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Sustainable Blood Supply Chain Modeling with Government Intervention: A Three-Level Stackelberg Programming Approach

Gita. Amirsadri Naeini[1], Davood. Mohammaditabar[1]*, Hamidreza. Kia[1]

[1] Department of industrial engineering, ST.C., Islamic Azad university, Tehran , Iran

*** Corresponding author email address**: mohammaditabar@iau.ac.ir

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ABSTRACT

The present study aimed to develop and evaluate a sustainable blood supply chain model incorporating government intervention through a three-level Stackelberg programming framework to improve rare blood collection, reduce shortages and waste, and enhance economic, social, and environmental performance under demand uncertainty. This applied quantitative study employed a mathematical optimization approach based on game theory and mixed-integer linear programming (MILP). A three-level Stackelberg structure was developed in which the government acted as the strategic leader, the Iranian Blood Transfusion Organization (IBTO) and provincial blood centers served as first-level followers, and distribution centers functioned as second-level followers. The model explicitly incorporated platelet perishability, rare blood group incentives, demand uncertainty, and sustainability objectives. Four categories of demand, including urgent-fresh, non-urgent-fresh, urgent-non-fresh, and non-urgent-non-fresh requests, were considered. Historical operational data from the Iranian Blood Transfusion Organization covering March 2022 to March 2023 were used for model calibration. Uncertainty was represented through ten stochastic demand scenarios generated using Latin Hypercube Sampling. The bilevel follower problem was transformed into a single-level formulation using Karush–Kuhn–Tucker conditions and optimized Big-M linearization. The resulting MILP model was solved using IBM ILOG CPLEX 22.1 with a 1% optimality gap. The results demonstrated that government incentives substantially improved the collection of rare Rh− platelet units, increasing collection volume from 5 units in the baseline scenario to 43 units under optimal conditions, representing a 760% improvement. The model reduced urgent-fresh demand shortages from 30% to 5% (83% reduction) and non-urgent-fresh shortages from 25% to 8% (68% reduction). Platelet waste decreased by 61% when shelf life increased from three to five days. Compared with the non-intervention scenario, the proposed framework reduced operational costs by 32%, decreased biological waste by 63%, and increased the social service level from 61% to 91%. Sensitivity analyses revealed diminishing marginal returns for government budgets beyond approximately 60 units. The proposed three-level Stackelberg model outperformed benchmark optimization approaches in terms of cost efficiency, shortage reduction, sustainability performance, and service quality. The findings indicate that integrating government intervention, hierarchical decision-making, demand prioritization, and sustainability objectives within a unified three-level Stackelberg framework significantly enhances blood supply chain performance. The proposed model effectively balances economic efficiency, social welfare, and environmental sustainability while maintaining computational tractability for large-scale healthcare networks. The results support the implementation of targeted government incentive policies and coordinated multi-echelon planning strategies to improve the resilience, effectiveness, and sustainability of blood supply systems.

Keywords: *Blood Supply Chain; Sustainable Supply Chain; Government Intervention; Stackelberg Game; Mixed-Integer Linear Programming*

1. Introduction

Supply chain management has evolved from a traditional logistics-oriented discipline into a strategic framework that integrates economic performance, environmental sustainability, social responsibility, technological innovation, and stakeholder coordination. Contemporary supply chains operate within increasingly uncertain and interconnected environments characterized by demand fluctuations, regulatory pressures, resource scarcity, technological disruptions, and sustainability challenges. As a result, decision-makers are required to balance multiple and often conflicting objectives while maintaining operational efficiency and resilience. Recent studies emphasize that modern supply chains can no longer be evaluated solely through cost minimization criteria; instead, organizations must adopt integrated decision-making approaches that simultaneously address economic viability, environmental stewardship, and social welfare (Dey et al., 2025; Golińska-Dawson et al., 2023; Kumar et al., 2021).

The growing importance of sustainable supply chain management has stimulated extensive research on the integration of triple-bottom-line principles into operational and strategic decision-making processes. Researchers have demonstrated that environmental concerns, carbon emission regulations, green innovation initiatives, and social welfare considerations significantly influence supply chain performance and competitive advantage. In particular, sustainability-oriented coordination mechanisms enable firms to improve resource utilization, reduce waste generation, and enhance service quality while preserving profitability (Kumari et al., 2024; Li et al., 2024; Santra et al., 2024). These developments have encouraged the adoption of advanced optimization techniques capable of capturing complex interactions among supply chain actors operating under heterogeneous objectives and resource constraints.

One of the most influential analytical approaches in contemporary supply chain research is game theory. Game-theoretic models provide powerful tools for analyzing strategic interactions among independent decision-makers whose actions influence one another's outcomes. Various forms of game theory, including cooperative games, non-cooperative games, Nash equilibrium models, and Stackelberg leader-follower frameworks, have been applied extensively to pricing, inventory management, logistics coordination, environmental policy implementation, and resource allocation problems (Kong et al., 2022; Sukmana et al., 2022a, 2022b). Among these approaches, Stackelberg games have attracted particular attention because they capture hierarchical decision structures frequently observed in real-world supply chains where dominant actors exert influence over downstream or upstream participants.

