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# Resilience and risk management in blood supply chains: a systematic review

Mohammad Javad Pahlevanzadeh, Mohammad Reza Fathi and Amirhossein Saffarinia
*College of Farabi, University of Tehran, Qom, Iran*

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## Abstract

**Purpose** – This study aims to explore how risk management and resilience have been addressed in the blood supply chain literature, focusing on dominant themes, methodological trends, and existing gaps. Given the sensitivity of blood products and the vulnerability of blood supply chains to disruptions, the study seeks to identify how researchers have approached uncertainty, network design and crisis management.

**Design/methodology/approach** – A systematic review was conducted following the PRISMA protocol. Scientific databases were screened for studies published up to 2024. From an initial pool of 436 papers, 34 met the inclusion criteria. These papers were analyzed using a combination of scientometric mapping and qualitative content analysis to uncover methodological patterns, thematic clusters and research trends.

**Findings** – Results show that 52.9% of the reviewed studies rely on quantitative approaches, especially mathematical modeling. Key research focuses include supply chain network design (38.2%), large-scale disruptions (26.6%), and demand fluctuations (17.6%). Stochastic, robust and multi-objective programming were the most commonly applied techniques. Despite noticeable conceptual development, 61.8% of studies lacked real-world applications or case-based validation, indicating a major gap between theory and practice.

**Originality/value** – This study offers a comprehensive and integrated perspective by combining scientometric analysis with qualitative synthesis. It clarifies prevailing paradigms, reveals ignored but critical research areas, and highlights the need for more empirical and field-based studies. The review provides a roadmap for future research aiming to enhance resilience and risk management in blood supply chains.

**Keywords** Blood supply chain, Risk management, Resilience, Systematic review, Uncertainty optimization

**Paper type** Research article

## Introduction

The Blood Supply Chain (BSC) stands as one of the most critical components of healthcare systems worldwide, playing an indispensable role in ensuring public health. Blood and its by-products are life-saving and irreplaceable resources, undeniably essential for complex surgeries, chronic disease management, emergency care, and disaster victim response (Agudelo-Ibarguen *et al.*, 2021; Pirabán *et al.*, 2019). However, the unique nature of this supply chain exposes it to complex challenges. The inherent perishability of blood with its short shelf life, the uncertainty and severe fluctuations in both supply (blood donations) and demand (medical needs), and logistical complexities have transformed the management of this chain into a highly challenging scientific and operational domain (Hu *et al.*, 2024; Maeng *et al.*, 2018).

The blood supply chain is an integrated, multi-echelon network that encompasses the processes of collecting blood from donors, testing, processing and separating it into various



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components, storage, and finally, distribution to hospitals and medical centers for transfusion to patients (Anthara *et al.*, 2024; Motamedi *et al.*, 2024). Optimal inventory management within this network is of paramount importance to prevent two adverse outcomes: "shortages," which endanger patient lives, and "wastage," which leads to the squandering of this precious resource (Afshar *et al.*, 2014; Meneses *et al.*, 2023).

This vital chain is perpetually exposed to a wide array of risks and disruptions that can severely impair its functionality. These risks include natural disasters such as earthquakes and floods, which cause a sudden surge in demand and destruction of infrastructure (Asadpour *et al.*, 2022; Haghjoo *et al.*, 2020), humanitarian crises like pandemics and strikes (Samani and Hosseini-Motlagh, 2019; Van Denakker *et al.*, 2023), and internal managerial and operational weaknesses (Boonyanusith and Jittamai, 2019). In recent years, emerging threats such as climate change have also been identified as a serious disruptive factor that can affect blood safety and availability at all stages (Viennet *et al.*, 2025). In such a high-risk environment, the concept of resilience emerges as a strategic capability for the blood supply chain. Resilience is defined as the ability of a system to anticipate, prepare for, resist, and rapidly recover from disruptions to maintain its critical functions. Enhancing resilience ensures operational continuity in crisis situations, reduces vulnerability, and increases the overall stability of the healthcare system (Sibevei and Roozkhosh, 2024; Zhao *et al.*, 2023). Despite the growing importance of this field and the numerous studies conducted, significant research gaps remain. Many previous studies have focused on optimizing a specific aspect of the chain or managing a particular risk, and there is a pressing need for the development of integrated and comprehensive risk management models that consider all uncertainties simultaneously. The profound impacts of climate change on this chain are not yet fully understood and require more detailed analysis. Furthermore, the full potential of emerging Industry 4.0 technologies, such as blockchain and the Internet of Things (IoT), to enhance transparency and efficiency in the blood supply chain is still in the early stages of investigation (Imamoglu *et al.*, 2023; Kumar *et al.*, 2024). Additionally, the limited use of hybrid and multi-criteria decision-making (MCDM) methods to support complex decision-making under crisis conditions is another overlooked issue in this area. Risk management focuses on identifying, assessing, and reducing the likelihood or severity of disruptions, whereas resilience emphasizes maintaining performance and enabling rapid recovery once such disruptions occur. The two concepts are complementary: risk management seeks to prevent disruptions from happening, while resilience ensures that the system can continue operating if a disruption does occur. In the BSC literature, risk is typically operationalized as a combination of the probability of disruption and the magnitude of its impact. Approaches such as disruption scenarios, probabilistic models, Markov chains, and Monte Carlo simulation have been used to quantify these risks. By contrast, resilience is often defined through metrics such as recovery time, service level maintained during the disruption, capacity flexibility, and the system's ability to absorb shocks. Various studies have employed simulation models, network-based indices, MCDM techniques, and system dynamics modeling to measure this concept. A further distinction is visible in the literature: risk-oriented studies mainly use quantitative, probability-based tools, disruption scenario simulation, and robust optimization to reduce the likelihood or severity of disruptions. In contrast, resilience-oriented studies focus more on designing system capabilities for rapid recovery and rely on methods such as multi-criteria assessment, network-based resilience analysis, and modeling of the chain's dynamic behavior. This methodological differentiation provides a clearer framework for analyzing the current state of the literature and for identifying research gaps. This review article is conducted with the aim of filling these gaps and presenting an integrated picture of the current state of knowledge in risk management and resilience of the blood supply chain. Accordingly, the main objectives and research questions are defined as follows:

*RQ1.* What are the most significant risks, disruptions, and resilience strategies identified in the literature for the blood supply chain?

*RQ2.* What are the dominant modeling approaches and quantitative methods (e.g. optimization, simulation, and multi-criteria decision-making) used to analyze and improve the resilience of the blood supply chain?

