Annals of Healthcare Systems Engineering

www.ahse.reapress.com

Ann. Healthc. Syst. Eng. Vol. 3, No. 3 (2026) 171–189.

Paper Type: Original Article

Sustainable Pharmaceutical Supply Chain Network Design Considering Reverse Logistics and Third-Party Logistics (3PL) Provider Selection

Abbas Foroozanfar[1], Mohammad Reza Akbari Jokar[1,*]

[1] Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran; forouzanfar.abbas@ie.sharif.edu; reza.akbari@sharif.edu.

Citation:

Received: 13 August 2025 *Revised: 10 November 2025* *Accepted: 20 February 2026*	Foroozanfar, A., & Akbari Jokar, M. R. (2026). Sustainable pharmaceutical supply chain network design considering reverse logistics and third-party logistics (3PL) provider selection. *Annals of Healthcare Systems Engineering*, *3*(3), 171-189.

Abstract

Designing sustainable Pharmaceutical Supply Chain (PSC) networks, while accounting for reverse flows and operational realities, represents an emerging challenge in healthcare supply chain management. This research develops a multi-objective mathematical model that simultaneously addresses facility location, Third-Party Logistics (3PL) provider selection, integration of distribution centers (for both forward and reverse logistics), and pharmaceutical return policies (donation vs. resale). The innovation of this model lies in the dynamic selection between in-house facilities and 3PL warehouses, the integration of return policies, and the strategic decision-making regarding the multi-purpose functionality of distribution centers. The model is solved using the epsilon-constraint method, revealing a Pareto front among the objectives of profitability, environmental sustainability, and job creation. Specifically, total profit ranges from 750 to 950 monetary units, CO_2 emissions vary between 130 and 310 units, and job creation fluctuates between 100 and 120 positions. Scenario analysis demonstrates that implementing a hybrid return policy leads to a 17% reduction in pharmaceutical waste and a 5% increase in profit compared to a donation-only approach. Furthermore, the utilization of 3PL warehouses in 60% of cases has successfully reduced capital expenditure for warehouse construction while increasing the rate of multi-purpose distribution center utilization by up to 50%.

Keywords: Third-party logistics providers, Pharmaceutical supply chain, Sustainability, Multi-purpose facilities, Multi-objective optimization, Pharmaceutical reverse logistics.

1 | Introduction

The optimal design of Pharmaceutical Supply Chain (PSC) networks, particularly in developing economies, has evolved into one of the most complex, multi-faceted imperatives in the contemporary landscape of industrial engineering and supply chain management [1]. The PSC is critically important because of its direct

Corresponding Author: reza.akbari@sharif.edu
https://doi.org/10.22105/ahse.v3i3.68

impact on human health and overall societal well-being [2]. PSCs possess unique characteristics—most notably the critical sensitivity of products, the necessity for stringent cold-chain maintenance, and the rigid regulatory compliance requirements for safety and efficacy. Consequently, these networks are no longer judged solely by their ability to ensure delivery precision and cost-efficiency; they are increasingly scrutinized for their performance against the triple bottom line of sustainability: Environmental footprint, social responsibility, and economic viability [3], [4].

The pressing global challenge of rising pharmaceutical waste, driven by expiration cycles and the ecological burden of improper drug disposal, has rendered the integration of closed-loop reverse logistics not merely an operational choice, but a strategic imperative. Despite this, a profound gap exists in the literature regarding the structural synchronization of forward and reverse channels. While recent advancements have seen Third-Party Logistics (3PL) providers play a pivotal role in augmenting the operational flexibility and scalability of PSCs [5], [6], their strategic incorporation remains largely disconnected from comprehensive network optimization models. Current methodologies often suffer from 'siloed' approaches, where either forward supply chain design ignores the structural implications of reverse flows, or 3PLs are treated as static outsourcing options rather than dynamic, decision-variable components of a holistic architecture.

To bridge this critical research gap, this study proposes a multi-objective mathematical optimization framework for a sustainable, closed-loop PSC. The model transcends traditional design by simultaneously integrating strategic and tactical decisions, including facility location, multi-echelon flow allocation, dynamic inventory management, and the sophisticated synchronization of transportation networks. A key innovation of this research is the endogenous treatment of 3PL capacity: Rather than treating 3PL usage as an exogenous parameter, our model treats it as a flexible decision variable, enabling a dynamic trade-off analysis between capital-intensive in-house infrastructure and agile outsourced services. Furthermore, we explore the operational complexities of reverse logistics by modeling various disposition pathways—specifically, secondary market resale, philanthropic donation, and environmentally sustainable disposal—to minimize the cumulative ecological and economic impact.

By constructing a framework that allows for the comparative evaluation of purely in-house, fully outsourced, and hybrid operational strategies, this research provides a robust platform for simulating real-world decision-making under conflicting goals. Consequently, this study is driven by three foundational Research Questions (RQs):

I. How can a mathematically rigorous, unified framework be constructed to operationalize the synergy between forward distribution and reverse collection channels within a sustainable closed-loop paradigm?

II. Through what formulation can the strategic integration of 3PL provider selection and the deployment of multi-purpose, hybrid facilities be optimized to enhance overall network resilience?

III. How can a Pareto-optimal equilibrium be achieved between disparate disposition strategies (such as secondary market resale and charitable donation) to satisfy the concurrent demands of profit maximization, environmental protection, and socio-economic contribution?"

2 | Literature Review

2.1 | Sustainable Network Design

In recent years, the design of sustainable closed-loop supply chain networks has emerged as a major stream of research in the advanced logistics and supply chain management literature. This growing interest is largely driven by increasing environmental concerns, regulatory pressures, resource scarcity, and the need to incorporate reverse flows into conventional supply chain structures. Within this body of research, several studies have attempted to address the integration of sustainability dimensions, uncertainty, and operational complexity across different industrial contexts, including pharmaceutical, steel, and automotive industries. Sazvar et al. [7] proposed a multi-objective programming model for the design of a PSC network under crisis conditions. Their network consisted of three facility levels, namely production plants, warehouses, and demand centers, and the model simultaneously considered economic, environmental, and social objectives. To capture the uncertainty associated with pharmaceutical demand, multiple scenarios were incorporated into the formulation. The proposed model was solved using the epsilon-constraint method, allowing the authors to generate trade-off solutions among the conflicting sustainability objectives.

Similarly, Savadkoohi et al. [8] developed a mathematical programming model for the design of a green and reliable closed-loop PSC network in which environmental sustainability, reverse flows, and uncertainty in demand, return rates, and facility capacity were simultaneously incorporated. To address uncertainty, they adopted an enhanced chance-constrained stochastic programming approach, which provides more effective control over the level of risk in comparison with the classical chance-constrained formulation. Their model included multiple types of facilities, such as collection, recycling, and remanufacturing centers, and captured both strategic location decisions and tactical product flow decisions within a unified framework. Pourjavad et al. [9] investigated closed-loop supply chain network design from a sustainable development perspective by proposing a fuzzy multi-objective mixed-integer linear programming model. Their study focused on minimizing total costs, reducing environmental impacts, and maximizing social benefits over a multi-period planning horizon. To cope with uncertainty in parameters such as return rates and facility capacities, a fuzzy approach was employed. The model was solved using a genetic algorithm, and the quality of the obtained solutions was further validated through comparison with the Non-dominated Ranked Genetic Algorithm (NRGA). The network structure in their study comprised four echelons in the forward logistics process and four echelons in the reverse logistics process, thereby reflecting a relatively comprehensive representation of closed-loop operations. Li et al. [10] examined an integrated location–inventory problem in a closed-loop supply chain that involved a hybrid production–recycling center, distribution–collection centers, and customers. In their stochastic-demand setting, the decisions related to facility location, customer allocation in both forward and reverse channels, and inventory levels were optimized simultaneously. The model explicitly incorporated various cost components, including facility opening costs, transportation costs, inventory holding costs, safety stock costs, return processing costs, and shortage penalties. To solve this complex problem, the authors designed a hybrid heuristic algorithm based on differential evolution and genetic algorithms. Easwaran and Üster [11] presented a mixed-integer programming model for the design of a multi-product closed-loop supply chain network in which forward and reverse flows were integrated under limited facility capacities. In their formulation, hybrid facilities for manufacturing/remanufacturing and distribution/collection were considered, and the model aimed to minimize the total costs of facility location, processing, and transportation. To enhance computational tractability, the authors employed a Benders decomposition approach augmented with strengthened cuts, which improved the efficiency of the solution procedure for large-scale instances. Beyond the pharmaceutical sector, Pourmehdi et al. [12] proposed a multi-objective mathematical model for designing a sustainable closed-loop supply chain network in the steel industry. Their formulation simultaneously addressed economic, environmental, and social dimensions, with environmental criteria including energy consumption, water usage, and CO2 emissions, while social performance was measured through job creation. Using scenario-based stochastic programming and preemptive fuzzy goal programming, the authors modeled uncertainty in market demand and scrap supply. They also investigated the effects of production technology shifts and the conversion of retail facilities into hybrid centers on the overall network configuration. Abbasi et al. [13] developed a mathematical model for the design of a green closed-loop supply chain network in the automotive industry during the COVID-19 pandemic. Their five-echelon structure included suppliers, plants, distribution/collection centers, recycling/disposal centers, and customers. By using a multi-objective integer programming model and the weighted-sum method, they simultaneously optimized conventional and health-related costs while minimizing CO2 emissions in a system characterized by both forward and reverse flows. This study highlights how crisis conditions and public health requirements can alter the priorities and design principles of sustainable supply chain systems.