Recent literature demonstrates the effectiveness of Stackelberg and bilevel optimization models in addressing complex supply chain coordination problems. Multi-level decision frameworks have been employed to investigate pricing strategies, inventory management, risk sharing, channel coordination, and sustainability initiatives under various market conditions. Studies have shown that hierarchical decision structures can generate superior outcomes compared with decentralized systems by aligning incentives and reducing operational inefficiencies (Marousi et al., 2025; Ye & Li, 2024; Yeh et al., 2022). Furthermore, bilevel and multilevel programming models provide realistic representations of situations in which policy makers, manufacturers, distributors, and retailers possess different levels of authority and information.

Government intervention has emerged as another critical theme in supply chain optimization research. Public authorities increasingly influence supply chain operations through subsidies, taxation policies, environmental regulations, financial incentives, and market supervision mechanisms. Government participation is particularly important in sectors involving public welfare, environmental protection, and strategic resources. Empirical and theoretical studies have demonstrated that appropriately designed subsidy programs can stimulate technological innovation, enhance environmental performance, improve resource allocation efficiency, and promote sustainable development outcomes (Gu et al., 2023; Li et al., 2024; Liu et al., 2024). Similarly, government intervention mechanisms have been shown to affect supply chain financing decisions, carbon reduction investments, green technology adoption, and operational coordination across multiple echelons (Deng et al., 2023; Dey et al., 2025; Tang et al., 2022).

The interaction between government policies and supply chain decisions becomes particularly significant in industries characterized by perishability, uncertainty, and social importance. Previous research indicates that subsidies and incentive mechanisms can alter the strategic behavior of supply chain members and improve system-wide performance when properly aligned with operational objectives (Gu et al., 2023; Li et al., 2024; Liu et al., 2024). However, the effectiveness of these interventions depends heavily on the structure of decision-making authority, information availability, and the incentives facing individual actors. Consequently, hierarchical game-theoretic models have become increasingly relevant for analyzing public-sector involvement in supply chain systems.

Another major trend in the literature concerns the management of uncertainty and risk. Supply chains frequently encounter stochastic demand, fluctuating prices, transportation disruptions, operational failures, and external shocks. Advanced optimization frameworks have therefore incorporated stochastic programming, robust optimization, and simulation-based approaches to improve resilience and decision quality under uncertainty (Hongjin, 2021; Marousi et al., 2025; Wu et al., 2024). These methods allow decision-makers to anticipate multiple scenarios and develop adaptive strategies capable of maintaining acceptable performance levels despite environmental variability.

Perishable-product supply chains represent one of the most challenging contexts for optimization and coordination. Products with limited shelf lives require highly synchronized collection, storage, transportation, and distribution activities to minimize spoilage and ensure service availability. Researchers have investigated dynamic pricing, inventory control, and coordination strategies for perishable supply chains under uncertain demand conditions, demonstrating the importance of integrated planning mechanisms for reducing waste and improving service performance (Rajabi et al., 2021; Zarouri et al., 2022). The complexity of these systems increases substantially when perishability interacts with uncertain demand, multiple stakeholders, and service-critical requirements.

Blood supply chains constitute a particularly important class of perishable supply chains due to their direct impact on public health and patient survival. Unlike conventional commercial products, blood products are donated rather than manufactured, exhibit limited shelf lives, require strict storage conditions, and must be allocated according to clinical priorities. Consequently, blood supply chains involve unique operational, ethical, and social challenges that distinguish them from traditional logistics systems. Any mismatch between supply and demand can result in severe consequences, including treatment delays, increased mortality risks, and substantial economic losses. Therefore, effective blood supply chain management requires coordinated decision-making across collection, processing, distribution, and healthcare delivery stages.

Among blood products, platelets present some of the most significant management challenges. Their short shelf life, typically limited to a few days, creates substantial risks of shortages and wastage. Inventory decisions must therefore balance service availability against spoilage costs while responding to uncertain demand patterns. The implementation of age-based inventory policies and prioritization rules has become increasingly important for improving system performance in healthcare logistics. These characteristics make blood supply chains particularly suitable for advanced optimization approaches capable of incorporating perishability, uncertainty, and multiple stakeholder objectives within a unified framework.

The increasing emphasis on sustainability further complicates blood supply chain management. From an economic perspective, healthcare systems seek to minimize collection, processing, transportation, inventory, and disposal costs. From a social perspective, they aim to maximize patient access to life-saving blood products and prioritize urgent clinical needs. From an environmental perspective, they seek to reduce biological waste and improve resource utilization. The simultaneous consideration of these objectives requires sophisticated modeling approaches capable of capturing trade-offs among competing performance dimensions (Golińska-Dawson et al., 2023; Huang & Yao, 2021; Kumar et al., 2021). Recent research has demonstrated that triple-bottom-line frameworks can substantially improve decision quality by integrating economic, environmental, and social considerations into supply chain planning.