## Theoretical foundations

The concept of "Supply Chain Management" (SCM), rooted in the literature of industrial and production management, focuses on the integrated management of the flow of materials, information, and financial resources from the point of origin to the point of consumption (Miles and Snow, 2007). As the application of this concept expanded into the service sector, the healthcare field also began to leverage SCM principles due to its logistical complexities and the critical nature of its products. Within this context, the "Blood Supply Chain" (BSC) emerged as a specialized and unique domain. The reason for this nomenclature is the structural similarity of blood flow to that of a product in classic supply chains; this flow originates from a source (donor), undergoes processing, storage, and distribution, and ultimately reaches its destination (patient) (Anthara *et al.*, 2024). This process-oriented and integrated perspective on blood flow is the rationale behind the term. Although pinpointing the exact date of the term's first use in scientific texts is difficult, reviews indicate that its application has grown significantly over the last two decades, coinciding with the increasing complexity of healthcare systems and the necessity of employing modern management approaches (Eghtesadifard and Jozan, 2022; Pirabán *et al.*, 2019). Indeed, the blood supply chain is a prominent example of adapting SCM principles to a product with exceptional characteristics: a product whose production is based on human altruism, has no artificial substitute, is highly perishable, and whose scarcity is directly tied to the life and death of patients (Nagurney, 2022). In the literature, numerous definitions have been proposed for the blood supply chain, each emphasizing a particular aspect of this complex system. Three key definitions are highlighted below:

From an optimization perspective, the blood supply chain is an integrated, multi-echelon system comprising donors, blood centers, and hospitals. This system, which considers multiple blood products, vehicle routing, and the possibility of transshipment between centers, requires optimization to minimize total costs (Anthara *et al.*, 2024).

From a systemic and logistical viewpoint, the blood supply chain is a key component of the healthcare system with a multi-level structure that includes blood donation, processing, storage centers, and hospitals. This definition emphasizes managing the perishability of products and optimizing logistical costs, including the costs of establishing facilities and transporting products (Nasrabadi and Seifbarghy, 2023).

From a process-oriented view, the blood supply chain refers to the sequence of blood management processes from collection to transfusion. These processes include procurement, production, inventory management, and distribution, involving multiple stakeholders, and aim to optimize distribution planning while considering constraints such as transportation capacity and shortage costs (Mansur *et al.*, 2018). For a deeper understanding, the blood supply chain must be distinguished from two related but distinct concepts: the "healthcare supply chain" and the "emergency supply chain." The main differences between these concepts are summarized in Table 1.

The special position of the blood supply chain becomes evident here; it is a hybrid system. Under normal conditions, it operates as a subset of the healthcare supply chain. However, during crises, disasters, or pandemics, it must immediately activate the capabilities of an emergency supply chain and respond to surge demand with maximum speed and flexibility. This dual nature makes its risk and resilience management significantly more complex.

## Risk, risk management, and resilience in the blood supply chain

Due to its complex and critical nature, the blood supply chain faces a wide range of risks, which are categorized in Table 2.

**Table 1.** Comparison of the healthcare supply chain and the emergency supply chain

| Criterion | Healthcare supply chain | Emergency supply chain |
|---|---|---|
| Primary Goal | Continuity, efficiency, and cost-effectiveness under normal conditions (Bvuchete *et al.*, 2021) | Rapid response, damage mitigation, and time prioritization during a crisis (Zeng, 2021) |
| Key Characteristic | Relative stability, cost management, product traceability (Langabeer, 2005) | High dynamism, maximum flexibility, immediate coordination (Sun and Liao, 2025) |
| Risk Management Focus | Managing operational inefficiencies and routine disruptions | Managing large-scale and sudden disruptions caused by crises |

**Table 2.** Types of risks in the blood supply chain

| Risk category | Examples and instances |
|---|---|
| Supply and demand | Uncertainty in blood donation rates, sudden fluctuations in hospital needs, perishability of products (Rekabi *et al.*, 2024) |
| Operational | Inventory shortages, wastage due to expiration, transportation disruptions, infrastructure destruction in disasters (Samani and Hosseini-Motlagh, 2019) |
| Managerial and Financial | Lack of financial resources, poor coordination between centers, insufficient and delayed information sharing (Boonyanusith and Jittamai, 2019) |
| Environmental | Disruptions from climate change (floods, storms), pandemics, and public health crises (Viennet *et al.*, 2025) |

To counter these threats, risk management methods are applied in two main phases: risk identification and assessment, using tools like the House of Risk (HOR) and the Analytic Hierarchy Process (AHP), and risk mitigation and control, through strategies such as enhancing collaboration and improving information sharing (Elleuch *et al.*, 2014). However, given the unpredictable nature and large scale of modern disruptions, risk management alone is insufficient. This is where the concept of resilience becomes essential as a proactive and preventative approach. Resilience refers to the supply chain's ability to withstand disruptions and quickly return to normal or even improved performance. Resilience tools include designing robust networks, using simulation models, and employing multi-criteria decision-making (MCDM) methods to prioritize barriers and solutions (Sibevei and Roozkhosh, 2024; Haghjoo *et al.*, 2020).

The blood supply chain has a multi-echelon structure, which generally includes four main stages: (1) donors and collection centers (fixed or mobile), (2) processing centers (for separating components like red blood cells, plasma, and platelets), (3) storage centers, and (4) distribution centers and hospitals as the final consumers (Nasrabadi and Seifbarghy, 2023; Triqui, 2024). This chain can be categorized based on various criteria, including by management structure into centralized types, where a main center manages the entire network, and decentralized types, which consist of independent regional centers (Kees *et al.*, 2022), as well as by the type of blood products, each requiring different storage and logistical conditions.

Research in the field of the blood supply chain has utilized various literature review methods to analyze and synthesize existing knowledge. Among the most important of these methods are the Systematic Review for systematically collecting and analyzing research, the Structured Review for categorizing quantitative models, and the Bibliometric Review for statistically analyzing trends and influential authors (Agac *et al.*, 2024; Osorio *et al.*, 2015). The present article falls into the category of a systematic review, which aims to provide a systematic and integrated analysis of the literature related to risk management and resilience in the blood supply chain to, while covering this topic, identify research gaps for future studies.

## Literature review

The Blood Supply Chain (BSC), as one of the most vital segments of the healthcare system, faces unique challenges, including product perishability, uncertainty in supply (donations) and demand (patient needs), and high vulnerability to disruptions. These complexities have driven researchers to employ various approaches to improve the resilience, efficiency, and risk management of this chain. This section categorizes and reviews the literature across several key domains: resilient and efficient network design; forecasting and inventory management; risk management frameworks; and finally, qualitative and novel perspectives in this field.

### Resilient and efficient network design

A significant portion of the research has focused on designing the physical structure of the blood supply chain network using optimization approaches. The primary objective in this category of studies is to create a network that performs optimally under both normal conditions and during crises. In this regard, Hamdan and Diabat (2020) and Diabat *et al.* (2019) developed two-stage and bi-objective robust optimization models for network design under disaster-induced disruptions. These models aim to simultaneously minimize both cost and blood delivery time, proposing resilient solutions by considering disruptions to facilities and routes and utilizing mobile facilities. To solve these complex models, algorithms such as Lagrangian relaxation have been employed. As the field has evolved, researchers have incorporated additional dimensions into network design models. Rekabi *et al.* (2024) proposed a multi-objective model for designing a responsive, sustainable-green, and resilient network that also accounts for the phenomenon of congestion at blood centers. Haeri *et al.* (2020), using a mixed resilient-efficient approach, developed a model that integrates Data Envelopment Analysis (DEA) to simultaneously pursue three objectives: reducing inefficiency, cost, and non-resilience. This study also showcased an innovative approach by considering socio-motivational aspects to encourage donors. Along the same lines, Larimi *et al.* (2023) integrated Geographic Information System (GIS) with robust-stochastic optimization to provide a practical framework for the optimal location of alternative and backup facilities, demonstrating that the cost of establishing backup facilities is negligible compared to the resulting increase in network resilience.