In the context of pharmaceutical distribution, Jalal et al. [14] proposed an integrated location–transportation model for PSC network design. Their network consisted of production plants, distribution centers, and retailers. By combining multi-scale time planning and robust optimization, the model captured decisions related to facility location, product flows, transportation fleet composition, security requirements, and taxation policies under demand uncertainty. The proposed approach was tested on real-world data using a Fix-and-Optimize algorithm, demonstrating its practical applicability in complex and uncertain decision environments. Abbasi et al. [15] introduced a bi-objective optimization model for the design of reliable supply chain networks in the context of 3PL companies. Their four-level network included suppliers, consolidation hubs, distribution centers, and customers. Considering the perishability of pharmaceutical products and the possibility of disruptions at hubs and distribution centers, the model incorporated resilience strategies such as backup facility deployment, facility fortification, and multiple sourcing. To handle uncertainty related to disruption probabilities, a credibility-based fuzzy programming approach was employed. A noteworthy aspect of this work is the explicit modeling of the direct relationship between facility failures and product deterioration, which adds significant realism to the reliability analysis. Zandkarimkhani et al. [16] developed a bi-objective mixed-integer programming model for the design of a multi-product, multi-period PSC network for perishable drugs. Under demand uncertainty, they simultaneously modeled location, inventory, and routing decisions in a three-echelon network composed of suppliers, distribution centers, and customers. To solve the problem, they proposed a hybrid approach combining fuzzy goal programming and probabilistic constraints. The effectiveness of the model was evaluated using real data from the Avonex pharmaceutical distribution chain in Tehran, thereby providing empirical support for the applicability of the proposed framework. Likewise, Zandieh et al. [17] designed a multi-objective model for a pharmaceutical distribution network based on the three pillars of sustainability: economic, environmental, and social performance. Their model was intended to support managers in making both strategic and technical decisions concerning the pharmaceutical distribution system, particularly with respect to the configuration of central and local distribution centers and the associated product flows. By minimizing costs, maximizing social welfare, and reducing adverse environmental effects, the model aimed to guide decision-makers toward more sustainable network configurations.

Overall, the existing literature demonstrates substantial progress in the development of sustainable and closed-loop supply chain network models. Researchers have increasingly incorporated uncertainty, reverse logistics, resilience, and multi-objective optimization into their formulations. However, despite these valuable contributions, several important research gaps remain. First, while some studies have considered reverse flows in PSCs, the integration of return disposition policies—such as resale, donation, and disposal—into the structural design of the network has received limited attention. Second, although 3PL providers have been recognized as important actors in improving flexibility and responsiveness, their role is often treated either as an external operational option or merely as an evaluation criterion, rather than as an endogenous decision variable within a network design model. Third, the concept of hybrid or multi-purpose facilities, capable of simultaneously supporting forward and reverse operations, has not been sufficiently explored in PSC settings in combination with sustainability and 3PL selection. These gaps indicate the need for a more integrated and realistic modeling framework capable of jointly addressing facility configuration, reverse logistics policy, sustainability objectives, and outsourcing decisions in pharmaceutical closed-loop supply chains.

2.2 | Rsearch Gap

Despite the significant growth in the literature regarding sustainable, Closed-Loop Supply Chain Network Design (CLSCND), a critical examination of existing methodologies reveals persistent limitations. Most contemporary models rely on static or pre-defined network configurations, or alternatively, treat 3PL providers as exogenous parameters—effectively decoupling them from the core network optimization logic. This research addresses this substantial structural gap by introducing a novel, integrated mathematical framework where the strategic utilization of 3PL services is internalized as an endogenous decision variable, inherently linked to the network's objective function and operational constraints.

The proposed model transcends conventional formulations by simultaneously optimizing facility location, flow allocation, inventory policies, and transportation routing. Crucially, it provides, for the first time, a dynamic mechanism for operational selection between two distinct logistical paradigms: Leveraging external 3PL-managed warehousing or deploying in-house, multi-purpose facilities equipped with transshipment capabilities. This flexibility allows the network to adapt to fluctuating demand and cost landscapes with unprecedented agility.

Furthermore, our model offers a sophisticated approach to reverse logistics. Rather than reducing the complexities of returned pharmaceuticals to simple recycling or disposal, we evaluate a multi-dimensional disposition strategy. The model incorporates a rigorous trade-off analysis between two conflicting policies: pharmaceutical donation, which generates positive social impact and potential tax advantages, versus secondary market resale, which serves as a vital revenue stream for economic optimization.

Finally, the architecture of our model treats the configuration of hybrid distribution/collection facilities as a primary decision variable. This ensures that the model systematically evaluates the cost-capacity trade-offs inherent in choosing between the capital-intensive construction of dedicated, single-purpose facilities versus the strategic, multi-purpose integration of existing infrastructure. By aligning economic profitability with social imperatives and environmental sustainability, this framework provides decision-makers with a robust, scientifically grounded tool for navigating the complexities of modern PSCs, thereby bridging the divide between theoretical optimization and real-world operational reality.

3 | Problem Definition

The pharmaceutical industry is characterized by a unique set of complexities in Supply Chain Network Design (SCND), stemming from the critical nature of medicinal products and the imperative to meet demand under stringent quality and regulatory conditions [18], [19]. A pivotal, yet often overlooked, operational reality within these networks is the management of pharmaceutical returns. Based on their physical integrity, these returns require a distinct disposition pathway: products with intact packaging can be reclaimed via secondary markets or charitable donations, while compromised items must be directed toward specialized disposal facilities.

This research proposes a multi-objective, closed-loop mathematical programming model for the design of a sustainable PSC. As illustrated in *Fig. 1*, the proposed network architecture comprises an integrated structure: raw material suppliers, production plants, distribution warehouses, multi-purpose distribution/collection centers, demand zones, secondary market channels, donation centers, and hazardous disposal facilities. In this framework, all transportation activities are exclusively outsourced to 3PL providers, reflecting modern trends toward asset-light operational models.

The model is formulated to perform a holistic and simultaneous optimization of critical strategic and tactical decisions, including: 1) 3PL service integration, 2) facility type selection (hybrid vs. dedicated), 3) location-allocation decisions, 4) dynamic inventory management, and 5) return disposition policies. By treating facility configuration as a decision variable rather than an exogenous parameter, the model empowers decision-makers to evaluate the trade-offs between dedicated, single-purpose infrastructure and multi-purpose (hybrid) facilities, contingent upon economic, social, and environmental performance indicators.

The multi-objective nature of the model is articulated through three foundational pillars:

I. Economic Sustainability: Maximizing total network profit, while incorporating budgetary constraints on raw material procurement and the availability of bank financing as a source of capital investment.

II. Social Responsibility: Maximizing job creation, quantified as a direct outcome of new facility establishment and operational expansion.

III. Environmental Stewardship: Minimizing the total CO_2 footprint attributed to transportation logistics across all echelons of the supply chain.

Several key assumptions define the model's operational environment: The geographical locations of suppliers, customers, and disposal/donation centers are treated as fixed throughout the planning horizon. To simplify computational complexity while maintaining validity, it is assumed that the shelf-life of pharmaceutical products exceeds the planning horizon, precluding expiration within the network. Furthermore, the disposition logic is strictly contingent on packaging integrity: Only unopened returns are eligible for re-entry into the market or donation cycles, whereas opened items are sequestered for disposal. Finally, to ensure operational continuity, demand shortages are modeled via backordering, allowing unmet demand to be deferred to subsequent periods.

Ultimately, this research bridges the gap between theoretical modeling and operational practice by providing a comprehensive framework where the supply chain structure is an endogenous result of optimization, rather than a rigid, pre-defined design.

