most urgent needs rather than being allocated solely according to cost.

Emerging-market healthcare systems face additional constraints, including limited infrastructure, fragmented information systems, resource scarcity, and uneven access to advanced technologies. Advanced supply chain optimization can support these systems by integrating network design, demand forecasting, inventory control, routing, resilience, and sustainability [2]. Nevertheless, transferable models must be adapted to local operational structures and validated against real data. The use of actual network information is essential because theoretically attractive models may perform poorly when facility capacities, travel distances, demand patterns, or donation behavior differ from assumed conditions.

Despite substantial progress, several important gaps remain. Many blood supply chain models focus on a single product, although red blood cells, platelets, and plasma compete for shared collection, processing, transportation, and distribution resources. Other studies represent demand uncertainty but assume stable donation capacity, thereby overlooking supply disruptions. Government is often treated as a passive regulator rather than an active decision-maker capable of using targeted subsidies. FEFO is sometimes mentioned as an operational rule without being explicitly embedded in age-indexed allocation variables. Environmental impacts, especially transportation-related carbon emissions, are also frequently omitted. Finally, numerous models are evaluated only through hypothetical examples and are not validated using observed operational data. Addressing these gaps requires an integrated framework combining hierarchical decision-making, two-sided uncertainty, multi-product coordination, explicit inventory aging, sustainability objectives, and empirical validation [5, 9, 15].

Accordingly, this study aimed to develop and validate a sustainable three-level Stackelberg blood supply chain model that integrates targeted government subsidies, simultaneous supply and demand uncertainty, independent age dynamics for red blood cells, platelets, and plasma, explicit FEFO allocation, demand prioritization, and transportation-related carbon emissions.

2. Methodology

This study employed a quantitative operations-research design based on mathematical modeling, game theory, stochastic programming, and mixed-integer linear optimization. The study was designed to develop a sustainable blood supply chain model capable of simultaneously addressing the perishability of blood products, uncertainty on both the supply and demand sides, government intervention, service-priority requirements, environmental considerations, and age-based inventory allocation. A three-level Stackelberg structure was adopted. At the upper level, the government acted as the leader and determined targeted subsidy levels for rare blood groups under a specified budget ceiling. At the second level, the Iranian Blood Transfusion Organization and provincial blood processing centers operated as the first followers and made decisions regarding collection, processing, transportation, and coordination of blood products. At the third level, distribution centers acted as the second followers and allocated available products to hospitals. Hospitals were treated as demand nodes and were incorporated into the model through product-specific, blood-group-specific, age-specific, and priority-specific demand constraints. The modeled network represented the Isfahan blood supply system and included one blood collection base, five processing centers located in Isfahan, Najafabad, Shahreza, Khansar, and Kashan, ten distribution centers, and thirty hospitals. Each hospital was assumed to require all three major blood products—red blood cells, platelets, and plasma—across the eight principal blood groups. The planning horizon consisted of discrete time periods, and the model incorporated product-specific maximum shelf lives of 42 days for red blood cells, 5 days for platelets, and 365 days for frozen plasma. Blood groups were modeled as non-substitutable to preserve compatibility requirements. The uncertainty structure included four combined supply–demand scenarios representing favorable, normal, unfavorable, and crisis conditions. These scenarios captured simultaneous fluctuations in donations and hospital requirements, including conditions in which increased demand coincided with reduced blood supply. The model was empirically validated using operational data from the Isfahan blood transfusion network, with particular emphasis on platelet demand and supply records from the first five months of 2023.

The principal data collection tools consisted of historical operational records, administrative blood supply data, cost and capacity parameters, product shelf-life information, transportation characteristics, and scenario-based estimates of supply and demand uncertainty. Historical data from the Isfahan blood transfusion organization were used to estimate the probabilities and magnitudes of the combined supply–demand scenarios. Five years of historical information were examined to characterize deviations from average donation capacity and hospital demand. The normal scenario represented supply and demand at their historical means, whereas the remaining scenarios reflected increases or decreases in supply and demand relative to those means. The crisis scenario was specifically defined to represent a simultaneous decline in donation availability and a substantial increase in hospital demand, as may occur during natural disasters, seasonal epidemics, or other disruptive events. The model parameters included the demand for each hospital according to product, blood group, time period, scenario, and urgency category; the donation capacity of each collection base; collection, processing, storage, shortage, disposal, and transportation costs; the capacities of collection, processing, and distribution facilities; product separation coefficients; government subsidy limits; transportation-related carbon emission coefficients; and the social cost of carbon. Demand was classified into four categories: immediate-fresh, normal-fresh, immediate-older, and normal-older. This classification allowed the model to assign substantially higher shortage penalties to clinically urgent and freshness-sensitive requests than to non-urgent demand that could be met using older units. Product aging was recorded through age-indexed inventory variables, allowing every unit to be followed according to its remaining shelf life. The First-Expired–First-Out principle was embedded through age-indexed allocation variables and age-adjusted holding costs, which created an economic incentive to allocate older units before newer units without introducing additional binary variables specifically for FEFO implementation. For external validation, predicted platelet supply values were compared with actual platelet demand and fulfillment records for Farvardin, Ordibehesht, Khordad, Tir, and Mordad 2023. The comparison was used to calculate the monthly prediction error and the overall mean validation error.