### Forecasting, inventory, and supply management

Uncertainty in supply and demand is the core operational challenge in the blood supply chain. Niakan *et al.* (2024) integrated time-series forecasting models with a multi-objective optimization model to offer a realistic tool for simultaneously managing prediction and distribution. During crises like the COVID-19 pandemic, the need for more accurate forecasting models became even more pronounced. Shokouhifar and Ranjbarimesan (2023) utilized a deep learning model (LSTM), incorporating disease infection and mortality data as external inputs, to develop a supply and demand forecasting model that significantly reduced shortage and wastage rates. From an inventory management perspective, Ejohwomu *et al.* (2021), using a multi-method simulation model (agent-based and discrete-event), determined optimal inventory levels for platelets and showed that this approach could reduce wastage by up to 78%. Hosseinifard and Abbasi (2018) investigated the strategy of inventory centralization at the hospital level, demonstrating that this approach could decrease wastage and shortages by 21% and 40%, respectively. On the other side of the chain supply management Fortsch and Perera (2018) introduced the "β-policy," based on a dual sourcing of donors (regular and emergency), offering an innovative solution to increase flexibility in donor call-ups and reduce dependency on forecast accuracy.

### Risk identification and management frameworks

The identification, assessment, and mitigation of risks is one of the most widely researched areas in the blood supply chain. Many studies have utilized structured frameworks for this purpose. The House of Risk (HOR) methodology is one of the most frequently used tools in this context. Boonyanusith and Jittamai (2018) and Achmadi and Mansur (2017) both used this two-stage model to identify and prioritize risk-generating factors and subsequently design effective preventive actions. The findings of both studies emphasized the importance of factors such as "lack of collaboration" and "limited information sharing" as root-cause risks. Dewantari *et al.* (2020) enhanced this approach by integrating the SCOR model for process mapping and designed a monitoring system for it. Other researchers have employed more systemic and advanced approaches for risk analysis. Cagliano *et al.* (2015) in two consecutive studies, developed a risk management framework. First, in 2015, they focused on the preventive analysis of logistical risks using FMECA (Cagliano *et al.*, 2015). Later, in 2021, they added Fault Tree Analysis (FTA) to conduct a root-cause analysis of the cause-and-effect relationships among adverse events throughout the entire chain (Cagliano *et al.*, 2021). Sibevei *et al.* (2022) also proposed an Integrated Systemic Framework (ISF) based on SSM, SNA, and ISM for identifying, selecting, and classifying risks, showing that macro-level risks like sanctions and earthquakes act as root-cause factors. This systemic perspective contributes to a deeper understanding of the complex and interdependent relationships among risks.

### Qualitative perspectives, performance measurement, and novel dimensions

In addition to quantitative approaches, some studies have adopted a qualitative perspective to gain a deeper understanding of the dynamics of the blood supply chain. Lusiantoro and Tjahjono (2017), through a case study in Indonesia, identified five key factors affecting blood safety and availability: policies, costs, donor management, inventory management, and facilities. From a highly innovative standpoint, Lusiantoro and Yates (2024) explored the role of "skepticism" as a form of non-physical redundancy, demonstrating how human behavior, through information repetition and mutual evaluation, can contribute to the robustness and agility of the chain. In the area of performance measurement, Matin *et al.* (2022) proposed a model based on Network DEA (NDEA) to assess the sustainability and resilience of the blood supply chain, capable of handling complex data types and undesirable outputs. Finally, identifying barriers to resilience is a critical step toward improvement. Sibevei and Roozkhosh (2024), using multi-criteria decision-making (MCDM) methods, prioritized barriers such as "lack of financial resources" and "managerial weaknesses" as the most significant obstacles to resilience in Iran's blood supply chain. Table 3 summarizes the reviewed studies.

This study presents a systematic review in the field of blood supply chain management, which differs substantially from previous works in several aspects. A structured and hierarchical methodology was used to identify, screen, and extract the most relevant and influential studies. Based on a systematic literature review framework, this research specifically examines studies focused on risk management and resilience within supply chain contexts. Hence, the application of this structured approach and its emphasis on uncertainty gaps constitute one of the key innovative aspects of the study. The research highlights a shared research gap in the blood supply network literature, situated at the intersection of supply chain management, resilience, and risk management. Therefore, the distinctiveness of this study lies not only in its mechanism, overall structure, and methodology, but also in its particular conceptual approach and the identified research gap within the blood supply chain domain. The main innovations of this study can be summarized as follows:

(1) Adoption of a novel integrative approach in the blood network domain (capturing the intersection of the three core concepts: supply chain, resilience, and risk),

(2) Application of a new research structure, and

**Table 3.** Summary of reviewed studies

| Researcher(s) and year | Main topic | Approach/Methodology | Key finding/Contribution |
|---|---|---|---|
| Niakan *et al.* (2024) | Forecasting and Distribution Optimization | Time-series Model and Multi-objective Optimization (GA, PSO) | Integrating forecasting and optimization to enhance resilience and health equity |
| Rekabi *et al.* (2024) | Design of a Responsive, Sustainable, and Resilient Network | Multi-objective MINLP Model and Linear Regression (LR) | Considering congestion, sustainability, and resilience in network design and solved using LR |
| Sibevei and Roozkhosh (2024) | Prioritization of Resilience Barriers | Multi-Criteria Decision Making (BWM, Delphi, PROMETHEE) | Identifying financial resource shortages and managerial shortcomings as main barriers |
| Lusiantoro and Yates (2024) | Role of Human Behavior in Resilience | Qualitative Case Study | Introducing “skepticism” as a type of non-physical redundancy to enhance robustness |
| Shokouhifar and Ranjbarimesan (2023) | Forecasting under Crisis Conditions (COVID-19) | Multivariate Deep Learning (LSTM) | Significant reduction in shortages and wastage using external data (disease) |
| Matin *et al.* (2022) | Measuring Sustainability and Resilience | Network Data Envelopment Analysis (NDEA) | Presenting a performance evaluation model capable of handling complex and undesirable data |
| Larimi *et al.* (2023) | Network Reorganization under Disruption | GIS and Robust-Stochastic Optimization | Integrating spatial analysis and optimization for optimal location of backup facilities |
| Sibevei *et al.* (2022) | Systemic Risk Identification and Assessment | Integrated Framework (SSM, SNA, ISM) | Identifying root risks (e.g. sanctions) and dependent risks (e.g. delayed delivery) |
| Cagliano *et al.* (2021) | Risk Management and Cause-and-Effect Analysis | Fault Tree Analysis (FTA) and KPI | Root cause analysis and proactive analysis of risk propagation throughout the chain |
| Cagliano *et al.* (2015) | Proactive Analysis of Logistics Risks | FMECA and KPI | Presenting a structured approach for analyzing logistics risks and measuring response effectiveness |
| Ejohwomu *et al.* (2021) | Platelet Inventory Management | Hybrid Simulation (Agent-Based, Discrete-Event) | 78% reduction in platelet wastage by determining optimal inventory levels |
| Dewantari *et al.* (2020) | Designing a Risk Mitigation and Monitoring System | SCOR and House of Risk (HOR) | Integrating standard tools for systematic risk identification, mitigation, and monitoring |
| Haeri *et al.* (2020) | Design of a Resilient-Efficient Network | Multi-objective Optimization and DEA | Simultaneously integrating cost, resilience, and efficiency criteria in network design |
| Hamdan and Diabat (2020) | Robust Network Design under Crisis | Two-stage Robust Optimization and LR | Minimizing cost and delivery time under facility and route disruption |
| Lusiantoro and Tjahjono (2017) | Identifying Factors Affecting Safety and Availability | Qualitative Case Study | Identifying 5 key factors (policies, costs, donor management, inventory, facilities) |
| Boonyanusith and Jittamai (2018) | Risk Management using HOR | House of Risk (HOR) | Identifying lack of collaboration and information as major risks |