The literature also highlights the importance of power structures and hierarchical relationships in determining supply chain outcomes. Different configurations of authority and influence can significantly affect pricing decisions, coordination effectiveness, investment strategies, and sustainability performance (Fu, Liu, & Han, 2021; Fu, Liu, Shen, et al., 2021; Ye & Li, 2024). Multi-echelon systems often exhibit asymmetric power distributions in which certain actors possess greater decision-making authority than others. Understanding these relationships is essential for designing effective coordination mechanisms and policy interventions. Studies examining vertical structures, mergers, strategic choices, and channel coordination consistently demonstrate the value of hierarchical modeling approaches for capturing real-world decision environments (Huang & Yao, 2021; Zhang et al., 2021, 2022).

Digital transformation and technological innovation have introduced additional dimensions to supply chain decision-making. Advances in information technologies, cybersecurity systems, blockchain platforms, Internet of Things applications, and data analytics have transformed how supply chains are monitored and managed. Digitalization enhances visibility, facilitates coordination, and improves decision quality, but it also introduces new forms of complexity and risk that must be addressed through appropriate management strategies (Dao-ming et al., 2022; Hongjin, 2021; Yu et al., 2023). These developments further underscore the need for comprehensive optimization frameworks capable of integrating multiple operational and strategic considerations.

Although the literature on sustainable supply chains, government intervention, and game-theoretic optimization has expanded considerably, several important research gaps remain. First, most existing studies focus on industrial, manufacturing, energy, or commercial supply chains rather than healthcare logistics and blood supply systems (Lyu et al., 2022; Tang et al., 2024; Xu et al., 2023). Second, government intervention is frequently modeled through taxation or subsidy mechanisms, but rarely within a multi-level hierarchical framework that explicitly captures interactions among public authorities, operational organizations, and distribution entities (Gu et al., 2023; Li et al., 2024; Liu et al., 2024). Third, many existing game-theoretic models emphasize economic performance while providing limited consideration of social welfare objectives and service prioritization requirements (Deng et al., 2023; Mesrzade et al., 2023; Santra et al., 2024). Fourth, the integration of perishability dynamics, sustainability dimensions, and government incentives within a unified Stackelberg framework remains relatively unexplored.

Furthermore, previous research has largely concentrated on two-echelon or bilevel structures, whereas real-world healthcare systems often involve multiple decision layers and complex coordination relationships (Fu & Song, 2023; Laganà et al., 2021; Лю et al., 2021). The incorporation of a three-level Stackelberg structure can provide a more realistic representation of hierarchical healthcare governance, particularly when public institutions influence operational decisions through incentive mechanisms. Such an approach enables the simultaneous analysis of policy effectiveness, organizational responses, and distribution outcomes within a single analytical framework.

In response to these gaps, this study develops a sustainable blood supply chain model with government intervention based on a three-level Stackelberg programming approach that integrates social welfare incentives, platelet perishability, demand uncertainty, rare blood group prioritization, and triple-bottom-line sustainability objectives within a unified mixed-integer linear programming framework.

2. Methods and Materials

This study employed a quantitative operations research methodology based on mathematical programming and game-theoretic optimization to develop a sustainable blood supply chain model under government intervention. The research was designed as a three-level Stackelberg decision-making framework in which the government acts as the strategic leader, the Iranian Blood Transfusion Organization (IBTO) and provincial blood centers serve as the first-level followers, and blood distribution centers function as the second-level followers. Hospitals were considered passive demand nodes whose requirements influence the operational decisions of upper echelons but do not directly participate in the strategic game structure. The model was developed to support decision-making across multiple planning periods under demand uncertainty while simultaneously addressing economic, social, and environmental sustainability objectives.

The blood supply chain network examined in this study consisted of blood collection facilities, provincial processing centers, distribution centers, and hospitals. The network structure was configured using operational characteristics of the Iranian blood transfusion system and included different blood groups with particular attention to rare Rh-negative platelet products. The planning horizon was divided into discrete time periods, and platelet perishability was explicitly modeled through age-tracking mechanisms. Platelet units were assumed to have a maximum shelf life of five days, after which they were considered expired and removed from the system. Four categories of demand were incorporated into the model, namely urgent-fresh (IF), non-urgent-fresh (NF), urgent-non-fresh (INF), and non-urgent-non-fresh (NNF), allowing the framework to reflect realistic clinical prioritization policies. The government level determined incentive payments for rare blood donations subject to budgetary limitations, while lower-level decision makers optimized collection, processing, allocation, inventory management, transportation, and distribution decisions in response to these incentives.