Data analysis was conducted through the formulation and solution of a three-level Stackelberg optimization problem. The government objective function minimized the net cost of subsidies while considering the resulting reduction in the operational cost of the blood supply system. The government's decisions were constrained by a maximum subsidy budget and were defined separately for each blood group, with particular attention to rare groups such as O-negative. The organizational-level objective function minimized the expected total system cost across all uncertainty scenarios. This objective included blood collection costs, transportation costs from collection bases to processing centers, shipment costs from processing centers to distribution centers, distribution costs from distribution centers to hospitals, shortage penalties, wastage costs for expired products, and transportation-related carbon costs. Scenario probabilities were incorporated into all uncertain cost components. Inventory balance equations were used to model the entry of newly processed products, the transfer of unused inventory to the next age category, the allocation of products to hospitals, and the disposal of products that reached the end of their shelf life. Demand constraints ensured that shortages were explicitly measured for each urgency and freshness category. Supply capacity constraints were applied separately under each uncertainty scenario to capture fluctuations in blood donation availability.

The lower-level optimization problems were transformed into a single-level mathematical program using the Karush–Kuhn–Tucker optimality conditions. Before applying these conditions, the linear independence constraint qualification was assessed and confirmed by examining the gradients of the active constraints. The capacity, flow-conservation, demand-satisfaction, and recursive inventory constraints were found to have a structurally independent or lower-triangular arrangement, supporting the validity of the KKT reformulation. Complementarity conditions were linearized using binary variables and optimized Big-M coefficients. Rather than adopting an arbitrary large value, the Big-M parameters were derived from the upper bounds of the relevant collection, processing, distribution, and transportation cost coefficients. The resulting formulation was a mixed-integer linear programming model containing continuous decision variables for subsidies, blood collection, shipments, allocations, inventory, shortages, and wastage, together with binary variables required for KKT linearization. The model was solved using IBM ILOG CPLEX version 22.1.1 on an Intel Xeon Gold 6148 processor with 64 GB of memory and 12 computational threads. A relative optimality gap of 1% was used. Direct CPLEX solution was applied to networks containing 30 and 50 hospitals, whereas scenario-based Benders decomposition was used for the larger 100-hospital scalability experiment.

Model performance was evaluated through validation, sensitivity analysis, benchmarking, and scalability testing. Validation was performed by comparing predicted and actual platelet fulfillment values and calculating the mean percentage error. Sensitivity analyses examined the effects of changes in the government subsidy budget, product shelf life, demand shortages, and Big-M values. The marginal benefit of subsidy expenditure was evaluated to identify the point at which additional governmental spending produced diminishing returns. Changes in immediate-fresh, normal-fresh, immediate-older, and normal-older shortages were assessed before and after model implementation. The effect of extending platelet shelf life was evaluated in terms of wastage reduction and carbon-emission savings. Numerical stability was examined by comparing optimized Big-M values with progressively larger alternatives in terms of objective value, linear-programming relaxation gap, mixed-integer programming gap, and solution time. The proposed model was also compared with several alternative formulations, including a single-product model, a model without demand prioritization, a model without government intervention, a direct two-level heuristic model, and a simplified expected-value stochastic model. Comparative criteria included total cost, immediate-fresh shortage, platelet wastage, and service level. Scalability was assessed by increasing the number of hospitals from 30 to 50 and 100 and recording the resulting numbers of variables and constraints, solution methods, and computation times.

3. Findings and Results

The empirical evaluation was conducted using the Isfahan blood supply network as the study setting. Because the study was based on an operational blood supply system rather than human participants, demographic characteristics such as age, sex, education, or marital status were not applicable. Accordingly, the descriptive profile of the study setting was reported in terms of the structural and operational characteristics of the network. The investigated network consisted of one blood collection base, five processing centers located in Isfahan, Najafabad, Shahreza, Khansar, and Kashan, ten distribution centers, and thirty hospitals. Each hospital generated demand for three principal blood products, namely red blood cells, platelets, and plasma, across eight blood groups: A-positive, A-negative, B-positive, B-negative, AB-positive, AB-negative, O-positive, and O-negative. Product-specific shelf lives were incorporated into the model, including 42 days for red blood cells, 5 days for platelets, and 365 days for frozen plasma. Demand was divided into four clinically differentiated categories consisting of immediate-fresh, normal-fresh, immediate-older, and normal-older demand. Supply and demand uncertainty was represented through four joint scenarios, while historical data from the Isfahan blood transfusion system were used to estimate scenario probabilities and validate the model. The proposed model was initially solved for the 30-hospital network and was subsequently tested on larger configurations of 50 and 100 hospitals to evaluate its computational scalability.

Table 1. Dimensions and Computational Characteristics of the Proposed Mixed-Integer Linear Programming Model

Model component	Calculation basis	Number in the 30-hospital network
Government subsidy variables	Number of blood groups	8
Blood collection variables	Collection bases × products × blood groups × periods	168
Shipment variables from collection bases to processing centers	Processing centers × collection bases × products × blood groups × periods	840
Shipment variables from processing centers to distribution centers	Processing centers × distribution centers × products × blood groups × periods	8,400
Age-indexed allocation variables	Distribution centers × hospitals × products × blood groups × periods × scenarios × age groups	Approximately 756,000
Total continuous variables	Sum of all continuous decision variables	Approximately 850,776
Binary variables for KKT linearization	Collection-capacity, processing-capacity, and distribution-capacity complementarity conditions	112
Total constraints	Inventory, demand, capacity, flow, KKT, and linearization constraints	Approximately 204,063
Solution time for 30 hospitals	Direct CPLEX solution	184 seconds
Final optimality gap for 30 hospitals	Relative mixed-integer programming gap	0.8%
Solution time for 50 hospitals	Direct CPLEX solution	621 seconds
Solution time for 100 hospitals	Scenario-based Benders decomposition	Approximately 2,800 seconds