(*continued*)

**Table 3.** Continued

| Researcher(s) and year | Main topic | Approach/Methodology | Key finding/Contribution |
|---|---|---|---|
| Diabat *et al.* (2019) | Network Design for Perishable Products in Crisis | Bi-objective Robust Optimization and LR | Emphasizing the crucial role of mobile bases in reducing delivery time during disruption |
| Fortsch and Perera (2018) | Resilient Donor Call Policy | Beta policy (β-policy) based on dual sourcing | Increasing supply flexibility and enabling longer lead-time planning |
| Achmadi and Mansur (2017) | Designing Risk Mitigation Actions using HOR | House of Risk (HOR) | Prioritizing risks such as uncertain demand and natural disasters |
| Hosseinifard and Abbasi (2018) | Impact of Inventory Centralization on Sustainability | Two-stage chain modeling | Reducing 21% wastage and 40% shortages through hospital inventory centralization |

(3) Use of a PRISMA-based systematic methodology for literature identification and analysis.

The objectives and innovations of this study are reflected in its research process and structure, which unfolds in three key stages:

(1) Holistic Perspective on the Core Domain (Descriptive Stage):
In this stage, a descriptive mapping of the blood supply chain literature is conducted. Preliminary data are extracted and statistically analyzed to provide an overview of trends and thematic distributions. Clustering analysis is then performed to identify the main research domains, leading to the detection of the primary research gap.

(2) In-depth Examination of the Identified Gap (Descriptive Stage):
This phase focuses on the specific gap located at the intersection of risk, supply chain, and resilience. A final set of 34 core articles is selected, followed by a detailed descriptive analysis of their methods, approaches, tools, and contributions.

(3) Prescriptive Insights and Recommendations (Prescriptive Stage):
Based on the identified gap and prior analyses, this stage proposes potential pathways for future research. It outlines missing tools, approaches, and innovative directions that remain underexplored and could significantly advance the field of blood supply chain management.

## Research methodology

This study was conducted using the Systematic Review methodology, strictly adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page *et al.*, 2021). The PRISMA framework is designed to ensure the transparency, accuracy, and reproducibility of the systematic review process, including a comprehensive checklist and a flow diagram for reporting the identification, screening, eligibility, and final selection of studies (Liberati *et al.*, 2009). This approach enables researchers to report all stages of the systematic review clearly and comprehensively by employing a standardized method. The protocol for this systematic review was drafted and registered prior to the commencement of the study to prevent bias and ensure research reproducibility. The literature identification and screening process was conducted through a structured and comprehensive approach. Initially, studies related to the blood supply chain (BSC) were identified by searching this term in the *titles* and *abstracts* of publications retrieved from reputable international databases such as Scopus, complemented by manual searches. To ensure inclusiveness, combined and synonymous terms related to “supply chain,” “resilience,” and “risk” were also incorporated. This step allowed the inclusion of relevant studies that might not have used the exact keyword “blood supply chain” but referred to associated concepts such as *resilient* or *risk assessment*. Boolean operators (*AND, OR, NOT*) were applied to merge related expressions and capture the full conceptual scope of the field. Using this expanded strategy, 143 preliminary articles were identified. Following a detailed content review, a final set of 34 core papers directly aligned with the focal themes of blood supply, resilience, and risk management was selected for in-depth analysis. This final selection phase was performed qualitatively with expert judgment to ensure thematic relevance and scientific rigor. The search covered the period 2000–2025 and was limited to English-language publications, including both academic and grey literature to minimize publication bias. Figure 1 illustrates the PRISMA flow diagram.

The study selection process followed the PRISMA flow diagram (Page *et al.*, 2021). After removing duplicates, the initial screening was performed based on the title and abstract. In the next stage, the full text of articles meeting the initial criteria was reviewed for final evaluation and eligibility determination. The inclusion and exclusion criteria were precisely defined, encompassing studies that examined resilience strategies and risk management in the blood supply chain. The methodological quality and risk of bias of the included studies were independently assessed by two researchers using standard tools such as the Cochrane Risk of Bias Tool for experimental studies and ROBINS-I for observational studies; discrepancies were resolved through discussion or consultation with a third researcher (Higgins *et al.*, 2019).

Data extraction was conducted using a standardized form designed for this study, which included information on study characteristics, methodology, study population, interventions, and outcomes. Due to the inherent heterogeneity of studies in the blood supply chain field in terms of methodology and measured outcomes, qualitative synthesis (narrative combination) was employed to aggregate and present the findings. In this method, the findings of different studies were organized and analyzed within key themes and concepts. The application of the PRISMA framework increased the transparency, reduced bias, and enhanced the methodological quality of this review study, providing a comprehensive report on the systematic review process (Liberati *et al.*, 2009; Page *et al.*, 2021).

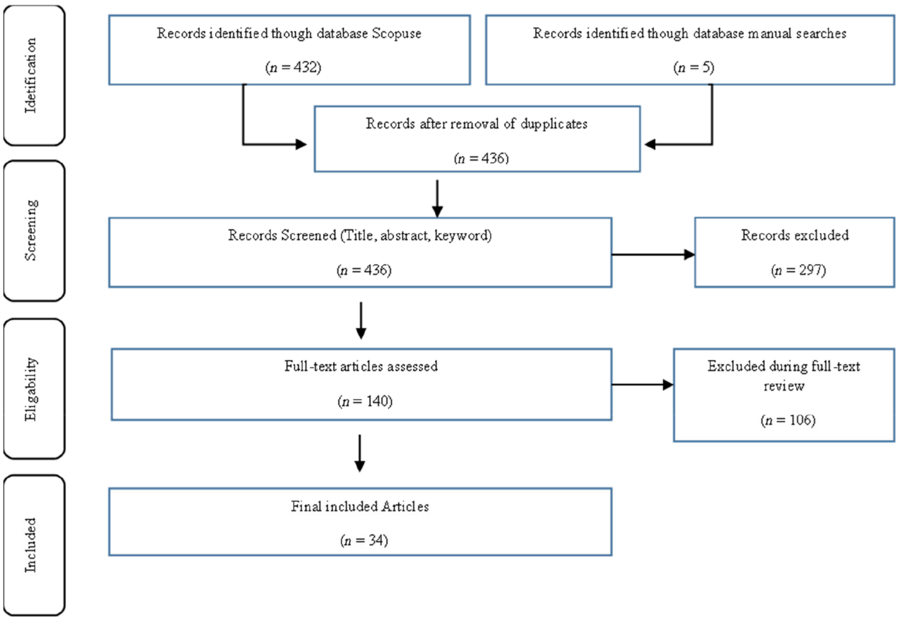


**Figure 1.** PRISMA flow diagram of the systematic review process

## Findings

The initial set of findings first includes the statistical data of the reviewed articles. Figure 2 presents the research trends and geographical scope.

Figure 3 shows the document types and thematic scope.