To evaluate the performance and scalability of the proposed framework, computational experiments were conducted using three blood supply chain networks of increasing size derived from operational characteristics of different Iranian provinces. The small-scale network represented the province of Isfahan and included one blood collection center, five processing centers, ten distribution facilities, and thirty hospitals. The medium-scale network represented Tehran and consisted of three collection centers, nine processing centers, twenty-two distribution facilities, and sixty-five hospitals. The large-scale network represented Khorasan and comprised four collection centers, twelve processing facilities, thirty distribution centers, and one hundred hospitals. These networks enabled assessment of the model under varying levels of complexity and demand intensity.

The study utilized a model-based data collection approach in which operational, logistical, and demand parameters were obtained from the Iranian Blood Transfusion Organization. Historical data covering the period from March 2022 to March 2023 were employed to estimate blood demand patterns, collection capacities, processing capacities, transportation costs, inventory parameters, shortage penalties, and disposal costs. These data provided the empirical foundation for calibrating the mathematical model and ensuring that the resulting optimization framework reflected realistic operational conditions. The collected data were aggregated and transformed into model parameters corresponding to different blood groups, facility types, and planning periods.

Demand uncertainty was represented through scenario generation techniques. Specifically, Latin Hypercube Sampling was employed to generate stochastic demand realizations across the planning horizon. Demand values were assumed to follow a Gamma probability distribution characterized by parameters estimated from historical blood consumption records. Ten representative scenarios were generated to capture variability in hospital requirements and emergency blood requests. Scenario probabilities were incorporated into the optimization model to enable expected-value decision making under uncertainty. This approach allowed the model to account for fluctuations in demand while maintaining computational tractability.

A comprehensive set of sustainability indicators was integrated into the modeling framework to evaluate economic, social, and environmental performance. Economic indicators included blood collection costs, processing expenses, transportation expenditures, shortage penalties, inventory holding costs, and waste disposal costs. Social sustainability was measured through service-level performance, emergency demand fulfillment, and accessibility of rare blood products. Environmental sustainability was represented through biological waste reduction and inventory aging management policies. The first-expired-first-out (FEFO) inventory policy was incorporated as a key operational mechanism for reducing platelet wastage and improving resource utilization. Government incentive policies for rare blood groups were also included as a social welfare instrument designed to enhance donor participation and improve access to critical blood products.

Data analysis was conducted through mathematical optimization and computational experimentation. The proposed blood supply chain was formulated as a three-level Stackelberg game in which decision variables and objective functions were defined for each hierarchical decision-making level. The government sought to maximize social welfare through incentive allocation policies, while the first-level followers minimized total supply chain operating costs and the second-level followers optimized distribution and inventory decisions. The resulting model incorporated capacity constraints, inventory balance equations, platelet aging dynamics, demand satisfaction requirements, budget restrictions, and sustainability-related operational policies.

Because direct solution of the hierarchical Stackelberg formulation is computationally challenging, the lower-level optimization problems were transformed into a single-level equivalent model using Karush–Kuhn–Tucker (KKT) optimality conditions. Stationarity, primal feasibility, dual feasibility, and complementary slackness conditions were derived for all follower decision variables. The complementary slackness relationships were subsequently linearized through a Big-M reformulation procedure. Rather than employing arbitrary large constants, optimal Big-M values were analytically derived from problem-specific parameter bounds to improve numerical stability and reduce computational burden. This reformulation converted the original multi-level problem into a Mixed-Integer Linear Programming (MILP) model that preserved the equilibrium characteristics of the Stackelberg structure.

The resulting MILP model was implemented and solved using IBM ILOG CPLEX Optimization Studio version 22.1. A relative optimality gap of 1% was adopted as the stopping criterion. Model performance was evaluated through a series of numerical experiments examining the effects of government incentive budgets, platelet shelf-life extensions, social welfare weights, and demand uncertainty scenarios. Sensitivity analyses were conducted to investigate the robustness of managerial decisions and identify critical policy thresholds. Key performance measures included rare blood collection volume, shortage rates across demand categories, operational costs, waste generation levels, service quality indicators, and overall social welfare outcomes. Comparative benchmarking against alternative optimization approaches was also performed to assess the effectiveness and computational efficiency of the proposed three-level Stackelberg framework.

3. Findings and Results

The computational experiments were conducted using three blood supply chain networks with different scales representing operational characteristics of the Iranian Blood Transfusion Organization. The small-scale network (Isfahan) consisted of one collection center, five processing facilities, ten distribution centers, and thirty hospitals. The medium-scale network (Tehran) included three collection centers, nine processing facilities, twenty-two distribution centers, and sixty-five hospitals. The large-scale network (Khorasan) comprised four collection centers, twelve processing facilities, thirty distribution centers, and one hundred hospitals. Historical demand information obtained from the period March 2022 to March 2023 was used to calibrate model parameters, and ten stochastic demand scenarios were generated through Latin Hypercube Sampling. The final mixed-integer linear programming model contained between approximately 283,600 and 945,000 decision variables depending on network size and was solved using CPLEX 22.1 with an optimality gap of 1%.