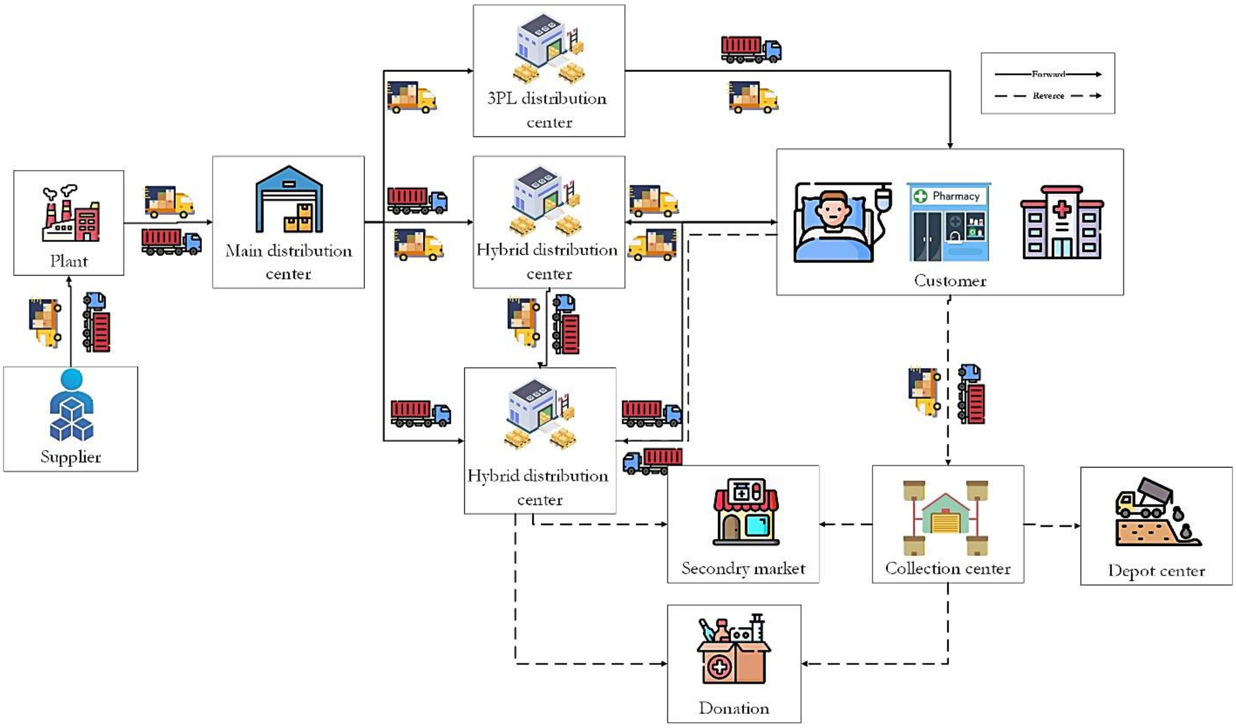

Fig. 1. Supply chain network structure.

3.1 | Mathematical Modeling

For modeling the defined network, the symbols are given in *Table 1*, and the model is written below.

Table 1 . Notations.

Indices	Definition
Sets	
I	Set of raw materials required for pharmaceutical production
P	Set of pharmaceutical product families
S	Set of raw material suppliers
H1	Set of available capacity levels for primary distribution centers
H2	Set of available capacity levels for hybrid distribution–collection centers
H3	Set of available capacity levels for collection centers
D	Set of candidate locations for establishing primary distribution centers
HDCC	Set of candidate locations for hybrid distribution–collection centers
CC	Set of candidate locations for collection centers
C	Set of customer zones
M	Set of candidate locations for manufacturing plants
MD	Set of pharmaceutical donation centers
K	Set of 3PL providers
War_k	Set of distribution warehouses owned by 3PL provider k
$Tech_p$	Set of available production technologies for product family p
h_k	Set of transportation modes or vehicles owned by 3PL provider k
DC	Set of pharmaceutical disposal centers
SM	Set of secondary markets for pharmaceutical products
T	Set of planning periods
Economic Parameters	
$P_{i,s,t}$	Unit purchasing cost of raw material i from supplier s in period t

$Tr_{z,\grave{z},\hat{z},k}^{h_k}$	Transportation cost of product type $\hat{z} \in \{i,p\}$ from node z to node z′ using vehicle type h_k operated by 3PL provider k
$Pr_{m,p}^{Tech_p}$	Unit production cost of pharmaceutical product p at plant m using technology $Tech_p$
$F_{m,p}^{Tech_p}$	Fixed cost of establishing plant m to produce product family p with technology $Tech_p$
F_z^H	Fixed establishment cost of facility z ∈ {D, HDCC, CC} with capacity level H
S_{zp}	Inventory holding cost of product p at facility z ∈ {D, HDCC, WAR_k}
B_t	Available budget for raw material procurement in period t
∂_t	Bank interest rate applied to financial loans in period t
ABC_t	Maximum bank credit available for raw material procurement in period t
$SMSP_{pt}$	Selling price of pharmaceutical product p in the secondary market during period t
HY_{hdcc}	Hybridization cost of a distribution center hdcc
HPL_k	Contracting cost for collaboration with 3PL provider k
$IC_{z,p}$	Inspection cost of product family p at facility z ∈ {CC, HDCC}
$DCC_{dc,p}$	Disposal cost of product p at disposal center dc
β	Tax rate applied to pharmaceutical product sales
$SHC_{c,p,t}$	Shortage penalty cost of product p for customer c in period t
SP_{pt}	Unit selling price of product p in period t
Environmental Parameters	
CE^{h_k}	CO_2 emission rate generated by transporting one unit of product per unit distance using vehicle type h_k of 3PL provider k
Operational Parameters	
$TPR_{i,p}$	Conversion coefficient of raw material i into pharmaceutical product p
cap_z^H	Capacity of facility z at capacity level H
$TPR_{i,s}$	Supply capacity of supplier s for raw material i
$cap_k^{h_k}$	Capacity of vehicle type h_k owned by 3PL provider k
$d_{c,p,t}$	Demand of customer c for product p in period t
$\alpha_{p,c}$	Return rate of product family p from customer c
$SS_{d,p}$	Safety stock level of product p at distribution center d
$SS_{hdcc,p}$	Safety stock level of product p at hybrid distribution center hdcc
γ_p	Proportion of returned pharmaceutical products p that remain usable for donation or secondary market resale
M	A sufficiently large positive constant (Big-M parameter)
Social Parameters	
FJ_z^H	Number of fixed jobs created when facility z is established with capacity level H
VJ_z^H	Number of variable jobs generated when facility z operates at capacity level H
UR_z	Unemployment rate in the region where facility z is located
Decision Variables	
$x_{mp}^{Tech_p}$	Binary variable equal to 1 if plant m is established to produce product p using technology $Tech_p$; 0 otherwise
y_z^H	Binary variable equal to 1 if facility z is established with capacity level H; 0 otherwise
y^{War_k}	Binary variable equal to 1 if the warehouse of 3PL provider k is utilized; 0 otherwise
z_{hdcc}	Binary variable equal to 1 if hybridization is applied to distribution center hdcc; 0 otherwise
y_s	Binary variable equal to 1 if supplier s is selected; 0 otherwise
y_k	Binary variable equal to 1 if 3PL provider k is used for transportation; 0 otherwise
$I_{z,p,t}$	Inventory level of usable product p at facility z in period t
$\hat{I}_{z,p,t}$	Inventory level of unusable returned product p at facility z in period t
$Q_{z,\grave{z},\hat{z},k,t}^{h_k}$	Quantity of product type $\hat{z}$ transported from node z to node z' by vehicle h_k of 3PL provider k in period t
BC_t	Bank credit received for raw material procurement in period t
$SH_{c,p,t}$	Unmet demand (backorder) of product p for customer c in period t

$$c1 = \sum_{m,p,Tech_p} F_{m,p}^{Tech_p} x_{mp}^{Tech_p} + \sum_{d,h1} F_d^{H1} y_d^{H1} + \sum_{hdcc,h2} F_{hdcc}^{H2} y_{hdcc}^{H2} + \sum_{cc,h3} F_{cc}^{H3} y_{cc}^{H3} + \sum_{k,War_k} F_k^{War_k} y^{War_k} + \sum_{hdcc} HY_{hdcc} z_{hdcc} + \sum_{k} HPL_k y_k + \sum_{s} F_s y_s + \sum_{d,p,t} S_{dp} I_{d,p,t} + \sum_{hdcc,p,t} S_{hdcc,p} I_{hdcc,p,t} + \sum_{k,War_k,p,t} S_{p,k}^{War_k} I_{k,War_k,p,t} + \sum_{cc,p,t} S_{ccp} I_{cc,p,t} \quad (1)$$

$$c2 = \sum_{t,p,k,h_k} \left(\sum_{cc,md} IC_{cc,p}\left(Q_{cc,md,p,k,t}^{h_k}\right) + \sum_{cc,sm} IC_{cc,p}\left(Q_{cc,sm,p,k,t}^{h_k}\right) + \sum_{hdcc,md} IC_{hdcc,p}\left(Q_{hdcc,md,p,k,t}^{h_k}\right) + \sum_{hdcc,sm} IC_{hdcc,p}\left(Q_{hdcc,sm,p,k,t}^{h_k}\right) + \sum_{dc,cc} DCC_{dc,p}\left(Q_{cc,dc,p,k,t}^{h_k}\right) + \sum_{dc,hdcc} DCC_{dc,p}\left(Q_{hdcc,dc,p,k,t}^{h_k}\right)\right) + \sum_{m,d,p,Tech_p,k,h_k,t} Pr_{m,p}^{Tech_p} Q_{m,d,p,k,t}^{Tech_p,h_k} + \sum_{c,p,t} SHC_{c,p,t} SH_{c,p,t} + \sum_{t} BC_t\, \partial_t \quad (2)$$