Statistical data indicate a significant growth in the volume of published articles over the past years, with researchers from Iran and the United States holding the largest share in this field. Furthermore, Computer Science, Decision Making, Engineering, and Management have been the most relevant domains to the blood supply chain, and the majority of published documents are in the form of journal articles. In the next section, the data obtained from scientometrics and bibliometrics will be examined, revealing the related keywords and shared thematic areas. Figure 4 shows the keyword co-occurrence map.

Figure 5 presents the keyword cloud map.

Figure 6 shows the full keyword cluster map.

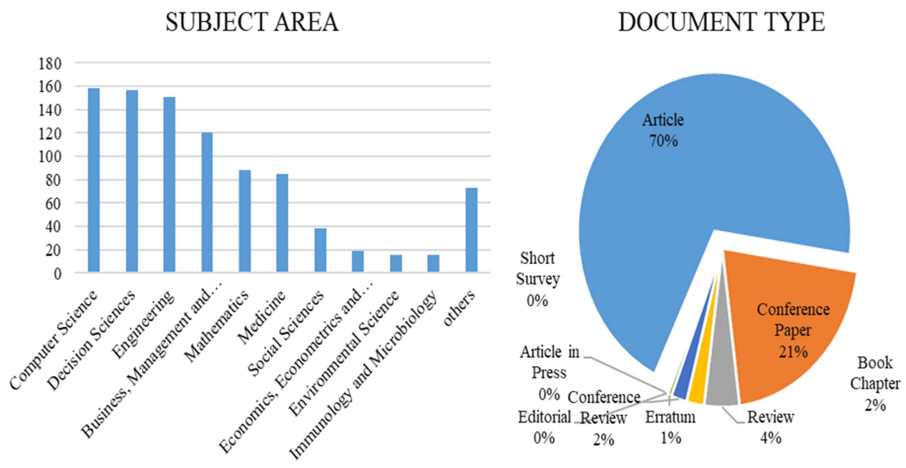


**Figure 2.** Trend of research studies over the years and geographical scope of published research

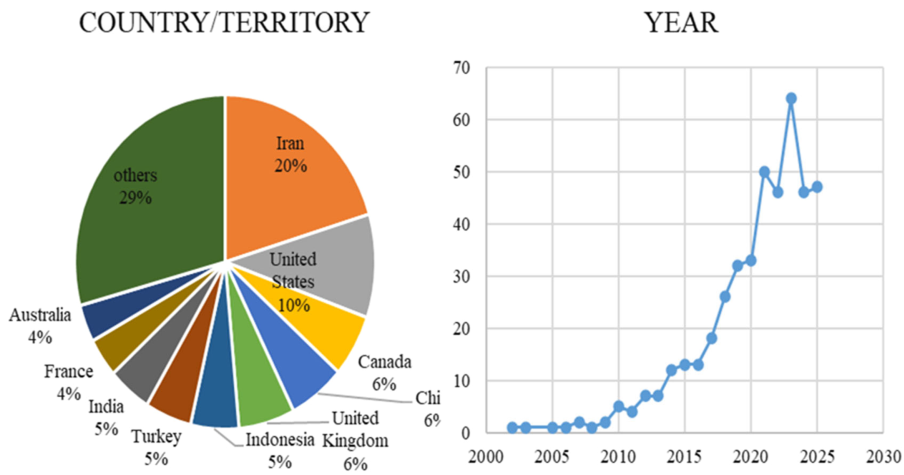


**Figure 3.** Document type and thematic scope of published research

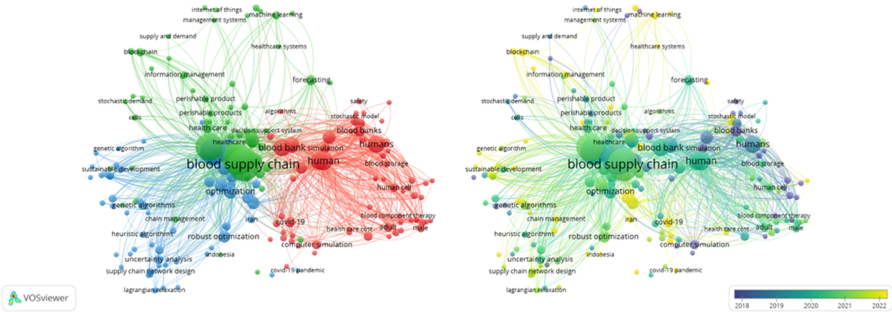


**Figure 4.** Co-occurrence scientometric map of keywords in the blood supply chain field based on clusters and time spectrum


**Figure 5.** Keyword cloud map of related keywords in the blood supply chain field

Temporal analysis of the maps reveals that in recent years, research focus has shifted toward Machine Learning and specific optimization algorithms such as Metaheuristic and Genetic algorithms. The revised analysis establishes a coherent conceptual connection between the co-occurrence maps and the thematic structure of the blood supply chain literature. The three primary clusters identified in the maps represent distinct subdomains: (1) engineering-focused studies emphasizing network design, optimization, and information management; (2) human-oriented research addressing donation, distribution, and behavioral aspects; and (3) emerging theoretical approaches concerning uncertainty, stochastic modeling, and predictive decision-making under risk. These clusters were systematically linked to the quantitative and qualitative outcomes of the systematic review, forming an integrated analytical framework that harmonizes scientometric insights with the central themes of the field. Temporal analysis further indicates a post-2019 shift in research focus from classical optimization models toward digital and data-driven paradigms such as artificial intelligence, blockchain, and smart analytics reflecting the field's ongoing transition from static network design to adaptive and intelligence-enabled supply chain management. Overall, the integrated interpretation demonstrates that the cluster analysis extends beyond descriptive keyword mapping, functioning as a diagnostic tool for tracing conceptual progressions, thematic evolutions, and research gaps. By aligning high-frequency terms with systematic review findings, the revised framework clarifies the maturity and deficiencies across key topics, thereby bridging the earlier divide between scientometric

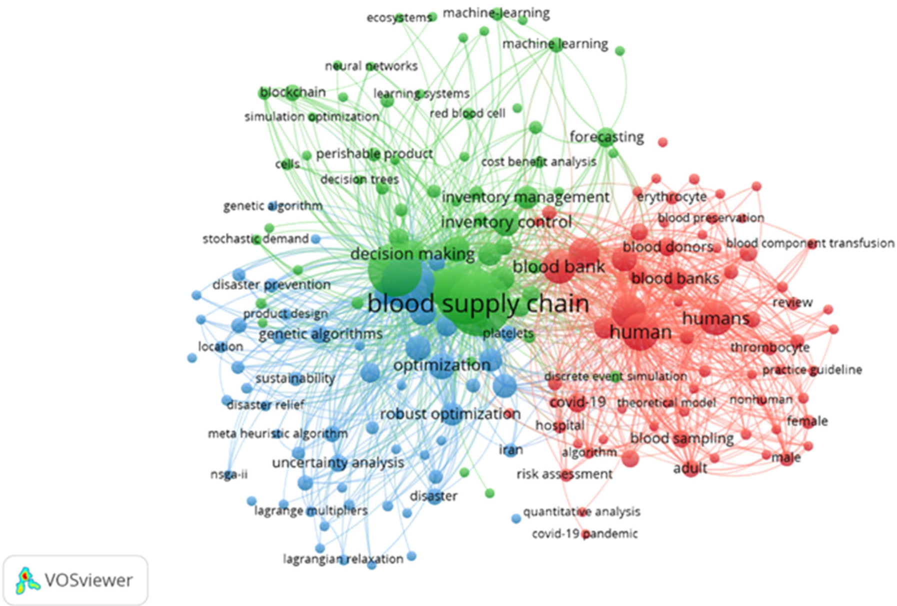


**Figure 6.** Full cluster scientometric map of keywords in the blood supply chain field

evidence and analytical discussion. Consequently, the updated manuscript presents a cohesive narrative illustrating how scientometric analysis enhances understanding of the principal research domains blood bank operations and safety, intelligent and integrated blood supply chain management, and resilient and sustainable network design under disruptions while outlining emerging directions and unresolved challenges within the field.