As shown in Table 1, the proposed formulation constituted a large-scale mixed-integer linear programming model, with the age-indexed allocation variables accounting for the largest share of the computational burden. In the 30-hospital network, the model included approximately 850,776 continuous variables and 204,063 constraints, while only 112 binary variables were required for linearizing the complementarity conditions derived from the Karush–Kuhn–Tucker reformulation. This distribution indicates that computational complexity was primarily attributable to the simultaneous representation of hospitals, blood products, blood groups, uncertainty scenarios, planning periods, and product ages rather than to an excessive number of binary decisions. The direct CPLEX solution procedure obtained a near-optimal solution for the 30-hospital instance in 184 seconds, with a final optimality gap of 0.8%, which was below the predefined 1% tolerance. Increasing the network to 50 hospitals raised the solution time to 621 seconds, reflecting the expected growth in the number of age-indexed allocation and demand-related variables. For the 100-hospital configuration, direct solution became less efficient; therefore, scenario-based Benders decomposition was employed, producing a solution in approximately 2,800 seconds. These results indicate that the proposed formulation was computationally feasible for small and medium provincial networks and remained tractable for substantially larger networks when decomposition techniques were applied.

Table 2. Validation of Predicted Platelet Fulfillment against Actual Operational Data

Period	Actual platelet demand	Actual platelet fulfillment	Model-predicted fulfillment	Prediction error
Farvardin 2023	182	164	171	4.3%
Ordibehesht 2023	195	180	187	3.9%
Khordad 2023	176	168	173	3.0%
Tir 2023	204	185	196	5.9%
Mordad 2023	189	177	183	3.4%
Mean	—	—	—	4.1%

Table 2 presents the validation results obtained by comparing model-predicted platelet fulfillment with actual operational fulfillment during the first five months of 2023. Platelets were selected for validation because they represented the most perishable and operationally sensitive blood product in the network. Across the five evaluated periods, prediction errors ranged from 3.0% to 5.9%, and the mean prediction error was 4.1%. The smallest discrepancy was observed in Khordad, when the model predicted 173 fulfilled units compared with 168 actual units, corresponding to an error of 3.0%. The largest discrepancy occurred in Tir, when predicted fulfillment was 196 units compared with 185 units actually fulfilled, producing an error of 5.9%. In all periods, the predicted values remained close to the observed operational values and followed the same temporal demand and fulfillment pattern. The relatively low mean error supports the external validity of the mathematical formulation and indicates that the optimized model was capable of reproducing real operational behavior with acceptable accuracy. The validation results also suggest that the assumptions related to platelet perishability, age progression, supply availability, demand prioritization, and distribution capacity were sufficiently realistic to represent the actual functioning of the provincial blood supply system.

Table 3. Sensitivity of System Performance to the Government Subsidy Budget

Government budget	O-negative blood collected	Immediate-fresh shortage, mean ± deviation	Platelet wastage, mean ± deviation	Service level	Marginal benefit
0	5	30% ± 4.2%	65% ± 5.8%	61%	—
20	30	15% ± 3.1%	45% ± 4.3%	77%	500%
40	39	8% ± 2.0%	28% ± 3.1%	86%	30%
60	43	5% ± 1.4%	25% ± 2.7%	91%	10%
80	44	4% ± 1.2%	24% ± 2.5%	92%	2%
100	45	4% ± 1.2%	24% ± 2.5%	93%	2%

The findings in Table 3 demonstrate that government subsidies substantially improved the availability of rare blood groups and the overall performance of the supply chain, particularly at lower and moderate budget levels. In the absence of government support, only five units of O-negative blood were collected, the immediate-fresh shortage rate was 30% ± 4.2%, platelet wastage reached 65% ± 5.8%, and the overall service level was limited to 61%. Increasing the budget to 20 units raised O-negative collection to 30 units, representing a fivefold marginal improvement over the baseline, while immediate-fresh shortages declined to 15% ± 3.1%, platelet wastage fell to 45% ± 4.3%, and the service level increased to 77%. At a budget of 40 units, O-negative collection increased further to 39 units, immediate-fresh shortage declined to 8% ± 2.0%, and the service level reached 86%. The most favorable balance between expenditure and system performance was observed at a budget of approximately 60 units. At this level, O-negative collection reached 43 units, corresponding to an increase of approximately 760% compared with the unsubsidized condition, immediate-fresh shortage decreased to 5% ± 1.4%, platelet wastage declined to 25% ± 2.7%, and the service level rose to 91%. Further budget increases produced only marginal improvements. Raising the budget from 60 to 80 units increased the service level by only one percentage point and O-negative collection by one unit, while a budget of 100 units generated only a further one-percentage-point increase in service level. Thus, the results identified a saturation threshold near 60 budget units, beyond which the marginal return on additional public expenditure fell to approximately 2%. This pattern confirms the presence of diminishing returns in subsidy allocation and indicates that targeted government intervention is highly effective up to a definable investment threshold, after which additional resources may be better directed toward storage, emergency reserves, donor recruitment, or transportation capacity.