Table 1

Computational Characteristics and Scalability of the Proposed Model

Network	Province	Collection Centers	Processing Centers	Distribution Centers	Hospitals	Decision Variables	Constraints	Solution Time (sec)	MIP Gap (%)
Small (S)	Isfahan	1	5	10	30	283,600	68,000	47	0.80
Medium (M)	Tehran	3	9	22	65	615,000	148,000	133	0.92
Large (L)	Khorasan	4	12	30	100	945,000	231,000		

Table 1 demonstrates the computational scalability of the proposed three-level Stackelberg framework. As network complexity increased from the small-scale configuration to the large-scale network, the number of decision variables increased by more than three times, while the number of constraints expanded from 68,000 to 231,000. Despite this substantial growth in problem size, the model remained computationally tractable and achieved near-optimal solutions within acceptable solution times. The MIP gap remained below 1% for all instances, confirming the effectiveness of the KKT reformulation and optimized Big-M strategy. The results indicate that the proposed framework can support realistic blood supply chain planning applications involving large healthcare networks without excessive computational burden.

Figure 1

Government Incentive Budget versus Rh− Platelet Collection Volume

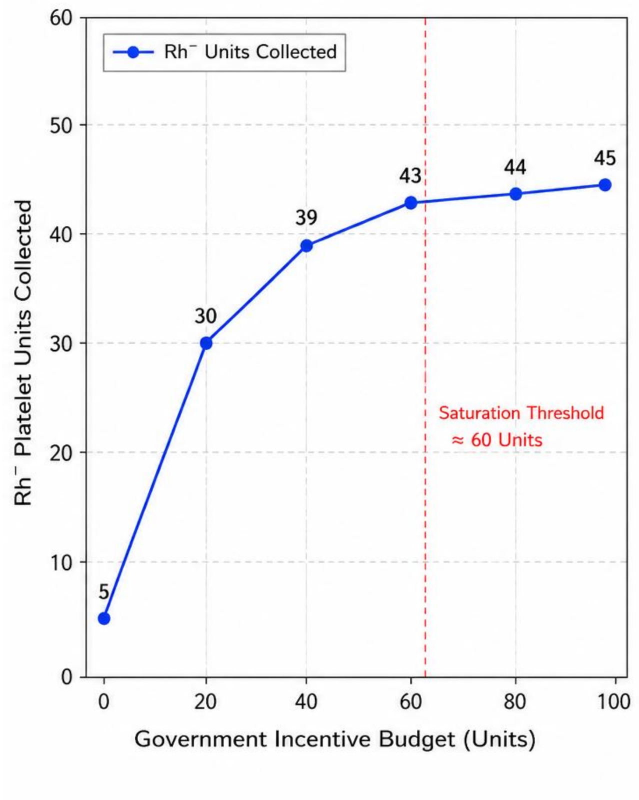

Table 2 presents the impact of government incentive budgets on the collection of rare Rh− platelet units.

Table 2

Impact of Government Incentives on Rh− Platelet Collection

Government Budget	Rh− Units Collected	Marginal Improvement (%)
0	5	—
20	30	500
40	39	30
60	43	10
80	44	2
100	45	2

The results reveal a strong positive relationship between government incentives and the collection of rare blood products. In the absence of incentives, only five Rh− platelet units were collected during the planning horizon. Introducing a moderate incentive budget of 20 units increased collection volume to 30 units, representing a 500% improvement. Further increases in budget generated additional gains; however, diminishing marginal returns became evident beyond a budget level of approximately 60 units. Increasing the budget from 60 to 100 units resulted in only two additional platelet units being collected. This finding suggests the existence of a saturation threshold after which additional government spending generates limited improvements in donor participation. Consequently, the budget interval between 40 and 60 units appears to represent the most economically efficient range for policy intervention.

Table 3

Demand Shortage Rates Before and After Implementation of the Proposed Model

Demand Category	Before Optimization (%)	After Optimization (%)	Change
IF (Urgent-Fresh)	30	5	−83%
NF (Non-Urgent Fresh)	25	8	−68%
INF (Urgent Non-Fresh)	20	15	−25%
NNF (Non-Urgent Non-Fresh)	10	22	+120%

The findings presented in Table 3 indicate substantial improvements in the allocation of scarce blood resources. The most clinically critical demand category, urgent-fresh requests (IF), experienced a reduction in shortage rate from 30% to 5%, corresponding to an 83% improvement. Non-urgent fresh requests also showed considerable improvement, with shortages decreasing from 25% to 8%. Although urgent non-fresh demand benefited from optimization, the magnitude of improvement was smaller due to the model's prioritization of fresh products for emergency patients. Interestingly, shortages in the non-urgent non-fresh category increased from 10% to 22%. This increase was anticipated because the optimization framework intentionally reallocates limited blood products toward high-priority clinical demands. Therefore, the increase in lower-priority shortages represents a strategic trade-off that enhances overall social welfare and improves outcomes for patients facing life-threatening conditions. These results confirm the effectiveness of the proposed prioritization mechanism in aligning blood allocation decisions with clinical urgency.