## Clustering of blood supply chain articles

Based on the scientometric maps, three main clusters can be identified for this domain:

*Cluster 1: blood bank operations and safety*

This cluster primarily focuses on the operational and clinical aspects of blood supply chain management at the hospital or blood center level. Key concepts include blood inventory management (e.g. platelets and red blood cells), transfusion safety, transfusion reactions, and standard practices in blood banking. The use of mathematical models, computer simulation, and operations research for optimizing processes like blood storage, preservation, and distribution is prominent in this cluster. Attention to the COVID-19 pandemic also highlights how health crises affect these operations. This cluster includes the following sub-clusters:

(1) Inventory Management and Operations Optimization: Keywords include blood inventory management, blood storage, computer simulation, operations research, mathematical model.

(2) Transfusion Safety and Clinical Issues: Keywords include blood safety, blood transfusion reaction, practice guideline, risk assessment, transfusion medicine.

(3) Blood Donation and Donor Management: Keywords include blood donor, blood donors, blood collection.

*Cluster 2: intelligent and integrated blood supply chain management*

This cluster clearly focuses on modern and technology-driven concepts in blood supply chain management. Its core centers on utilizing technologies such as Artificial Intelligence (AI), Machine Learning, Internet of Things (IoT), and Blockchain to enhance efficiency, accurate demand forecasting, and management of perishable products. Issues like managing demand uncertainty, decision support, and supply chain optimization using advanced analytical and simulation methods are the main features of this cluster. This cluster includes the following sub-clusters:

(1) Digital Technologies and Smartization: Keywords include artificial intelligence, machine learning, internet of things, blockchain, rfid.

(2) Demand Forecasting and Inventory Management under Uncertainty: Keywords include demand forecasting, stochastic demand, perishable inventory, inventory control.

(3) Advanced Optimization and Simulation for Decision Making: Keywords include simulation optimization, decision support systems, two-stage stochastic programming.

*Cluster 3: resilient and sustainable network design under disruptions*

This cluster focuses on strategic design and macro-level planning of the blood supply chain network. The main component is addressing conditions of high uncertainty, disasters, and crises (such as the COVID-19 pandemic) and designing a resilient and sustainable network. The main axes of this cluster include the use of advanced mathematical programming models (such as two-stage stochastic programming, probabilistic programming, robust programming, multi-objective), metaheuristic algorithms for solving complex problems, and topics like facility location, vehicle routing, and equitable distribution of resources in emergency situations. The proposed sub-clusters are:

(1) Multi-objective Programming and Network Design under Uncertainty: Keywords include multi-objective optimization, robust optimization, stochastic programming, blood supply chain network design.

(2) Crisis Management and Disaster Relief Logistics: Keywords include disaster management, disaster relief, emergency services, vehicle routing problem.

(3) Application of Metaheuristic Algorithms for Complex Problem Solving: Keywords include genetic algorithm, meta heuristic algorithm, nsga-ii, heuristic algorithms.

Cluster analysis indicates that risk management represents a more general concept appearing across all three clusters, and can therefore be considered a common theme among them. In contrast, the concept of resilience is explicitly discussed in the context of disruptions and is depicted only within Cluster 3. In the next step, we will focus more specifically on articles addressing both risk and resilience to examine this topic in greater depth. After the initial review of articles in the blood supply chain domain using the PRISMA method, 34 final articles were selected. The table below categorizes and analyzes the articles based on six key indicators:

Based on the table above (Table 4), the statistical analysis of articles in the field of risk management and resilience in the blood supply chain, according to the 6 indicators, is as follows:

Figure 7 shows the frequency distribution by main approach.

(1) Frequency Distribution by "Main Approach"

The research domain is strongly rooted in mathematical modeling and optimization, indicating a focus on providing quantitative and practical solutions for supply chain design and management. Qualitative approaches mainly focus on risk identification and providing conceptual frameworks.

**Table 4.** Analysis table of articles based on different indicators

| No | Article title | Main approach | Type of uncertainty/Context | Focus area | Main objective | Key method/Tool | Study context (case study) |
|---|---|---|---|---|---|---|---|
| 1 | A possibilistic programming approach . . . | Quantitative, Optimization | Possibilistic (Fuzzy), Periodic | Platelet Inventory Management, Clustering | Optimizing the Platelet Supply Chain considering Uncertainty | Possibilistic Programming, Clustering Strategy | – |
| 2 | A quantitative analysis of the factors . . . | Data Analysis | Clinical Factors Affecting Demand | Demand Forecasting | Quantitative analysis of clinical factors affecting blood demand | Quantitative Analysis, Probably Regression | Suzhou, China |
| 3 | A data-driven approach to optimize . . . | Quantitative, Optimization | Stochastic, Industry 5.0 | Data-Driven Supply Chain Design | Optimizing the Supply Chain within the Industry 5.0 Framework | Stochastic Optimization, Data-Driven Approach | – |
| 4 | Hybrid neural network-based metaheuristics . . . | Quantitative, Optimization | Pre-disaster | Resilient Supply Chain Design | Designing a resilient supply chain prior to a disaster | Neural Network-based Metaheuristics | Case-specific (Probably Iran) |
| 5 | Resilient coordination of test sampling . . . | Quantitative, Optimization | Distributionally Robust | Coordination of Testing and Requirement Fulfillment | Resilient coordination of the laboratory supply chain under worst-case scenario | Soft Worst-Case Distributionally Robust Optimization | – |
| 6 | Blood under pressure . . . | Qualitative, Review | Climate Change | Environmental Risks | Reviewing climate change threats on blood safety and supply chains | Qualitative Analysis, Review | – |
| 7 | Optimization Strategy of Supply Chain . . . | Quantitative, Optimization | – | Network Design, Timeliness, Blood Compatibility | Network optimization considering time and blood compatibility | Mathematical Programming | – |
| 8 | A column generation-based approach . . . | Quantitative, Optimization | Adaptive-Stochastic | Donor Management, Customization | Solving the customized blood donation problem under uncertainty | Column Generation | – |
| 9 | Blood supply chain configuration . . . | Quantitative, Optimization | COVID-19 Pandemic | Supply Chain Configuration and Optimization | Optimizing the supply chain during the COVID-19 pandemic | Benders Decomposition-based Heuristic Algorithm | – |

(*continued*)