$$c3 = \sum_{t,k,h_k} \Big(\sum_{i,s,t,m} Tr_{s,m,i,k}^{h_k} Q_{s,m,i,k,t}^{h_k} + \sum_{m,d,p,Tech_p} Tr_{m,d,p,k}^{h_k} Q_{m,d,p,k,t}^{Tech_p,h_k} + \sum_{d,hdcc,p} Tr_{d,hdcc,p,k}^{h_k} Q_{d,hdcc,p,k,t}^{h_k} + \sum_{d,War_k,p} Tr_{d,War_k,p,k}^{h_k} Q_{d,War_k,p,k,t}^{h_k} + \sum_{hdcc,c,p} Tr_{hdcc,c,p,k}^{h_k} Q_{hdcc,c,p,k,t}^{h_k} + \sum_{War_k,c,p} Tr_{War_k,c,p,k}^{h_k} Q_{War_k,c,p,k,t}^{h_k} + \sum_{c,hdcc,p} Tr_{c,hdcc,p,k}^{h_k} Q_{c,hdcc,p,k,t}^{h_k} + \sum_{c,cc,p} Tr_{c,cc,p,k}^{h_k} Q_{c,cc,p,k,t}^{h_k} + \sum_{hdcc,p} Tr_{hdcc,hdcc,p,k}^{h_k} Q_{hdcc,hdcc,p,k,t}^{h_k} + \sum_{cc,md,p} Tr_{cc,md,p,k}^{h_k} Q_{cc,md,p,k,t}^{h_k} + \sum_{cc,sm,p} Tr_{cc,sm,p,k}^{h_k} Q_{cc,sm,p,k,t}^{h_k} + \sum_{hdcc,md,p} Tr_{hdcc,md,p,k}^{h_k} Q_{hdcc,md,p,k,t}^{h_k} + \sum_{hdcc,sm,p} Tr_{hdcc,sm,p,k}^{h_k} Q_{hdcc,sm,p,k,t}^{h_k} + \sum_{dc,cc} Tr_{cc,dc,p,k}^{h_k} Q_{cc,dc,p,k,t}^{h_k} + \sum_{dc,hdcc} Tr_{hdcc,dc,p,k}^{h_k} Q_{hdcc,dc,p,k,t}^{h_k} \Big) \quad (3)$$

$$Re = \sum_{p,k,h_k,t} \Big(ta_p \sum_{cc,md} Q_{cc,md,p,k,t}^{h_k} + \sum_{hdcc,md} Q_{hdcc,md,p,k,t}^{h_k} \Big) + (1-\beta) \sum_{hdcc,c,p,k,h_k,t} SP_{pt} Q_{hdcc,c,p,k,t}^{h_k} + \sum_{k,War_k,c,p,h_k,t} SP_{pt} Q_{War_k,c,p,k,t}^{h_k} + (1-\beta) \sum_{cc,sm,p,k,h_k,t} SMSP_{pt} Q_{cc,sm,p,k,t}^{h_k} + \sum_{hdcc,sm,p,k,h_k,t} SMSP_{pt} Q_{hdcc,sm,p,k,t}^{h_k} \quad (4)$$

$$\text{Max } Z_1 = Re - c1 - c2 - c3 \quad (5)$$

$$\text{Min } Z_2 = \sum_{t,k,h_k} \Big(\sum_{i,s,t,m} CE^{h_k} Q^{h_k}_{s,m,i,k,t} + \sum_{m,d,p,Tech_p} CE^{h_k} Q^{Tech_p,h_k}_{m,d,p,k,t} + \sum_{d,hdcc,p} CE^{h_k} Q^{h_k}_{d,hdcc,p,k,t} + \sum_{d,War_k,p} CE^{h_k} Q^{h_k}_{d,War_k,p,k,t} + \sum_{hdcc,c,p} CE^{h_k} Q^{h_k}_{hdcc,c,p,k,t} + \sum_{War_k,c,p} CE^{h_k} Q^{h_k}_{War_k,c,p,k,t} + \sum_{c,hdcc,p} CE^{h_k} Q^{h_k}_{c,hdcc,p,k,t} + \sum_{c,cc,p} CE^{h_k} Q^{h_k}_{c,cc,p,k,t} + \sum_{hdcc,p} CE^{h_k} Q^{h_k}_{hdcc,hdcc,p,k,t} + \sum_{cc,md,p} CE^{h_k} Q^{h_k}_{cc,md,p,k,t} + \sum_{cc,sm,p} CE^{h_k} Q^{h_k}_{cc,sm,p,k,t} + \sum_{hdcc,md,p} CE^{h_k} Q^{h_k}_{hdcc,md,p,k,t} + \sum_{hdcc,sm,p} CE^{h_k} Q^{h_k}_{hdcc,sm,p,k,t} + \sum_{hdcc,dc,p} CE^{h_k} Q^{h_k}_{hdcc,dc,p,k,t} + \sum_{cc,dc,p} CE^{h_k} Q^{h_k}_{cc,dc,p,k,t} \Big) \quad (6)$$

$$\text{Max } Z_3 = \sum_{m,p,Tech_p} UR_m x_{mp}^{Tech_p} (FJ_{m,p}^{Tech_p} + VJ_{m,p}^{Tech_p}) + \sum_{d,h1} UR_d y_d^{H1} (FJ_d^{H1} + VJ_d^{H1}) + \sum_{hdcc,h2} UR_{hdcc} y_{hdcc}^{H2} (FJ_{hdcc}^{H2} + VJ_{hdcc}^{H2}) + \sum_{cc,h3} UR_{cc} y_{cc}^{H3} (FJ_{cc}^{H3} + VJ_{cc}^{H3}) + \sum_{hdcc} UR_{hdcc} z_{hdcc} (HFJ_{hdcc} + HVJ_{hdcc}) \quad (7)$$

S.t.

$$Q^{h_k}_{s,m,i,k,t} \le M \sum_{p,Tech_p} x_{mp}^{Tech_p} \ , \forall s, m, i, k, h_k, t \quad (8)$$

$$Q^{Tech_p,h_k}_{m,d,p,k,t} \le M \textstyle\sum_{H1} y_d^{H1} \ , \forall m, d, k, p, Tech_p, h_k, t \quad (9)$$

$$Q^{h_k}_{d,hdcc,p,k,t} \le M \sum_{H2} y_{hdcc}^{H2} \ , \forall hdcc, d, k, p, h_k, t \quad (10)$$

$$Q^{h_k}_{d,War_k,p,k,t} \le M y^{War_k} \ , \forall hdcc, d, k, p, h_k, War_k, t \quad (11)$$

$$Q^{h_k}_{c,cc,p,k,t} \le M \sum_{H3} y_{cc}^{H3} \ , \forall c, cc, k, p, h_k, t \quad (12)$$

$$Q^{h_k}_{c,hdcc,p,k,t} \le M z_{hdcc} \ , \forall c, hdcc, k, p, h_k, t \quad (13)$$

$$Q^{h_k}_{hdcc,z,p,k,t} \le M z_{hdcc} \ , \forall z \in \{sm, md, dc\}, hdcc, k, p, h_k, t \quad (14)$$

$$\sum_{m,i,k,h_k,t} Q^{h_k}_{s,m,i,k,t} \le M y_s \ , \forall s \quad (15)$$

$$\sum_{Tech_p} x_{mp}^{Tech_p} = 1 \ , \forall m, p \quad (16)$$

$$\sum_{H1} y_d^{H1} \le 1 \ , \forall d \quad (17)$$

$$\sum_{H2} y_{hdcc}^{H2} \le 1 \ , \forall hdcc \quad (18)$$

$$\sum_{H3} y_{cc}^{H3} \le 1 \ , \forall cc \quad (19)$$

$$\sum_{d,k,h_k} Q^{Tech_p,h_k}_{m,d,p,k,t} \le cap_{m,p}^{Tech_p} x_{mp}^{Tech_p} \ , \forall m, p, Tech_p, t \quad (20)$$

$$\sum_{m,k,h_k,p,Tech_p} Q_{m,d,p,k,t}^{Tech_p,h_k} + \sum_{p} I_{d,p,t-1} \leq \sum_{H1} cap_d^{H1} y_d^{H1} \quad ,\forall d,t \tag{21}$$

$$\sum_{d,k,h_k,p} Q_{d,hdcc,p,k,t}^{h_k} + \sum_{c,k,h_k,p} Q_{c,hdcc,p,k,t}^{h_k} + \sum_{h\grave{d}cc,k,h_k,p} Q_{h\grave{d}cc,hdcc,p,k,t}^{h_k} + \sum_{p} I_{hdcc,p,t-1} + \sum_{p} \hat{I}_{hdcc,p,t-1} \leq \sum_{H2} cap_{hdcc}^{H2} y_{hdcc}^{H2} \quad ,\forall hdcc,t \tag{22}$$