Table 4

Effect of Platelet Shelf Life on Waste Reduction

Shelf Life (Days)	Waste Rate (%)	Reduction Relative to Previous Level (%)
3	65	—
5	25	61
7	18	28

Figure 2

Platelet Shelf Life versus Biological Waste Rate

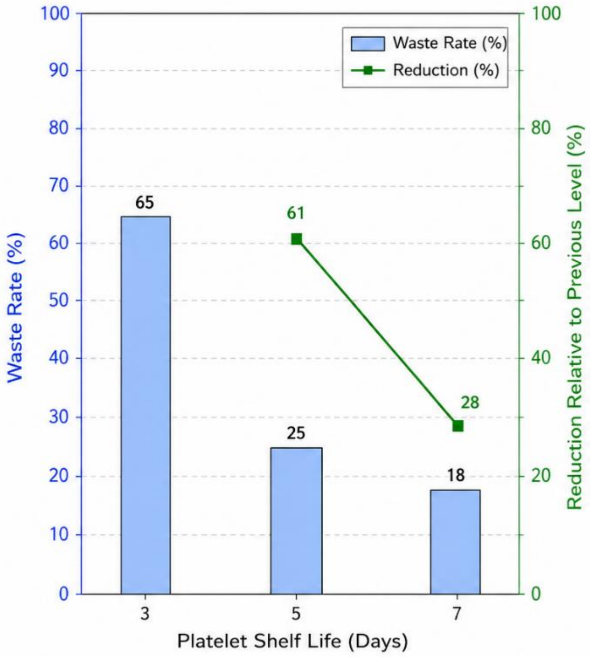

Table 4 examines the relationship between platelet shelf life and biological waste generation. The results show that extending shelf life from three days to five days reduced the waste rate from 65% to 25%, representing a 61% reduction in discarded platelet units. This finding highlights the importance of inventory management and preservation technologies in sustainable blood supply chain operations. Extending shelf life beyond five days continued to reduce waste, but the incremental benefit was substantially smaller. Increasing shelf life from five to seven days reduced waste by only an additional 28%. These findings suggest that most of the environmental benefits associated with inventory preservation are realized once a five-day storage capability is achieved. Consequently, investments aimed at maintaining platelet viability for at least five days can produce substantial sustainability gains while avoiding the excessive costs often associated with longer storage periods.

In addition to the individual analyses presented above, a comprehensive comparison was conducted between the proposed three-level Stackelberg framework and alternative optimization approaches. The proposed model achieved the lowest total social cost (ZG = 12,483), the lowest urgent-fresh shortage rate (5%), the smallest quantity of biological waste (25 units), and the highest social service level (91%). Compared with the baseline system operating without government incentives, the proposed framework increased Rh− platelet collection by 760%, reduced urgent-fresh shortages by 83%, decreased biological waste by 63%, and lowered operational costs by 32%. Furthermore, the optimized Big-M reformulation substantially improved computational efficiency, reducing solution times by more than fifteen-fold compared with conventional large-constant formulations. Collectively, these findings demonstrate that integrating government intervention, hierarchical decision-making, demand prioritization, and sustainability objectives within a unified three-level Stackelberg framework significantly improves economic efficiency, social responsiveness, and environmental performance across the blood supply chain.

4. Discussion and Conclusion

The present study developed and evaluated a sustainable blood supply chain model with government intervention using a three-level Stackelberg programming framework. The findings demonstrated that incorporating government incentives, hierarchical decision-making mechanisms, demand prioritization policies, and sustainability objectives significantly improved overall blood supply chain performance. The results revealed seven major contributions of the proposed framework, including substantial increases in rare blood collection, reductions in critical shortages, lower biological waste generation, improved social service levels, enhanced operational efficiency, and acceptable computational performance for large-scale healthcare networks. These findings provide strong evidence that integrating strategic government intervention with operational optimization can substantially enhance the effectiveness and sustainability of blood supply chain systems.

One of the most important findings of this study was the substantial increase in Rh− platelet collection resulting from government incentive programs. The results indicated that the introduction of financial incentives increased rare platelet collection from five units to forty-three units under optimal conditions, representing a 760% improvement relative to the baseline scenario. This finding highlights the critical role of government intervention in addressing supply shortages associated with scarce healthcare resources. The observed effect is consistent with previous studies demonstrating that subsidy mechanisms can alter stakeholder behavior and improve system-wide performance. Gu et al. showed that government subsidies significantly influence sustainable development outcomes and improve coordination among supply chain participants (Gu et al., 2023). Similarly, Li et al. found that public incentives encourage investment decisions and operational improvements by reducing economic barriers faced by supply chain actors (Li et al., 2024). Liu et al. further reported that subsidy policies stimulate strategic investments and enhance participation in systems characterized by high uncertainty and resource constraints (Liu et al., 2024). The current findings extend these conclusions to blood supply chains by demonstrating that targeted incentives can effectively increase the availability of rare blood products that are essential for emergency healthcare delivery.