**Table 4.** Continued

| No | Article title | Main approach | Type of uncertainty/Context | Focus area | Main objective | Key method/Tool | Study context (case study) |
|---|---|---|---|---|---|---|---|
| 10 | Insights and lessons from recent conflicts . . . | Qualitative, Narrative Review | Military Conflicts | Military Medicine, Lessons Learned | Reviewing lessons learned from conflicts for military medicine | Narrative Review | Recent Conflicts |
| 11 | LOGISTICS NETWORK DESIGN FOR . . . | Quantitative, Simulation | Disasters | Sustainable Logistics Network Design | Designing a sustainable logistics network for the blood supply chain under disasters | Simulation | – |
| 12 | An Integrated Supply Chain Model . . . | Quantitative, Integrated | – | Demand and Supply Forecasting, Distribution | Integrated forecasting of supply and demand and optimization of blood distribution | Integrated Model, Forecasting, Optimization | – |
| 13 | Designing a responsive-sustainable-resilient . . . | Quantitative, Optimization | Congestion | Responsive-Sustainable-Resilient Network Design | Designing a triple-objective network (Responsive, Sustainable, Resilient) | Linear Regression for Congestion Modeling | – |
| 14 | Prioritizing Barriers to Resilience . . . | Qualitative-Quantitative, MCDM | – | Prioritization of Resilience Barriers | Prioritizing resilience barriers in the blood supply chain | Multi-Criteria Decision Making (MCDM) | – |
| 15 | Bloodmobile location selection . . . | Qualitative-Quantitative, MCDM | – | Bloodmobile Location Selection | Selecting bloodmobile locations for a resilient supply chain | Spherical Fuzzy AHP + Spherical Fuzzy COPRAS | – |
| 16 | Reliable design of humanitarian supply chain . . . | Quantitative, Optimization | Correlated Disruptions | Humanitarian Supply Chain Design | Reliable design of the supply chain under correlated disruptions | Two-stage Distributionally Robust Optimization | – |
| 17 | Embracing scepticism as a non-physical . . . | Qualitative, Case Study | Trust Gap (Skepticism) | Organizational Resilience, Trust Management | Examining skepticism as a non-physical form of redundancy | Qualitative Case Study | UK Blood Supply Chain |

*(continued)*

**Table 4.** Continued

| No | Article title | Main approach | Type of uncertainty/Context | Focus area | Main objective | Key method/Tool | Study context (case study) |
|---|---|---|---|---|---|---|---|
| 18 | Multivariate time-series blood donation . . . | Quantitative, Forecasting | COVID-19 Pandemic | Multivariate Donation/ Demand Forecasting | Multivariate time-series forecasting of donation and demand for resilient management | Multivariate Time-Series Forecasting | – |
| 19 | Measuring the sustainability and resilience . . . | Qualitative-Quantitative | – | Measuring Sustainability and Resilience | Providing metrics for measuring sustainability and resilience | Probably Assessment/ Measurement Method | – |
| 20 | Integrating GIS in reorganizing blood supply . . . | Quantitative, Integrated | Disruptions, Robust-Stochastic Approach | Network Redesign with GIS | Redesigning the blood supply network with Geographic Information System | GIS, Robust-Stochastic Programming | – |
| 21 | Developing a Risk Reduction Support System . . . | Qualitative, Case Study | – | Health System Risk Management | Developing a Risk Reduction Support System for the Health System | Case Study | Iran (Blood Supply Chain) |
| 22 | An enhanced framework for blood supply chain . . . | Qualitative, Framework | – | Risk Management | Providing an enhanced framework for risk management | Qualitative Framework | – |
| 23 | A structured approach to analyse logistics risks . . . | Qualitative, Risk Analysis | – | Logistics Risks in Blood Transfusion | Structured analysis of logistics risks in the blood transfusion process | Structured Risk Analysis | – |
| 24 | A resilient approach to modelling the supply . . . | Quantitative, Modeling | – | Platelet Supply and Demand Modeling | Resilient modeling of platelet supply and demand | Mathematical Modeling | United Kingdom |
| 25 | Design Mitigation and Monitoring System . . . | Qualitative, Framework | – | Operational Risk Management | Designing a risk mitigation and monitoring system using SCOR and HOR | SCOR Model and House of Risk (HOR) | – |

(*continued*)

**Table 4.** Continued

| No | Article title | Main approach | Type of uncertainty/Context | Focus area | Main objective | Key method/Tool | Study context (case study) |
|---|---|---|---|---|---|---|---|
| 26 | A mixed resilient-efficient approach . . . | Quantitative, Optimization | – | Supply Chain Network Design | Network design simultaneously considering resilience and efficiency | Multi-objective Mathematical Programming | – |
| 27 | Robust design of blood supply chains . . . | Quantitative, Optimization | Risk of Disruptions | Robust Supply Chain Design | Robust design of the supply chain under risk of disruptions | Lagrangian Relaxation | – |
| 28 | Managing Blood Safety and Availability . . . | Qualitative, Case Study | – | Supply Chain Dynamics | Preliminary investigation of blood supply chain dynamics | Case Study, Systems Analysis | Indonesia |
| 29 | Blood supply chain risk management using . . . | Qualitative, Framework | – | Risk Management | Blood supply chain risk management using the House of Risk model | House of Risk (HOR) Model | – |
| 30 | A perishable product supply chain network . . . | Quantitative, Optimization | Disruptions, Reliability | Network Design for Perishable Products | Network design considering reliability and disruptions | Mathematical Programming | – |
| 31 | A resilient donor arrival policy for blood | Quantitative, Modeling | – | Donor Policies | Developing a resilient policy for donor arrival scheduling | Policy Modeling | – |
| 32 | Design mitigation of blood supply chain . . . | Qualitative, Framework | – | Supply Chain Risk Management | Designing risk mitigation strategies using the SCRM approach | Supply Chain Risk Management (SCRM) Approach | – |
| 33 | The inventory centralization impacts . . . | Quantitative, Modeling | – | Inventory Centralization/ Decentralization, Sustainability | Analyzing the impact of inventory centralization on blood supply chain sustainability | Modeling | – |
| 34 | Malaria and blood transfusion . . . | Qualitative, Review | Malaria Endemic Areas | Blood Safety, Risk Mitigation | Examining blood safety issues and malaria risk mitigation strategies | Qualitative Review | Malaria Endemic Countries |

(2) Frequency Distribution by "Main Focus Area"

Figure 8 shows the frequency distribution by main focus area.

The dominant focus of the articles is on strategic network design and integrated risk management, which form the core challenge of resilience.

(3) Frequency Distribution by "Key Method/Tool"

Figure 9 shows the frequency distribution by key method/tool.