$$\sum_{d,h_k,p} Q_{d,War_k,p,k,t}^{h_k} + \sum_{p} I_{War_k,p,t-1} \leq cap^{War_k} y^{War_k} \quad ,\forall k,t \tag{23}$$

$$\sum_{c,k,h_k,p} Q_{c,cc,p,k,t}^{h_k} + \sum_{p} I_{cc,p,t-1} \leq \sum_{H3} cap_{cc}^{H3} y_{cc}^{H3} \quad ,\forall cc,t \tag{24}$$

$$\sum_{m,k,h_k} Q_{s,m,i,k,t}^{h_k} \leq TPR_{i,s} \quad ,\forall s,i,t \tag{25}$$

$$I_{d,p,t} = I_{d,p,t-1} + \sum_{k,h_k}\Big(\sum_{m,Tech_p} Q_{m,d,p,k,t}^{Tech_p,h_k} - \sum_{hdcc} Q_{d,hdcc,p,k,t}^{h_k} - \sum_{War_k} Q_{d,War_k,p,k,t}^{h_k}\Big) \quad ,\forall d,p,t \tag{26}$$

$$\begin{aligned} I_{hdcc,p,t} = I_{hdcc,p,t-1} &+ \sum_{k,h_k}\Big(\sum_{d} Q_{d,hdcc,p,k,t}^{h_k} + \sum_{h\grave{d}cc} Q_{h\grave{d}cc,hdcc,p,k,t}^{h_k} + \sum_{c} \gamma_p Q_{c,hdcc,p,k,t}^{h_k} \\ &- \sum_{h\grave{d}cc} Q_{hdcc,h\grave{d}cc,p,k,t}^{h_k} - \sum_{c} Q_{hdcc,c,p,k,t}^{h_k} - \sum_{md} Q_{hdcc,md,p,k,t}^{h_k} \\ &- \sum_{sm} Q_{hdcc,sm,p,k,t}^{h_k}\Big) \quad ,\forall hdcc,p,t \end{aligned} \tag{27}$$

$$\hat{I}_{hdcc,p,t} = \hat{I}_{hdcc,p,t-1} + \sum_{c,k,h_k} (1-\gamma_p) Q_{c,hdcc,p,k,t}^{h_k} - \sum_{dc} Q_{hdcc,dc,p,k,t}^{h_k} \quad ,\forall hdcc,p,t \tag{28}$$

$$I_{cc,p,t} = I_{cc,p,t-1} + \sum_{k,h_k}\Big(\sum_{c} \gamma_p Q_{c,cc,p,k,t}^{h_k} - \sum_{md} Q_{cc,md,p,k,t}^{h_k} - \sum_{sm} Q_{cc,sm,p,k,t}^{h_k}\Big) \quad ,\forall cc,p,t \tag{29}$$

$$\hat{I}_{cc,p,t} = \hat{I}_{cc,p,t-1} + \sum_{c,k,h_k} (1-\gamma_p) Q_{c,cc,p,k,t}^{h_k} - \sum_{dc} Q_{cc,dc,p,k,t}^{h_k} \quad ,\forall cc,p,t \tag{30}$$

$$I_{War_k,p,t} = I_{War_k,p,t-1} + \sum_{d,h_k} Q_{d,War_k,p,k,t}^{h_k} - \sum_{c,h_k} Q_{War_k,c,p,k,t}^{h_k} \quad ,\forall k,War_k,p,t \tag{31}$$

$$I_{d,p,t} \geq SS_{d,p} \;, \qquad \forall d,p,t \tag{32}$$

$$I_{hdcc,p,t} \geq SS_{hdcc,p} \;, \qquad \forall hdcc,p,t \tag{33}$$

$$\sum_{s,k,h_k} Q_{s,m,i,k,t}^{h_k} = \sum_{p} TPR_{i,p} \sum_{d,k,h_k,Tech_p} Q_{m,d,p,k,t}^{Tech_p,h_k} \quad ,\forall m,i,t \tag{34}$$

$$\sum_{hdcc,k,h_k} Q_{d,hdcc,p,k,t}^{h_k} + \sum_{k,War_k,h_k} Q_{d,War_k,p,k,t}^{h_k} \leq \sum_{m,k,h_k,Tech_p} Q_{m,d,p,k,t}^{Tech_p,h_k} + I_{d,p,t-1} \;,\forall d,p,t \tag{35}$$

$$\begin{aligned} &\sum_{k,h_k}\Big(\sum_{c} Q_{hdcc,c,p,k,t}^{h_k} + \sum_{h\grave{d}cc} Q_{hdcc,h\grave{d}cc,p,k,t}^{h_k} + \sum_{md} Q_{hdcc,md,p,k,t}^{h_k} + \sum_{sm} Q_{hdcc,sm,p,k,t}^{h_k}\Big) \\ &\leq \sum_{k,h_k}\Big(\sum_{d} Q_{d,hdcc,p,k,t}^{h_k} + \sum_{h\grave{d}cc} Q_{h\grave{d}cc,hdcc,p,k,t}^{h_k} + \sum_{c} \gamma_p Q_{c,hdcc,p,k,t}^{h_k}\Big) \\ &+ I_{hdcc,p,t-1} \;,\forall hdcc,p,t \end{aligned} \tag{36}$$

$$\sum_{dc,k,h_k} Q^{h_k}_{hdcc,dc,p,k,t} \leq \sum_{c,k,h_k} (1-\gamma_p) Q^{h_k}_{c,hdcc,p,k,t} + \hat{I}_{hdcc,p,t-1}, \forall hdcc, p, t \quad (37)$$

$$\sum_{c,h_k} Q^{h_k}_{War_k,c,p,k,t} \leq \sum_{d,h_k} Q^{h_k}_{d,War_k,p,k,t} + I_{War_k,p,t-1}, \forall k, War_k, p, t \quad (38)$$

$$\sum_{k,h_k} \Big(\sum_{md} Q^{h_k}_{cc,md,p,k,t} + \sum_{sm} Q^{h_k}_{cc,sm,p,k,t}\Big) \leq \sum_{c,k,h_k} \gamma_p Q^{h_k}_{c,cc,p,k,t} + I_{cc,p,t-1}, \forall cc, p, t \quad (39)$$

$$\sum_{dc,k,h_k} Q^{h_k}_{cc,dc,p,k,t} \leq \sum_{c,k,h_k} (1-\gamma_p) Q^{h_k}_{c,cc,p,k,t} + \hat{I}_{cc,p,t-1}, \forall cc, p, t \quad (40)$$

$$\sum_{cc,k,h_k} Q^{h_k}_{c,cc,p,k,t} + \sum_{hdcc,,k,h_k} Q^{h_k}_{c,hdcc,p,k,t} \leq \alpha_{p,c} \left(\sum_{hdcc,k,h_k} Q^{h_k}_{hdcc,c,p,k,t} + \sum_{War_k,k,h_k} Q^{h_k}_{War_k,c,p,k,t} \right), \forall c, p, t \quad (41)$$

$$\sum_{k,h_k} \Big(\sum_{hdcc} Q^{h_k}_{hdcc,c,p,k,t} + \sum_{War_k} Q^{h_k}_{War_k,c,p,k,t}\Big) + SH_{c,p,t} = d_{c,p,t} + SH_{c,p,t-1}, \forall c, p, t \quad (42)$$

$$\sum_{s,m,i,k,h_k} Q^{h_k}_{s,m,i,k,t} P_{i,s,t} - BC_t \leq B_t, \forall t \quad (43)$$