Table 4. Demand Shortages before and after Implementation of the Proposed Model

Demand category	Shortage before implementation, mean ± deviation	Shortage after implementation, mean ± deviation	Relative change	Principal associated product
Immediate-fresh	30% ± 4.2%	5% ± 1.4%	83% reduction	Platelets and O-negative blood
Normal-fresh	25% ± 3.5%	8% ± 1.8%	68% reduction	Red blood cells
Immediate-older	20% ± 2.9%	15% ± 2.2%	25% reduction	Plasma
Normal-older	10% ± 1.8%	22% ± 2.6%	120% increase	Intentional reallocation

As reported in Table 4, implementation of the proposed model significantly changed the distribution of shortages across the four demand-priority categories. The greatest improvement occurred in the immediate-fresh category, which included clinically urgent demands requiring recently collected products. The shortage rate in this category decreased from 30% ± 4.2% before implementation to 5% ± 1.4% after implementation, representing an 83% reduction. This improvement was particularly important for platelet and O-negative blood requirements, because both were associated with high clinical urgency and elevated scarcity or perishability. The normal-fresh shortage rate also declined substantially, from 25% ± 3.5% to 8% ± 1.8%, corresponding to a 68% reduction and indicating more effective fulfillment of fresh red blood cell demand. The immediate-older category showed a smaller but still meaningful reduction from 20% ± 2.9% to 15% ± 2.2%, equivalent to a 25% improvement. In contrast, the normal-older shortage rate increased from 10% ± 1.8% to 22% ± 2.6%. This increase did not indicate model failure; rather, it reflected a deliberate prioritization decision embedded in the objective function. When available blood units were insufficient to satisfy all categories, the model allocated scarce products to immediate and life-saving demands and permitted a greater proportion of non-urgent, older-product demand to remain unmet. Consequently, the 120% increase in the normal-older shortage category represented an intentional trade-off that protected clinically urgent patients and improved the ethical and operational prioritization of scarce blood resources. Overall, the findings confirm that the proposed model did not merely reduce aggregate shortages but redistributed unavoidable shortages toward the least critical demand category.

Table 5. Comparison of the Proposed Model with Alternative Blood Supply Chain Models

Model	Total cost	Immediate-fresh shortage	Platelet wastage	Service level

Proposed three-product model with KKT reformulation and stochastic supply	12,483	5%	25%	91%
Single-product model considering platelets only	14,210	18%	31%	74%
Model without demand prioritization	13,640	22%	27%	70%
Model without government intervention	18,420	30%	65%	61%
Direct two-level model without KKT, solved heuristically	12,891	8%	28%	88%
Simplified stochastic expected-value model	13,110	11%	30%	85%

The comparative findings presented in Table 5 indicate that the proposed three-product Stackelberg model outperformed all alternative formulations across the principal economic and service-related criteria. The proposed model achieved the lowest total cost, equal to 12,483 units, while maintaining the lowest immediate-fresh shortage rate of 5% and the highest service level of 91%. Compared with the single-product platelet model, the proposed integrated formulation reduced total cost from 14,210 to 12,483, corresponding to an approximate 14% cost advantage, and increased the service level from 74% to 91%, representing a 17-percentage-point improvement. These results demonstrate that simultaneous coordination of red blood cells, platelets, and plasma allowed the system to use shared transportation, processing, and distribution capacities more efficiently than a product-specific approach. The model without demand prioritization generated a lower service level of 70% and an immediate-fresh shortage rate of 22%, indicating that the explicit classification of demand according to urgency and freshness was essential for protecting critical requests. The poorest performance was observed in the model without government intervention, which produced the highest total cost of 18,420, the highest immediate-fresh shortage rate of 30%, the highest platelet wastage rate of 65%, and the lowest service level of 61%. This comparison demonstrates that government subsidies played a central role in improving rare-group collection and reducing shortages. The direct two-level heuristic model yielded relatively favorable results, including a service level of 88% and total cost of 12,891; however, it remained inferior to the KKT-based formulation in terms of cost, shortage, and wastage. Similarly, the simplified expected-value stochastic model achieved a service level of 85%, but its immediate-fresh shortage and platelet wastage rates were higher than those of the proposed model. Taken together, these comparisons confirm that the superior performance of the proposed framework was attributable to the combined effects of three-product integration, explicit government participation, two-sided uncertainty, demand prioritization, age-based FEFO allocation, and exact hierarchical optimization.

4. Discussion and Conclusion

The present study developed and evaluated a sustainable three-level Stackelberg blood supply chain model that simultaneously incorporated government intervention, supply and demand uncertainty, the coordinated management of red blood cells, platelets, and plasma, age-dependent inventory dynamics, explicit First-Expired–First-Out allocation, demand prioritization, and transportation-related carbon emissions. The findings showed that the proposed model improved system performance across several economic, operational, social, and environmental indicators. Targeted government subsidies substantially increased the collection of O-negative blood, immediate-fresh shortages declined markedly, service levels improved, platelet wastage decreased, and total system cost was lower than that of the single-product and non-prioritized benchmark models. The model also demonstrated acceptable empirical validity, with a mean prediction error of 4.1% when platelet fulfillment estimates were compared with actual operational data. These findings support the argument that blood supply chain performance cannot be optimized through isolated inventory or transportation decisions and instead requires coordinated, multi-echelon, uncertainty-sensitive, and policy-responsive planning [2, 4, 5].