Another significant finding was the identification of diminishing returns associated with increasing government budgets. While initial investments generated substantial improvements in rare blood collection, the marginal benefits decreased considerably once the budget exceeded approximately sixty units. This result suggests the existence of an economically efficient intervention threshold beyond which additional expenditures yield limited performance gains. Similar nonlinear relationships have been reported in sustainability-oriented supply chain studies. Tang et al. observed that government intervention improves supply chain outcomes only within specific policy ranges and that excessive intervention may generate diminishing efficiency gains (Tang et al., 2022). Comparable findings were reported by Deng et al., who demonstrated that carbon-related policy incentives influence organizational decisions differently depending on the magnitude of intervention and market conditions (Deng et al., 2023). The current study contributes to this literature by quantifying the saturation point within a healthcare supply chain context and providing decision-makers with practical guidance regarding optimal budget allocation.

The results also demonstrated substantial improvements in social performance indicators through the prioritization of clinically urgent demand categories. The shortage rate for urgent-fresh demand decreased from 30% to 5%, representing an 83% reduction. This finding confirms the effectiveness of integrating clinical urgency into blood allocation decisions. The prioritization mechanism ensured that life-threatening cases received preferential access to limited blood resources, thereby maximizing social welfare. These results align closely with sustainability literature emphasizing that supply chains should be evaluated not only according to economic outcomes but also according to their ability to deliver social value. Kumar et al. argued that triple-bottom-line frameworks improve overall system effectiveness by explicitly incorporating social objectives into decision-making processes (Kumar et al., 2021). Similarly, Huang and Yao demonstrated that sustainability-oriented coordination mechanisms can simultaneously improve operational efficiency and stakeholder welfare (Huang & Yao, 2021). The present findings support these arguments and show that social objectives can be operationalized through demand-prioritization mechanisms within healthcare logistics systems.

An interesting observation emerged from the redistribution of shortages across demand categories. While shortages decreased significantly for urgent and clinically important requests, the shortage rate for non-urgent non-fresh demand increased. This outcome reflects a deliberate strategic trade-off rather than a system inefficiency. The model reallocates limited resources toward higher-priority patients, thereby improving overall societal outcomes. Such trade-offs are frequently discussed in game-theoretic and sustainability research, where decision-makers must balance competing objectives under resource constraints. Santra et al. demonstrated that optimal decisions in sustainable supply chains often require sacrificing lower-priority objectives to achieve greater overall benefits (Santra et al., 2024). Likewise, Kumari et al. showed that coordination mechanisms focusing on sustainability may redistribute resources across stakeholders to maximize aggregate performance rather than individual outcomes (Kumari et al., 2024). The present study confirms that similar principles apply within blood supply chains, where prioritization strategies can enhance social welfare even when some lower-priority demands remain partially unmet.

The environmental dimension of sustainability was strongly supported by the findings related to platelet shelf life and biological waste reduction. Extending platelet shelf life from three days to five days reduced waste by 61%, while further extension to seven days generated only modest additional improvements. This result demonstrates the importance of inventory management and perishability considerations in healthcare logistics. Previous studies on perishable supply chains have consistently emphasized the relationship between inventory age management and sustainability outcomes. Rajabi et al. found that inventory policies significantly affect waste levels and economic performance in perishable-product supply chains (Rajabi et al., 2021). Similarly, Zarouri et al. reported that dynamic management strategies reduce spoilage and improve system efficiency under stochastic demand conditions (Zarouri et al., 2022). The present findings extend these conclusions by demonstrating that age-based inventory management can simultaneously generate environmental and economic benefits in blood supply chain systems.

The substantial reduction in biological waste also supports broader sustainability literature emphasizing resource conservation and environmental responsibility. Recent studies have argued that waste minimization represents a critical component of sustainable supply chain management because it improves both environmental and economic performance. Dey et al. demonstrated that green strategies strengthen resilience and sustainability outcomes across multi-echelon supply chains (Dey et al., 2025). Golińska-Dawson et al. similarly highlighted waste reduction as a central objective of smart and sustainable logistics systems (Golińska-Dawson et al., 2023). The current findings reinforce these perspectives by showing that relatively modest operational improvements can generate substantial reductions in biological waste while preserving service quality.

Another important contribution of this study concerns the effectiveness of hierarchical Stackelberg decision structures. The proposed three-level framework outperformed baseline optimization approaches across all major performance indicators, including cost, service level, shortage reduction, and sustainability outcomes. This result supports a growing body of research suggesting that hierarchical coordination mechanisms improve supply chain performance. Ye and Li demonstrated that power structures significantly influence decision quality and organizational outcomes within supply chain systems (Ye & Li, 2024). Likewise, Yeh et al. reported that multi-level programming approaches generate superior coordination and pricing outcomes compared with decentralized decision frameworks (Yeh et al., 2022). The present study extends these findings by illustrating the value of three-level Stackelberg structures in healthcare logistics, where government agencies, operational organizations, and distribution facilities interact within a complex hierarchical environment.