$$BC_t \leq ABC_t, \forall t \quad (44)$$

$$y, x, z \in \{0,1\} \quad (45)$$

$$Q, I, SH, BC \geq 0 \quad (46)$$

The proposed mathematical formulation is composed of several groups of equations that collectively capture the economic, environmental, and social dimensions of the sustainable PSC network. *Eq. (1)* represents the fixed investment and operational costs associated with the establishment and operation of the network infrastructure. This includes the fixed costs of opening facilities, the contractual costs of collaborating with 3PL providers, the costs of establishing partnerships with suppliers, and the inventory holding costs for pharmaceutical products stored at distribution facilities. *Eq. (2)* accounts for operational processing costs within the network. Specifically, it includes the inspection costs incurred when returned pharmaceutical products are evaluated at collection or hybrid facilities, the disposal costs associated with non-usable medicines sent to disposal centers, and the production costs of pharmaceutical products at manufacturing plants. *Eq. (3)* captures the transportation costs generated by moving raw materials and pharmaceutical products between different nodes of the supply chain. These costs arise from shipments carried out by 3PLs providers using different transportation modes across multiple echelons of the network. *Eq. (4)* represents the revenue structure of the supply chain. The total income of the network is generated from three sources: The sale of pharmaceutical products to primary customer markets, the resale of eligible returned medicines in secondary markets, and tax reduction benefits obtained through pharmaceutical donation programs. *Eq. (5)* defines the first objective function of the model, which aims to maximize the overall profit of the supply chain network. This objective is obtained by maximizing total revenues while subtracting all relevant operational, transportation, and infrastructure costs incurred throughout the network. *Eq. (6)* formulates the environmental objective of the model. This objective minimizes the total carbon emissions generated by transportation activities across the supply chain, thereby capturing the environmental impact of logistics operations and supporting the development of a greener pharmaceutical distribution system. *Eq. (7)* represents the social objective of the model, which aims to maximize employment generation resulting from the establishment and operation of new facilities. Both fixed and variable jobs are considered, and the contribution of job creation is weighted according to the unemployment rate of each region in order to reflect the socio-economic importance of facility location decisions. *Constraints (8)–(15)* ensure the logical consistency of the network structure. These constraints guarantee that material flows can only occur through facilities that have been established. In other words, pharmaceutical products or raw materials cannot be shipped from a facility unless that facility is selected and activated within the network. *Constraints (16)–(19)* enforce the selection of only one capacity level for each candidate facility. This ensures that if a facility is established, it operates under a single predefined capacity level rather than multiple simultaneous capacity configurations. *Constraints (20)–(25)* impose capacity limitations on the facilities. These constraints ensure that the total volume of pharmaceutical products processed or stored at any facility does not exceed its available operational capacity. *Constraints (26)–(31)* represent the inventory balance equations of the network. These constraints track the inflow, outflow, and storage of pharmaceutical products at each facility over the planning horizon, enabling the model to capture the dynamic evolution of inventory levels across time periods. *Constraints (32) and (33)* enforce safety stock requirements at distribution facilities. These constraints ensure that a minimum level of inventory is maintained in order to protect the supply chain against demand uncertainty and potential supply disruptions. *Eq. (34)* determines the amount of raw materials required for pharmaceutical production. This relationship links production quantities with raw material consumption through predefined conversion coefficients. *Constraints (35)–(41)* represent the flow balance relationships throughout the supply chain network. These constraints maintain material conservation at each node by ensuring that incoming flows, outgoing flows, production, returns, and inventory levels remain consistent across the entire network structure. *Eq. (42)* corresponds to the demand satisfaction constraint for customer zones. This constraint ensures that customer demand is fulfilled either through direct supply or through backordering mechanisms when shortages occur. *Constraints (43) and (44)* describe the financial constraints related to raw material procurement. These constraints model the availability of financial resources by incorporating the maximum amount of credit that can be obtained from banks or financial institutions, as well as the borrowing conditions associated with such financing. Finally, *Constraints (45) and (46)* define the domain of the decision variables. These constraints specify the binary nature of location and selection variables, as well as the non-negativity conditions for continuous decision variables such as flow quantities, inventory levels, and financial variables.

3.2 | Multi Objectivr Optimization Method

To solve the proposed multi-objective optimization model, the ε-constraint method is employed. In this approach, one of the objective functions is selected as the primary objective, while the remaining objectives are transformed into constraints bounded by predefined ε levels. This method enables the systematic generation of Pareto-optimal solutions and facilitates the analysis of trade-offs among the economic, environmental, and social dimensions of the supply chain.

In the present study, the economic objective—maximization of the total profit of the PSC—is considered as the primary objective function. Accordingly, the environmental objective (carbon emission minimization) and the social objective (employment maximization) are incorporated into the model as additional constraints with specified ε thresholds. By iteratively adjusting these ε values, different feasible solutions can be obtained, each representing a distinct balance among profitability, environmental impact, and social benefits. *Eqs. (47) and (48)* present the reformulated structure of the model under the ε-constraint framework.

$$\max z_1 \tag{47}$$

S.t.

$$x \in \chi \ , -z_2 \leq \varepsilon_2 \ , z_3 \leq \varepsilon_3 \tag{48}$$

4 | Results

To evaluate the performance and validity of the proposed multi-objective mathematical model, a medium-sized test instance was designed and analyzed. The model was implemented using the Python programming language within the Pyomo environment, an advanced algebraic modeling system. Optimization was performed using the CPLEX 22.1 solver, known for its efficiency in handling complex Mixed-Integer Linear programming (MILP) problems. All computational experiments were conducted on a workstation equipped with an Intel Core i7 processor (2.6 GHz) and 16 GB of RAM under a 64-bit operating system.

The structural configuration of the test instance includes three suppliers, two manufacturing plants, three primary distribution centers, ten distinct customer zones, two collection centers, and three 3PL companies. The planning horizon was set to four discrete time periods, and the analysis was conducted across two major pharmaceutical product families. To ensure the practical relevance of the numerical study, the input parameters and operational data were elicited based on expert judgment and empirical insights from Soha Pharmaceutical Company (a leading player in the Iranian pharmaceutical sector).

4.2 | Analysis of the Pareto Frontier

The multi-objective nature of the problem necessitates a careful analysis of the trade-offs between conflicting goals. *Fig. 2* illustrates the Pareto-optimal frontier between the total network profit (Economic Objective) and the total $CO2$ emissions (Environmental Objective).

The results demonstrate a clear conflicting relationship between these two dimensions: an increase in total profit is strictly associated with a rise in carbon emissions. This phenomenon occurs because achieving higher profitability often requires more intensive transportation activities, larger shipment volumes, and the utilization of faster or higher-capacity logistics routes that are typically more carbon-intensive.

Key observations from the Pareto analysis include:

Non-Dominance: All points presented in *Fig. 2* are non-dominated solutions. This means that no single solution can improve the economic objective without deteriorating the environmental performance, and vice versa.

Trade-off Sensitivity: The slope of the Pareto front indicates the "marginal cost of environmental protection." As the model moves towards more eco-friendly solutions (lower $CO2$ emissions), the supply chain must sacrifice a portion of its profit to accommodate more sustainable (but potentially more expensive or less efficient) logistics and facility configurations.

Managerial Decision Support: The existence of this frontier provides a powerful decision-support tool for supply chain managers. Rather than providing a single "optimal" answer, the model offers a set of efficient alternatives. The final selection among these Pareto solutions depends on the strategic priorities of the policy-makers and the regulatory requirements regarding carbon footprints in the pharmaceutical industry.

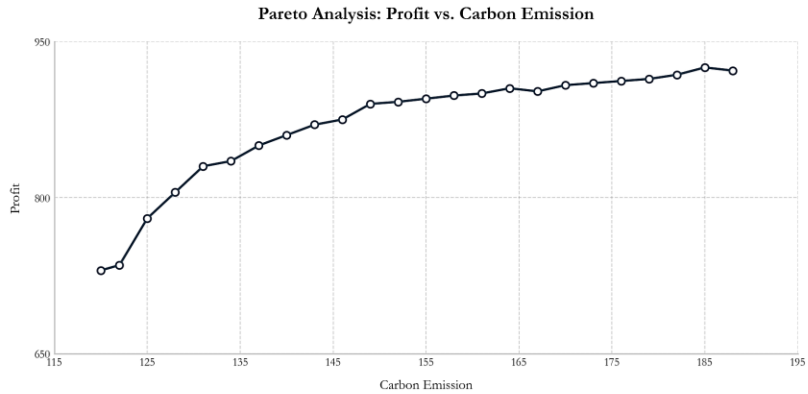

Fig. 2. Pareto diagram of the profit objective function versus carbon emissions.

4.3 | Evaluation of Pharmaceutical Return Policies

To evaluate the operational and strategic implications of different reverse logistics strategies, we define and analyze three distinct scenarios representing alternative pharmaceutical return policies:

Scenario 1 (Resale-Only Policy): All conforming returned pharmaceuticals are directed exclusively to secondary markets to maximize economic recovery.

Scenario 2 (Donation-Only Policy): All eligible returned medicines are donated to charity centers, prioritizing corporate social responsibility (CSR) and tax incentives over direct sales revenue.

Scenario 3 (Hybrid Policy - Proposed): The model dynamically allocates returned pharmaceuticals between secondary market resale and charitable donation based on global network optimization.

Table 2 presents the performance metrics of the supply chain network under these three scenarios.

Table 2. Quantitative comparison of pharmaceutical return policy scenarios.

Return Policy Scenario	Total Network Profit	Donated Pharmaceuticals	Resold Pharmaceuticals	Disposed Pharmaceuticals
Resale-Only (Scenario 1)	950.21	0	480.74	120.68
Donation-Only (Scenario 2)	870.49	500.41	0	100.47
Hybrid Policy (Scenario 3)	910.54	300.85	200.17	100.47

The numerical results in *Table 2* reveal critical trade-offs. The Resale-Only policy yields the highest total profit (950.21monetary units) by commercializing all usable returns. However, this economic dominance comes at a significant cost: it leads to the highest volume of pharmaceutical waste disposal (120.68 units), representing a suboptimal environmental footprint and zero direct social contribution through donations.

Conversely, the Donation-Only policy minimizes direct waste (100.47 units) and maximizes social outreach, but results in the lowest profitability (870.49 units) due to the absence of secondary market revenues.