One of the most important findings was the substantial effect of government subsidy intervention on the collection of rare blood groups. O-negative collection increased from five units in the unsubsidized condition to 43 units at a government budget of 60 units, representing an increase of approximately 760%. This result indicates that public intervention can correct an operational imbalance that may not be resolved through routine collection planning alone. Rare blood groups generate a distinctive policy problem because their clinical importance is high, their donor population is limited, and their collection may require additional recruitment, communication, reservation, and logistics expenditure. Government funding can compensate for these additional costs and encourage the blood transfusion organization to prioritize strategically important groups. This interpretation is consistent with broader supply chain finance perspectives, which emphasize that financing arrangements and targeted resource allocation can alter operational decisions, reduce underinvestment, and improve supply continuity [25]. It is also aligned with the medical supply chain literature, which identifies government support, institutional coordination, and resource prioritization as important mechanisms for maintaining the availability of socially critical products [3, 8].

However, the analysis also revealed diminishing marginal returns after the subsidy budget reached approximately 60 units. Increasing the budget beyond this threshold produced only minor improvements in O-negative collection and service level, while the marginal benefit fell to nearly 2%. This finding is operationally important because it indicates that greater public expenditure does not automatically generate proportionate improvements in system performance. At lower budget levels, subsidies address severe undercapacity and enable major improvements in collection and allocation. Once the most important constraints have been relieved, additional funds encounter other limiting factors, including donor availability, processing capacity, storage restrictions, transportation capacity, and the finite size of the rare-group donor pool. The result supports the broader view that supply chain improvement requires balanced investment across several interconnected capabilities rather than unrestricted spending on a single intervention [6, 7]. It also corresponds with research emphasizing that resilience emerges from coordinated preparedness, capacity planning, inventory policy, and information visibility rather than from financial input alone [1, 17].

The proposed model reduced immediate-fresh shortages from 30% ± 4.2% to 5% ± 1.4%, corresponding to an 83% reduction. This was the largest improvement among the four demand categories and represented one of the most clinically significant outcomes of the study. Immediate-fresh demand included urgent requests for products with limited age, particularly platelets and O-negative blood. The strong reduction occurred because the model assigned higher shortage penalties to life-saving and freshness-sensitive demand and coordinated supply, inventory age, and allocation decisions accordingly. This result confirms that explicit demand prioritization is essential in healthcare supply chains, where all shortages cannot be treated as equally harmful. Research on intensive care and immunization supply chains similarly emphasizes that resource allocation should be guided by patient safety, urgency, and continuity of care rather than by aggregate cost alone [1, 8]. The finding also reflects the logic observed in humanitarian supply chains, in which scarce donated resources must be distributed according to urgency, vulnerability, and service impact [27].

The normal-fresh shortage rate also decreased from 25% to 8%, while the immediate-older shortage rate declined from 20% to 15%. In contrast, the normal-older shortage rate increased from 10% to 22%. Although an increase in one shortage category may initially appear unfavorable, it reflected deliberate and ethically defensible reallocation. The model permitted a larger proportion of non-urgent, older-product demand to remain unmet in order to protect urgent and clinically sensitive categories. This redistribution demonstrates the advantage of evaluating shortage composition rather than only total shortage. A model that minimizes aggregate unmet demand without recognizing urgency may produce an apparently efficient solution while failing to protect patients with the greatest clinical need. The findings therefore support the use of multiclass demand structures in healthcare optimization. Similar conclusions can be drawn from research on resource-constrained humanitarian systems, where fairness and urgency must be embedded directly in allocation models rather than assessed only after optimization [27]. They are also consistent with the patient-centered orientation recommended in advanced healthcare supply chain optimization [2].

The proposed three-product model achieved a total cost of 12,483 units, compared with 14,210 units for the single-product platelet model, indicating an approximate 14% cost reduction. The integrated model also increased the service level from 74% to 91%, a 17-percentage-point improvement. These results indicate that managing red blood cells, platelets, and plasma in a common network creates coordination benefits that cannot be captured through product-specific optimization. The three products share collection inputs, processing facilities, transportation resources, distribution centers, and hospital demand points. When modeled separately, the system may duplicate transportation, underuse capacity, or create inventory imbalances across products. Integrated optimization allows capacity and logistics resources to be assigned across products according to system-wide priorities. This finding is consistent with sustainable supply chain network design research, which emphasizes that integrated network decisions generally outperform fragmented decisions because location, capacity, inventory, and transportation are interdependent [15]. It also aligns with studies showing that coordinated sustainable supply chain practices can improve operational and financial performance [13, 14].

The model without government intervention produced the weakest performance, with a total cost of 18,420 units, an immediate-fresh shortage rate of 30%, platelet wastage of 65%, and a service level of only 61%. This comparison demonstrates that public policy was not a peripheral feature of the proposed framework but a central determinant of supply availability and downstream performance. Without government intervention, the system lacked sufficient incentive or financial capacity to expand the collection of rare blood groups, which subsequently increased shortages and reduced the efficiency of allocation. The finding supports the broader argument that healthcare supply chains often require institutional coordination and public governance because social value is not fully represented by organizational cost objectives [3]. It is also consistent with evidence that resource centers and coordinated support structures can strengthen healthcare product availability and reduce operational fragmentation [8].

The model without demand prioritization also performed poorly, producing a service level of 70% and an immediate-fresh shortage rate of 22%. This finding confirms that merely increasing supply or reducing cost is insufficient when products must be allocated among demands with different clinical consequences. A non-prioritized system may satisfy a larger volume of low-risk demand while leaving urgent requirements unmet. By contrast, the proposed model translated clinical priorities into differential shortage penalties and age-specific allocation constraints. This approach is compatible with sustainable medical supply chain principles, which define performance in terms of safety, access, continuity, and social value in addition to economic efficiency [3]. It also reinforces the argument that operational excellence requires alignment between technical optimization and the strategic purpose of the healthcare system [16].