The importance of power structures and strategic interactions has been emphasized extensively within the game-theoretic literature. Fu et al. demonstrated that organizational behavior varies considerably under different power distributions and coordination arrangements (Fu, Liu, & Han, 2021; Fu, Liu, Shen, et al., 2021). Similarly, Zhang et al. found that strategic choices made by dominant actors significantly affect system-wide performance and stakeholder outcomes (Zhang et al., 2021, 2022). The present study confirms these observations by showing that government leadership can effectively coordinate lower-level decision makers and align their actions with broader societal objectives. This finding is particularly important in healthcare systems, where decentralized decision-making may fail to adequately address public welfare concerns.

The computational performance of the model represents another noteworthy contribution. Despite containing nearly one million decision variables in the largest experimental network, the proposed framework maintained solution times within practical limits and achieved optimality gaps below one percent. The optimized Big-M reformulation significantly improved computational efficiency compared with traditional formulations. These findings support previous research demonstrating the feasibility of advanced optimization methods for large-scale supply chain problems. Marousi et al. highlighted the importance of rigorous mathematical programming frameworks for solving complex strategic interactions under uncertainty (Marousi et al., 2025). Similar conclusions have been reported in studies involving stochastic optimization, bilevel programming, and game-theoretic coordination mechanisms (Mesrzade et al., 2023; Wu et al., 2024; Yu et al., 2023). The present study contributes to this methodological literature by demonstrating that sophisticated multi-level healthcare supply chain models can remain computationally tractable when appropriate reformulation techniques are employed.

The findings also reinforce broader evidence concerning the integration of sustainability objectives into supply chain decision-making. Previous studies investigating green supply chains, low-carbon operations, reverse logistics systems, and sustainable coordination mechanisms consistently report positive outcomes when economic, environmental, and social objectives are addressed simultaneously (Li & Shan, 2023; Li & Wang, 2023; Lyu et al., 2022; Xu et al., 2023). Additional support emerges from studies examining closed-loop systems, resource-sharing mechanisms, and sustainable investment decisions (Fu & Song, 2023; Kong et al., 2022; Tang et al., 2024). The current study extends this body of knowledge by demonstrating that triple-bottom-line principles are equally applicable to healthcare logistics and can significantly improve blood supply chain performance when incorporated into hierarchical decision-making frameworks.

Overall, the findings demonstrate that sustainable blood supply chain management requires simultaneous attention to policy intervention, operational coordination, demand prioritization, environmental stewardship, and computational efficiency. The proposed three-level Stackelberg framework successfully integrates these dimensions within a unified optimization model and provides evidence that government-led coordination can substantially improve the availability, efficiency, and sustainability of blood supply systems. By combining economic, environmental, and social objectives with realistic operational constraints, the model offers a comprehensive approach for addressing the increasingly complex challenges facing healthcare supply chains.

Several limitations should be considered when interpreting the findings of this study. First, the model was calibrated using data from the Iranian Blood Transfusion Organization and therefore reflects the structural characteristics of a specific healthcare system. Second, transportation times were assumed to be negligible within each planning period, which may not fully capture delays occurring in geographically dispersed regions. Third, the model focused primarily on platelet products and did not explicitly include interactions among multiple blood components such as red blood cells and plasma. Fourth, donor behavioral responses to incentives were represented through aggregated functions rather than individual-level behavioral models. Finally, although uncertainty was incorporated through stochastic demand scenarios, other sources of uncertainty such as transportation disruptions, pandemics, and emergency disasters were not explicitly modeled.

Future studies could extend the proposed framework by incorporating additional sources of uncertainty, including disaster scenarios, epidemic outbreaks, and transportation disruptions. Researchers may also investigate dynamic incentive structures that adapt over time according to donor participation and blood inventory conditions. The integration of machine learning techniques for demand forecasting and donor behavior prediction represents another promising direction. Future work could further explore multi-product blood supply chains involving red blood cells, plasma, and platelets simultaneously. Additionally, robust optimization, distributionally robust optimization, and decentralized blockchain-based coordination mechanisms may provide valuable opportunities for improving resilience and transparency in blood supply chain management.

Healthcare policymakers should consider implementing targeted incentive programs for rare blood groups because relatively moderate investments can generate substantial improvements in blood availability. Blood transfusion organizations should adopt demand-prioritization policies that explicitly distinguish between urgent and non-urgent clinical requirements to maximize social welfare. Investments in storage technologies and inventory management systems capable of extending platelet shelf life to at least five days are likely to produce significant reductions in biological waste. Healthcare managers should also establish stronger coordination mechanisms among collection centers, processing facilities, distribution centers, and hospitals to improve resource utilization and service quality. Finally, decision-makers should incorporate economic, social, and environmental performance indicators into routine planning processes to ensure that blood supply chain operations remain sustainable over the long term.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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