The proposed Hybrid Policy acts as a Pareto-efficient compromise. While it generates slightly less profit (910.54 units) than the purely commercial resale policy, it achieves the minimum waste level (100.47 units)—matching the donation-only policy—while keeping a balanced mix of resale (200.17 units) and donation (300.85 units). By integrating these options, the hybrid policy balances economic viability with social responsibility, proving to be the most sustainable choice for high-level decision-makers.

4.4 | Sensitivity Analysis: The Impact of Product Return Rate

To analyze how changes in customer behavior affect the network, we conducted a sensitivity analysis on the pharmaceutical return rate, varying it from a low return regime (0.02) to a high return regime (0.20). The resulting trends are illustrated in *Fig. 3*.

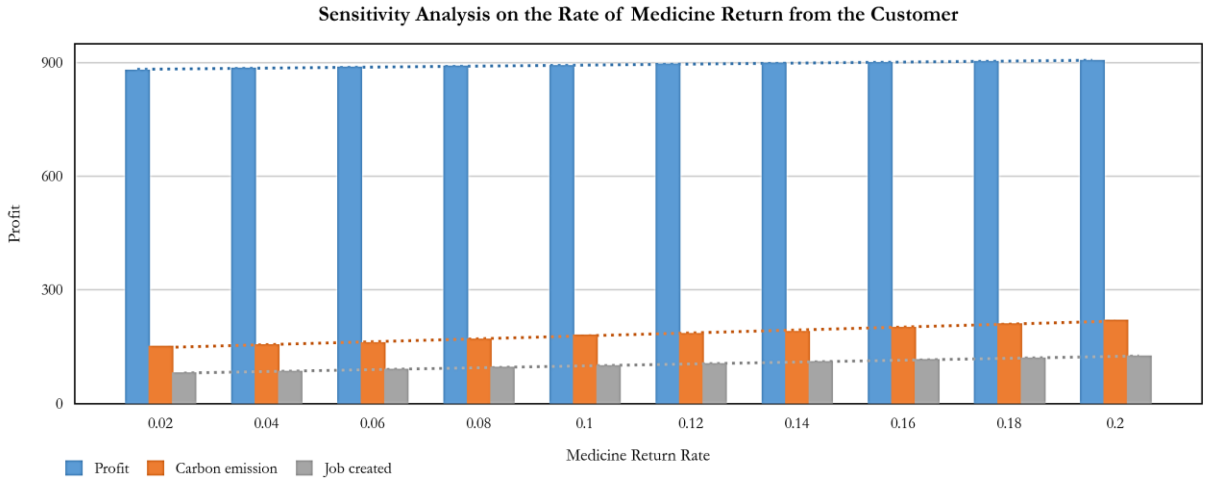

Fig. 3. Sensitivity analysis on the customer return rate.

Economic Implications: As the return rate increases, the total profit of the network experiences a positive growth trajectory. This upward trend indicates that the economic value recovered from the returned pharmaceuticals (via secondary market sales and tax exemptions from donations) outweighs the extra logistics costs of collection, inspection, and reverse transport.

Environmental Implications: Simultaneously, a higher return rate leads to a marked increase in total $CO2$ emissions. This negative environmental impact is a direct consequence of the increased transport workload. Moving returned products from customer zones back to collection and hybrid centers requires more frequent vehicle trips, increasing fuel consumption and greenhouse gas emissions.

Social Implications (Job Creation): A key finding of this sensitivity analysis is the positive impact of the return rate on the social objective. When return volumes rise, the existing network capacity becomes constrained. To handle the larger flow of returned products, the optimization model is forced to either establish new collection centers or upgrade existing distribution centers into hybrid facilities. This physical expansion directly generates new fixed and variable jobs, which significantly boosts employment in regions with high unemployment rates.

These sensitivity trends highlight a core challenge in sustainable supply chain management. Higher return rates improve both economic performance (through asset recovery) and social welfare (through job creation in processing facilities), but worsen the network's environmental impact (due to transport emissions). Therefore, high-level policy-makers must establish a balanced framework. This can be achieved by using greener transport options, such as low-emission 3PL fleets, to offset the carbon footprint of reverse logistics, while leveraging the economic and social benefits of a robust circular economy.

4.5 | Effects of 3PL Warehousing and the Hybridization of Secondary Distribution Centers

To investigate the role of 3PL providers in shaping the optimal configuration of the PSC, the selected storage facilities and the extent to which secondary distribution centers were converted into hybrid facilities were examined across the optimal solutions. In the proposed network, a hybrid facility simultaneously supports forward and reverse logistics activities. In addition to storing and distributing pharmaceutical products to customer zones, such a facility can receive returned medicines and facilitate their consolidation, temporary storage, inspection, sorting, and subsequent transfer for resale, donation, recovery, or safe disposal. The computational results indicate that 3PL storage facilities are selected in more than 60% of the optimal solutions. Their selection is particularly frequent in low-demand regions and geographically remote areas located far from manufacturing plants. In these areas, establishing a company-owned warehouse may not be economically justified because the expected throughput is insufficient to offset the associated fixed investment and operating costs. By contrast, outsourcing warehousing activities to 3PL providers allows the pharmaceutical company to access logistics capacity without committing substantial capital to the construction, equipment, and long-term operation of dedicated facilities.

The frequent selection of 3PL warehouses therefore highlights their strategic value as a flexible capacity mechanism rather than merely as an outsourcing alternative. By replacing part of the network's fixed infrastructure with externally provided capacity, 3PL participation can transform a portion of fixed capital expenditure into more flexible, usage-dependent logistics expenditure. This flexibility is particularly valuable under spatially dispersed or fluctuating demand, where maintaining sufficient internal capacity for peak conditions may lead to low facility utilization during normal periods. Accordingly, the use of 3PL warehouses reduces the risk of overinvestment while improving the network's ability to respond to changes in regional demand and return volumes.

The results also reveal a noteworthy relationship between the use of 3PL warehouses and the hybridization of logistics facilities. In scenarios in which 3PL warehousing capacity is actively employed, approximately 50% of the selected 3PL warehouses operate as hybrid facilities supporting both forward distribution and reverse product flows. In contrast, the hybridization rate remains below 30% in network configurations that rely primarily on company-owned warehouses. Thus, the observed difference is at least 20 percentage points, indicating that hybrid operation occurs considerably more frequently in 3PL-based network structures.

This result can be explained by the greater operational adaptability of 3PL providers. Compared with dedicated internal warehouses, 3PL facilities often have access to shared transportation resources, scalable storage capacity, specialized handling capabilities, and established regional logistics networks. These capabilities make it easier to consolidate forward and reverse flows at the same location. For example, vehicles that deliver medicines to a customer region may collect eligible returned products on their return journeys, thereby reducing empty vehicle movements and improving vehicle utilization. Similarly, shared warehousing capacity can be reallocated between regular inventory and returned products as flow volumes change over time.

From a reverse-logistics perspective, the hybridization of 3PL warehouses can improve the accessibility and responsiveness of the collection network. Locating hybrid facilities closer to geographically dispersed customer zones shortens the distance over which returned medicines must initially be transported and provides additional consolidation points for low-volume return flows. This feature is especially important in PSCs, where returned products may require controlled storage, traceability, timely inspection, and segregation according to quality status. A geographically distributed network of capable 3PL facilities can therefore help prevent recoverable medicines from being prematurely classified as waste simply because collection or processing capacity is unavailable.

Moreover, integrating forward distribution and reverse collection activities within the same facility can create operational synergies. The network may use common infrastructure, labor, information systems, and transportation resources for both flow directions. Such integration can reduce duplicated facility investment and enhance coordination among delivery, collection, inspection, and recovery operations. Consequently, hybrid facilities may increase the proportion of returned medicines that can be successfully directed toward secondary-market resale or donation rather than disposal.

Nevertheless, the greater use of 3PL and hybrid facilities does not automatically guarantee improved performance across all sustainability dimensions. Although outsourcing can lower infrastructure costs and improve responsiveness, it may introduce additional coordination challenges, dependence on external providers, and difficulties in monitoring service quality. These concerns are particularly important in pharmaceutical logistics because returned medicines require strict compliance with product-safety, traceability, temperature-control, and regulatory requirements. Therefore, 3PL selection should not be based exclusively on cost and available capacity. It should also consider the provider's technical competence, environmental performance, regulatory compliance, information-sharing capabilities, geographical coverage, and ability to handle pharmaceutical returns safely.

Overall, the findings suggest that 3PL participation and facility hybridization are complementary network-design decisions. The presence of 3PL providers not only reduces the need for capital-intensive internal infrastructure but also enables a more adaptable configuration in which forward and reverse flows can be integrated more effectively. This integration improves the network's capacity to collect, consolidate, and recover returned medicines, particularly in remote or low-demand regions where dedicated internal facilities would otherwise be economically unattractive. Therefore, 3PL providers should be viewed as strategic enablers of circularity and supply chain resilience rather than solely as instruments for reducing logistics costs.