Another important finding concerned platelet wastage. Extending platelet shelf life from three to five days reduced wastage by 61%, from 65% ± 5.8% to 25% ± 2.7%, and generated estimated monthly carbon savings of 12.4 kg. Platelets are especially vulnerable to wastage because their short shelf life leaves little time to correct forecasting or allocation errors. Even a modest increase in usable shelf life therefore expands the opportunity for redistribution and consumption before expiration. The finding is consistent with research on perishable supply chains, which shows that shelf-life extension, inventory rotation, storage improvement, and age-sensitive allocation can substantially reduce waste [9, 10]. It also corresponds with broader waste-reduction research emphasizing that effective management of perishable products depends on coordinated forecasting, storage, transportation, and inventory practices [12].

The effectiveness of explicit FEFO implementation further explains the observed decline in wastage. In the proposed formulation, FEFO was embedded through age-indexed allocation variables and age-adjusted holding costs rather than through a separate set of binary sequencing constraints. This structure encouraged older products to be allocated before newer ones while preserving computational compatibility with the linear lower-level problem. The result demonstrates that clinically meaningful inventory rules can be represented without excessive computational complexity. This is particularly important in large blood supply networks, where detailed age tracking creates a very large number of continuous variables. The finding supports the inventory management literature, which identifies product age visibility and systematic stock rotation as important requirements for reducing expiration and improving sustainable performance [11]. It also aligns with the broader argument that digital inventory visibility and integrated information systems improve the responsiveness of supply chains [19, 20].

The inclusion of carbon emissions in the objective function extended the model beyond conventional cost and shortage minimization. The results showed that operational improvements, particularly reduced wastage and more coordinated distribution, could produce environmental benefits alongside economic and social gains. This is consistent with the triple-bottom-line perspective, according to which sustainable supply chain performance requires the joint consideration of financial outcomes, service or social outcomes, and environmental consequences. Reviews of sustainable network design indicate that carbon emissions, energy use, transportation distances, and waste should be incorporated directly into optimization models because environmental performance is strongly influenced by network decisions [15]. The present findings similarly suggest that blood supply chain sustainability cannot be evaluated solely through cost per delivered unit, because expired products and inefficient shipments also represent avoidable environmental burdens.

The model's validation against five months of actual platelet data yielded a mean prediction error of 4.1%, with monthly errors ranging from 3.0% to 5.9%. This relatively low error supports the practical relevance of the model and suggests that its assumptions adequately represented the operational behavior of the Isfahan blood supply network. Validation is especially important in optimization research because a mathematically optimal solution may have limited managerial value if parameter estimates do not reflect actual demand, capacity, or supply conditions. The use of real operational data distinguishes the present model from purely hypothetical formulations and strengthens confidence in its decision-support potential. This finding is consistent with calls for evidence-based and context-sensitive healthcare supply chain planning [1]. It also supports the use of scenario-based methods in blood inventory systems, as such methods can reproduce different demand and supply conditions more realistically than deterministic models [4, 5].

The comparison with the expected-value stochastic model further demonstrated the importance of representing uncertainty explicitly. The simplified expected-value model had a higher total cost, a higher immediate-fresh shortage rate, greater platelet wastage, and a lower service level than the proposed scenario-based formulation. Expected-value models replace uncertain parameters with average values and may therefore conceal severe but plausible conditions, such as simultaneous increases in demand and declines in donation. In blood supply chains, this can lead to insufficient emergency capacity and an overly optimistic assessment of availability. The superior performance of the proposed model is consistent with research emphasizing robust, scenario-based, and resilience-oriented planning in healthcare and perishable supply chains [5, 7, 10].

The optimized Big-M formulation also produced a major computational advantage. Using the cost-derived Big-M value of approximately 73 reduced solution time to 184 seconds, whereas the conventional arbitrary value of one million increased the linear programming relaxation gap to 22.6% and extended solution time by more than fifteenfold. This finding shows that numerical formulation quality is not merely a technical issue but directly affects the practical usability of large optimization models. Poorly selected Big-M values weaken the relaxation, increase the search space, and may result in unstable or excessively slow solutions. The optimized formulation enabled the model to solve the 30-hospital and 50-hospital cases directly and supported the use of Benders decomposition for the 100-hospital case. This scalability is important because advanced healthcare optimization must remain computationally feasible in real decision environments [2]. The result also complements digital and artificial-intelligence research by showing that advanced decision support depends not only on data availability but also on efficient and interpretable analytical structures [21, 22].

Overall, the findings indicate that sustainable blood supply chain performance emerges from the interaction of policy, finance, inventory management, uncertainty modeling, service prioritization, logistics coordination, and environmental control. No single intervention accounted for all improvements. Government subsidies increased rare-group availability, integrated product management reduced cost, FEFO limited expiration, demand prioritization protected urgent cases, scenario analysis improved resilience, and carbon costing incorporated environmental responsibility. This integrated interpretation is consistent with research describing sustainable and resilient supply chains as systems of mutually reinforcing capabilities rather than collections of isolated practices [13, 14, 16]. It also reflects the growing emphasis on digital coordination, logistics visibility, and adaptive planning across modern supply chains [18-20]. Effective implementation will additionally require strong relationships and communication among government bodies, transfusion organizations, processing centers, hospitals, transport providers, and donor communities [24], as well as compliance with the legal and regulatory standards governing the collection, traceability, storage, and movement of blood products [26].

The study had several limitations. First, the model assumed that the government possessed complete information about the cost structures, capacities, and responses of downstream organizations, whereas actual decision environments may involve information asymmetry, delayed reporting, and strategic behavior. Second, uncertainty was represented through four discrete supply–demand scenarios estimated from historical data, which may not fully capture rare events, distributional ambiguity, rapidly evolving emergencies, or spatially correlated disruptions. Third, blood groups were modeled as non-substitutable, and the formulation did not explicitly incorporate complex compatibility and substitution rules that may be applied under emergency clinical conditions. Fourth, validation was conducted using platelet data from a single provincial network and a five-month period; therefore, the generalizability of the findings to other regions, national systems, or longer time horizons should be interpreted cautiously. Fifth, some operational factors, including donor appointment behavior, staff availability, testing delays, vehicle failures, and temporary facility closures, were not modeled explicitly. Finally, the carbon assessment focused mainly on transportation emissions and did not include the full environmental impacts of refrigeration, freezing, processing, testing, packaging, or waste treatment.

Future studies should extend the proposed framework by applying distributionally robust or adaptive robust optimization to address ambiguity in the probability distributions of donations and hospital demand. Models with asymmetric information could be developed to examine how government agencies design incentives when they cannot directly observe the actual costs or effort levels of blood collection organizations. Future research should also incorporate blood-group compatibility and controlled substitution, particularly for emergency situations in which alternative groups may be clinically acceptable. Multi-period donor behavior models could connect subsidy and recruitment policies with donor retention, appointment attendance, and repeated donation. Predictive methods such as long short-term memory networks, gradient boosting, or hybrid time-series models could be integrated with optimization to produce short-horizon forecasts for platelet demand and donation levels. Additional validation across several provinces and national networks would improve external validity. Researchers should also investigate decentralized solution algorithms, digital twins, and real-time rolling-horizon optimization for larger networks. A more comprehensive environmental analysis could include electricity consumption, refrigeration, freezing, processing, packaging, and disposal emissions.

Government agencies should use targeted rather than uniform subsidies and should identify the budget level at which marginal gains begin to decline. In the studied setting, the results indicate that approximately 60 budget units provided the most favorable balance between public expenditure and system improvement. Blood transfusion organizations should manage red blood cells, platelets, and plasma within an integrated planning system instead of optimizing each product independently. Inventory information systems should record product age at the unit or batch level and automatically support FEFO allocation. Urgent and freshness-sensitive hospital requests should receive explicitly higher priority in allocation rules, while unavoidable shortages should be shifted toward less critical demand categories. Provincial networks should establish dashboards linking donation availability, hospital demand, inventory age, transportation capacity, and shortage risk. Platelet shelf-life extension strategies, where clinically and technically feasible, should be prioritized because even small improvements can substantially reduce waste. Finally, optimization outputs should be reviewed jointly by policymakers, transfusion specialists, hospital representatives, and logistics managers to ensure that recommended decisions remain clinically appropriate, operationally feasible, and ethically defensible.

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Authors equally contributed to this article.

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Declaration of Interest

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All procedures performed in this study were under the ethical standards.

References

[1] N. Hasmee, H. Joshi, M. Gurung, B. Singh, and S. Naseema, "Optimising ICU Supply Chains: Evidence-Based Strategies for Efficiency, Resilience and Patient Safety—a Structured Narrative Review," *BMJ Open Quality,* vol. 15, no. 2, p. e003422, 2026, doi: 10.1136/bmjoq-2025-003422.

[2] P. A. Usuemerai, O. E. Ibikunle, L. A. Abass, V. Alemede, E. I. Nwankwo, and A. O. Mbata, "Advanced Supply Chain Optimization for Emerging Market Healthcare Systems," *International Journal of Management & Entrepreneurship Research,* vol. 6, no. 10, pp. 3321-3356, 2024, doi: 10.51594/ijmer.v6i10.1637.

[3] E. A. Abaku and A. C. Odimarha, "Sustainable Supply Chain Management in the Medical Industry: A Theoretical and Practical Examination," *International Medical Science Research Journal,* vol. 4, no. 3, pp. 319-340, 2024, doi: 10.51594/imsrj.v4i3.931.

[4] M. Arani, X. Liu, and S. Abdolmaleki, "Scenario-based simulation approach for an integrated inventory blood supply chain system," in *2020 Winter Simulation Conference (WSC)*, 2020: IEEE, pp. 1348-1359, doi: 10.1109/WSC48552.2020.9384018.

[5] A. Baba Zadeh Rafiei, T. Sohrabi, M. Motamedi, and M. H. Darvish Motavalli, "A Robust Model for Risk Management in the Blood Supply Chain During the COVID-19 Pandemic," ed, 2024.

[6] A. K. Siti-Nabiha and N. Nordin, "Post-Covid Impact on Supply Chain Risk Management: A Case Study of a

Semiconductor Company," *International Journal of Academic Research in Progressive Education and Development,* vol. 13, no. 4, 2024, doi: 10.6007/ijarped/v13-i4/23473.

[7] B. Thakur-Weigold, "Promoting Resilience and Preparedness in Supply Chains," 2024, doi: 10.1787/be692d01-en.