4.6 | Managerial Implications

The results provide several implications for PSC decision-makers:

Selective outsourcing is more beneficial than uniform outsourcing: The superiority of 3PL facilities is particularly evident in remote and low-demand regions. Therefore, managers should adopt a differentiated facility strategy in which internal warehouses serve high-volume and strategically important markets, while 3PL capacity supports geographically dispersed or demand-uncertain regions.

3PL selection should be integrated with facility-role decisions: Decisions concerning the selection of logistics providers and the hybridization of distribution centers should not be made independently. A provider capable of supporting both product delivery and pharmaceutical return collection may generate greater network-wide value than a lower-cost provider offering only conventional warehousing services.

Contracts should support scalable and bidirectional operations: Agreements with 3PL providers should include flexible capacity clauses, service-level requirements for return collection, and explicit responsibilities for inspection, segregation, documentation, and temporary storage. Performance-based contracts can encourage providers to improve both delivery efficiency and the recovery rate of returned medicines.

Regulatory and quality requirements remain critical: The use of shared or outsourced infrastructure should not compromise pharmaceutical safety. Managers must verify that selected 3PL providers comply with relevant good distribution practices, traceability protocols, storage conditions, and requirements for handling returned, damaged, or expired medicines.

Environmental performance should be evaluated at the network level: Although hybridization may reduce empty trips and duplicated infrastructure, additional collection activities can increase transportation and processing emissions. Consequently, the environmental benefit of 3PL participation depends on route consolidation, vehicle technology, facility location, and the efficiency of return-processing operations.

5 | Conclusion

This study presented a multi-objective model for the design of a sustainable PSC network by simultaneously considering economic, environmental, and social goals. The proposed framework integrates forward and reverse logistics decisions, including facility selection, return flow management, 3PL provider selection, and the hybrid use of distribution facilities. The numerical results confirm the existence of a clear trade-off between profitability and environmental performance. In particular, the Pareto solutions show that increasing total profit from 750 to 950 monetary units is accompanied by an increase in CO_2 emissions from 130 to 310 units, highlighting the conflicting nature of sustainability objectives in PSC design.

The scenario analysis demonstrated that the hybrid return policy, which combines resale and donation, provides a more balanced performance than the single-option policies. Although the resale-only policy achieves the highest profit, the hybrid strategy reduces the amount of disposed medicine from 120.68 to 100.47 units while still maintaining a higher profit than the donation-only scenario. This finding suggests that combining economic recovery with social contribution can significantly improve the overall sustainability of the network. In addition, the sensitivity analysis showed that increasing the return rate enhances value recovery and social benefits, but at the same time leads to higher $CO2$ emissions because of additional transportation and processing activities. The results also highlighted the strategic role of 3PL providers, as they were selected in about 60% of the Pareto solutions and were associated with a higher level of hybrid facility utilization, indicating their contribution to network flexibility and infrastructure efficiency.

Despite these contributions, this study has some limitations. The numerical analysis was conducted based on a medium-sized case instance and several parameters were estimated using expert judgment, which may limit the generalizability of the results. In addition, uncertainty in demand, return rates, transportation conditions, and the quality of returned medicines was not explicitly modeled. Future research can address these limitations by extending the model to large-scale and real-world case studies, incorporating uncertainty through robust or stochastic optimization approaches, and investigating decentralized multi-echelon structures with competitive interactions among supply chain members, particularly 3PL providers and policy-makers, within a game-theoretic framework.

Author's Contributaions

All authors contributed equally to the conception, design, and preparation of this manuscript. All authors have read and agreed to the published version of the manuscript.

Funding

No funding was received for this study.

Data Availability

Data will be available on request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Jia, F., Aboagye, S., Shahzadi, G., & Chen, L. (2026). Sustainable practices in healthcare supply chains: A review of strategies, challenges, and impacts. *International Journal of Logistics Research and Applications*, *29*(4), 417–441. https://doi.org/10.1080/13675567.2025.2461102

[2] Esmaeili, B., & Ghomi, S. M. T. F. (2026). Designing a mathematical model for a sustainable pharmaceutical supply chain considering transshipment and demand uncertainty. *Opsearch*, 1–45. https://doi.org/10.1007/s12597-025-01070-1

[3] Evangelista, P., Santoro, L., & Thomas, A. (2018). Environmental sustainability in third-party logistics service providers: A systematic literature review from 2000–2016. *Sustainability*, *10*(5), 1627. https://doi.org/10.3390/su10051627

[4] Hussain, M., Ajmal, M. M., Gunasekaran, A., & Khan, M. (2018). Exploration of social sustainability in healthcare supply chain. *Journal of Cleaner Production*, *203*, 977–989. https://doi.org/10.1016/j.jclepro.2018.08.157

[5] Abbasi, S., Sıcakyüz, Ç., Gonzalez, E. D. R. S., & Ghasemi, P. (2024). A systematic literature review of logistics services outsourcing. *Heliyon*. https://doi.org/10.1016/j.heliyon.2024.e33374

[6] Çıkmak, S. (2025). Sustainable 3PL service provider selection in the pharmaceutical industry using fuzzy-based SWARA and MAIRCA methods. *Abant Sosyal Bilimler Dergisi*, *25*(1), 306–333.

[7] Sazvar, Z., Zokaee, M., Tavakkoli-Moghaddam, R., Salari, S. A., & Nayeri, S. (2022). Designing a sustainable closed-loop pharmaceutical supply chain in a competitive market considering demand uncertainty, manufacturer's brand and waste management. *Annals of Operations Research*, 1–32. https://doi.org/10.1007/s10479-021-03961-0

[8] Savadkoohi, E., Mousazadeh, M., & Torabi, S. A. (2018). A possibilistic location-inventory model for multi-period perishable pharmaceutical supply chain network design. *Chemical Engineering Research and Design*, *138*, 490–505. https://doi.org/10.1016/j.cherd.2018.09.008

[9] Pourjavad, E., & Mayorga, R. V. (2018). Optimization of a sustainable closed loop supply chain network design under uncertainty using multi-objective evolutionary algorithms. *Adv Prod Eng Manag*, *13*(2), 216–228.

[10] Li, Y., Guo, H., & Zhang, Y. (2018). An integrated location-inventory problem in a closed-loop supply chain with third-party logistics. *International Journal of Production Research*, *56*(10), 3462–3481. https://doi.org/10.1080/00207543.2017.1338781

[11] Easwaran, G., & Üster, H. (2010). A closed-loop supply chain network design problem with integrated forward and reverse channel decisions. *Iie Transactions*, *42*(11), 779–792. https://doi.org/10.1080/0740817X.2010.504689

[12] Pourmehdi, M., Paydar, M. M., & Asadi-Gangraj, E. (2020). Scenario-based design of a steel sustainable closed-loop supply chain network considering production technology. *Journal of Cleaner Production*, *277*, 123298. https://doi.org/10.1016/j.jclepro.2020.123298

[13] Abbasi, S., Daneshmand-Mehr, M., & Ghane Kanafi, A. (2023). Green closed-loop supply chain network design during the coronavirus (COVID-19) pandemic: A case study in the Iranian automotive industry. *Environmental Modeling & Assessment*, *28*(1), 69–103. https://doi.org/10.1007/s10666-022-09863-

[14] Jalal, A., Toso, E. A. V., & Morabito, R. (2023). A location–transportation problem under demand uncertainty for a pharmaceutical network in Brazil. *Computers & Chemical Engineering*, *174*, 108233. https://doi.org/10.1016/j.compchemeng.2023.108233

[15] Abbasi, S., Saboury, A., & Jabalameli, M. S. (2021). Reliable supply chain network design for 3PL providers using consolidation hubs under disruption risks considering product perishability: An application to a pharmaceutical distribution network. *Computers & Industrial Engineering*, *152*, 107019. https://doi.org/10.1016/j.cie.2020.107019

[16] Zandkarimkhani, S., Mina, H., Biuki, M., & Govindan, K. (2020). A chance constrained fuzzy goal programming approach for perishable pharmaceutical supply chain network design. *Annals of Operations Research*, *295*, 425–452. https://doi.org/10.1007/s10479-020-03677-7

[17] Zandieh, M., Janatyan, N., Alem-Tabriz, A., & Rabieh, M. (2018). Designing sustainable distribution network in pharmaceutical supply chain: A case study. *International Journal of Supply and Operations Management*, *5*(2), 122–133. https://doi.org/10.22034/2018.2.2

[18] Habibi, F., Chakrabortty, R. K., Abbasi, A., & Ho, W. (2026). Building resilient closed-loop supply chains: resilience enablers and diversified sourcing under global disruptions. *International Journal of Production Research*, *64*(1), 192–219. https://doi.org/10.1080/00207543.2025.2546653

[19] Schleifenheimer, M., & Ivanov, D. (2026). Pharmaceutical retail supply chain responses to the COVID-19 pandemic. *Annals of Operations Research*, *359*(1), 1033–1058. https://doi.org/10.1007/s10479-024-05866-0