[8] S. Singh *et al.*, "Leveraging Resource Centers for Strengthening Immunization Supply Chain," *Cureus,* 2024, doi: 10.7759/cureus.58966.

[9] M. Zarreh, M. Khandan, A. Goli, A. Aazami, and S. Kummer, "Integrating Perishables Into Closed-Loop Supply Chains: A Comprehensive Review," *Sustainability,* vol. 16, no. 15, p. 6705, 2024, doi: 10.3390/su16156705.

[10] A. A. Zijoodi, S. J. Sadjadi, and M. Tayefeh, "The Strategies of Hub Facility Location and Its Utilization in Managing the Supply Chain of Perishable Products for Sustainability and Uncertainty Mitigation: A Literature Review," *Journal of Future Sustainability,* pp. 127-140, 2025, doi: 10.5267/j.jfs.2025.4.003.

[11] S. Holloway, "The Role of Inventory Management in Achieving Sustainability in Supply Chains," 2024, doi: 10.20944/preprints202407.1016.v1.

[12] M. M. Urugo *et al.*, "A Comprehensive Review of Current Approaches on Food Waste Reduction Strategies," *Comprehensive Reviews in Food Science and Food Safety,* vol. 23, no. 5, 2024, doi: 10.1111/1541-4337.70011.

[13] T. A. Anisulowo, A. A. Sofayo, B. O. Anthony, C. O. Sanni, O. S. Onasanya, and A. M. Adeleke, "Sustainable Supply Chain Management Practices and Financial Sustainability of Listed Consumer Goods Firm in Nigeria," *Asian Journal of Economics Business and Accounting,* vol. 24, no. 10, pp. 142-160, 2024, doi: 10.9734/ajeba/2024/v24i101519.

[14] Y. Ma, "The Impact of Sustainable Supply Chain Management Practices on Business Performance: A Case Study of Huawei," *SHS Web of Conferences,* vol. 181, p. 03015, 2024, doi: 10.1051/shsconf/202418103015.

[15] B. Madani, A. Saihi, and A. Abdelfatah, "A Systematic Review of Sustainable Supply Chain Network Design: Optimization Approaches and Research Trends," *Sustainability,* vol. 16, no. 8, p. 3226, 2024, doi: 10.3390/su16083226.

[16] Y. Fernando, F. Mergeresa, I. S. Wahyuni-Td, and N. S. Hazarasim, "Halal Beauty Supply Chain and Sustainable Operational Excellence: A Moderator of the Post-Sars-CoV-2 Mitigation Strategy," *Journal of Islamic Marketing,* vol. 15, no. 12, pp. 3748-3777, 2024, doi: 10.1108/jima-07-2023-0205.

[17] N. L. Rane and J. Rane, "Enhancing Resilience in Various Business Sectors With ChatGPT and Generative Artificial Intelligence," 2024, doi: 10.70593/978-81-981367-8-7_4.

[18] A. Abubakar, "Impact of E-Procurement Implementation on Supply Chain Performance: A Case Study of Nigeria," *Global Journal of Purchasing and Procurement Management,* vol. 3, no. 1, pp. 14-27, 2024, doi: 10.47604/gjppm.2467.

[19] W. L. Brown, O. Johnson, and G. R. Wilson, "Influence of E-Commerce Technologies on Supply Chain Management in Retail," 2024, doi: 10.20944/preprints202407.1140.v1.

[20] M. Mutale and B. G. Mwanza, "The Effects of Industry 4.0 Technologies on Supply Chain Management Performance: A Case Study of DHL Zambia," *African Journal of Commercial Studies,* vol. 5, no. 2, pp. 80-106, 2024, doi: 10.59413/ajocs/v5.i.2.4.

[21] J. Mwangi, "Analyzing the Role of Artificial Intelligence and Machine Learning in Optimizing Supply Chain Processes in Kenya," *International Journal of Supply Chain Management,* vol. 9, no. 1, pp. 39-50, 2024, doi: 10.47604/ijscm.2322.

[22] R. Kumar, A. Singh, A. S. A. Kassar, M. I. Humaida, and M. Sharma, "Adoption Challenges to Artificial Intelligence Literacy in Public Healthcare: An Evidence Based Study in Saudi Arabia," *Frontiers in Public Health,* vol. 13, 2025, doi: 10.3389/fpubh.2025.1558772.

[23] A. Sarjito, "Enhancing Logistics Distribution Efficiency for Indonesian Navy Warships in Operations Area," *West Science Interdisciplinary Studies,* vol. 2, no. 02, pp. 345-356, 2024, doi: 10.58812/wsis.v2i02.644.

[24] I. Warwick, "Exploring Supplier Relationship Dynamics: Insights From Italian Restaurant Managers," 2024, doi: 10.20944/preprints202407.0641.v1.

[25] J. Jansen, "Supply Chain Finance Perspectives," 2024, doi: 10.5772/intechopen.114030.

[26] I. R. Maruf, M. Budiman, and T. Rastuti, "Legal Compliance for Cross-Border Supply Chain: Challenge and Measurements," pp. 141-152, 2024, doi: 10.2991/978-2-38476-208-8_19.

[27] A. F. Rivera, N. R. Smith, and Á. Ruiz, "A Systematic Literature Review of Food Banks' Supply Chain Operations With a Focus on Optimization Models," *Journal of Humanitarian Logistics and Supply Chain Management,* vol. 13, no. 1, pp. 10-25, 2023, doi: 10.1108/jhlscm-09-2021-0087.