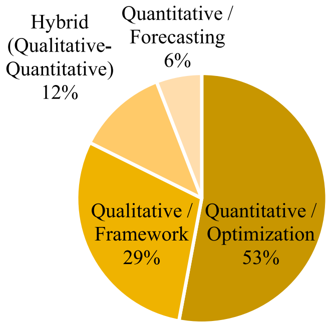


**Figure 7.** Frequency distribution by "main approach"

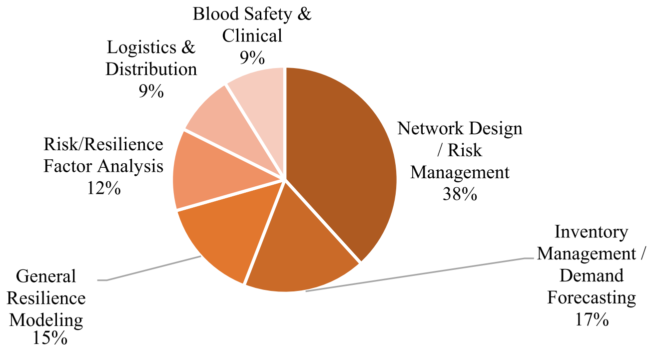


**Figure 8.** Frequency distribution by "main focus area"

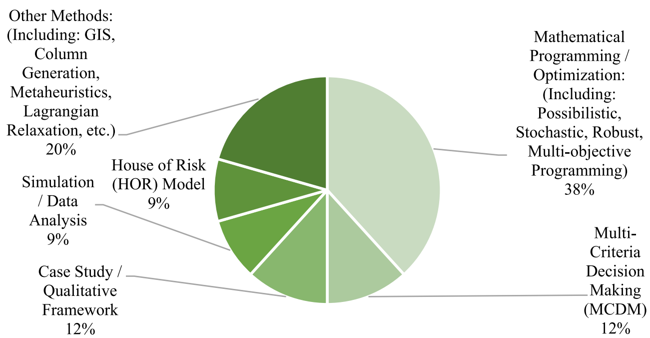


**Figure 9.** Frequency distribution by "key method/tool"

Powerful optimization tools, such as programming under uncertainty, are the primary methods for tackling the complexity of the problem.

(4) Frequency Distribution by "Study Context (Case Study)"

Figure 10 shows the frequency distribution by study context.

Although a significant portion of the articles are theoretical, field studies—especially in Iran, the UK, and Indonesia—have contributed substantial richness to the literature, highlighting the importance of localizing solutions.

(5) Frequency Distribution by "Type of Uncertainty/Modeled Risk"

Figure 11 shows the frequency distribution by type of uncertainty or modeled risk.

The risk of widespread disruptions (disasters) and inherent demand uncertainty are the two main categories of risks that articles have focused on modeling and managing.

## Conclusion

By reviewing the titles of the 34 selected articles, it is evident that the field of Risk Management and Resilience in the blood supply chain is a highly dynamic and applied research area, seeking to address both the inherent challenges of this chain (such as product perishability, demand and supply uncertainty) and external shocks (such as disasters, pandemics, and conflicts). These articles can be broadly categorized into two groups: Conceptual-Policy-based and Quantitative-Optimization-based. The first group includes articles that offer qualitative frameworks, risk

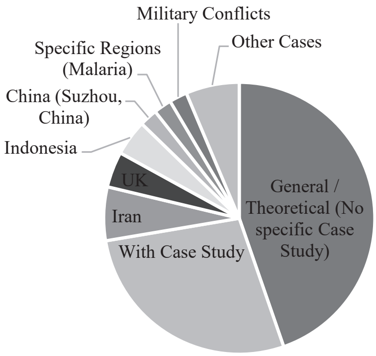


**Figure 10.** Frequency distribution by "study context (case study)"

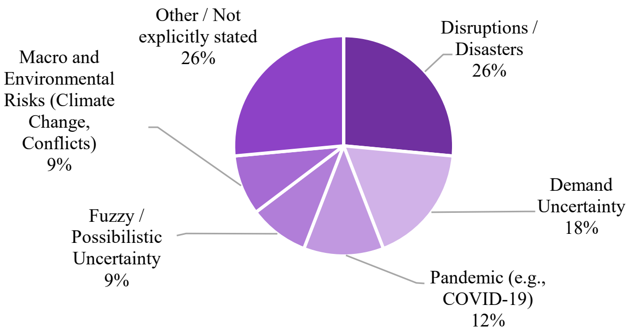


**Figure 11.** Frequency distribution by "type of uncertainty/modeled risk"

modeling, prioritization of threatening factors, and lessons learned from real crises. Articles such as "Embracing scepticism as a non-physical form of redundancy" (Lusiantoro and Yates, 2024), "Insights and lessons from recent conflicts" (assumed to be a relevant paper in military/crisis logistics), and "Blood under pressure: how climate change threatens blood safety" (Viennet *et al.*, 2025) indicate that the perspective on risk extends beyond mathematical models to encompass social dimensions (e.g. trust gap), geopolitical (military conflicts), and even long-term global threats (e.g. climate change). Approaches like the House of Risk (HOR) model and the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) are powerful tools for identifying and prioritizing risks in this area.The second group, which constitutes the majority of articles, focuses on developing risk-averse and resilient models for the design and optimization of the blood supply chain network. The core of these articles is the integration of various uncertainties (stochastic, fuzzy, robust) into mathematical programming models (such as two-stage stochastic programming, chance-constrained programming, robust programming) and the use of powerful solution algorithms (such as Bender's decomposition, Lagrangian Relaxation, metaheuristics, and neural networks). The ultimate goal of these models is to design a network that simultaneously pursues multiple criteria: resilience (resistance to disruptions and rapid recovery), responsiveness (timely blood supply), sustainability (waste reduction, attention to social and environmental dimensions), and economic efficiency. Concepts such as "location-allocation" of blood collection and distribution centers, "routing" of vehicles, decentralized "inventory management," and "donor policies" under crisis conditions are among the key topics addressed by these models. In summary, the current literature suggests that the future approach is moving toward integrated, data-driven, and intelligent models that can dynamically and proactively keep the blood supply chain safe and stable against a wide range of risks.

## Final summary and future research

This study utilized the rigorous PRISMA methodology to review and analyze the literature on risk management and resilience in the blood supply chain. The careful screening process of 436 initial articles ultimately led to the selection of 34 key, highly relevant articles that form the core body of work in this field. Initial scientometric analysis mapped the conceptual landscape, and in-depth content analysis of the final articles revealed valuable insights. Dominance of Quantitative and Solution-Oriented Approaches: The findings indicate that the literature is heavily dominated by quantitative approaches (53%) and mathematical modeling. This suggests that researchers primarily concentrate their efforts on providing operational and optimized solutions for the complex challenges of the blood supply chain. The main tools are advanced mathematical programming models under uncertainty (stochastic, robust, possibilistic, and multi-objective). Focus on Strategic Resilient Network Design: The most prominent focus area in the selected articles is "Supply Chain Network Design" (38%). This emphasizes that the foundation of a resilient supply chain lies in its initial design and configuration. Research stresses that the network must be designed from the outset to resist disruptions and quickly regain its efficiency.

Wide Spectrum of Risks Considered: The reviewed articles addressed a broad range of risks, from routine operational risks like demand uncertainty to catastrophic risks such as natural disasters, pandemics (like COVID-19), and even the impacts of climate change. This demonstrates the field's maturity in identifying diverse threats. Existence of a Gap Between Theory and Field Application: Despite the wealth of theoretical models, about 62% of the articles lacked a specific case study. This highlights the urgent need for the validation of these models in real-world contexts and the local settings of different countries. Existing case studies primarily focused on specific countries such as Iran, the UK, and Indonesia.

The dominance of mathematical modeling approaches (52.9%) demonstrates the technical maturity of the blood supply chain (BSC) research domain; however, it simultaneously highlights a clear gap between theoretical knowledge and practical implementation. Most studies remain at the conceptual design level and rarely incorporate real network data, indicating that the translation of theoretical models into operational practice is still limited. While this quantitative emphasis has contributed to the accumulation of computational expertise, it has constrained the theoretical growth of the field particularly the development of a coherent framework explaining the interaction between risk and resilience in BSCs. From an applied perspective, the findings reveal that current research remains noticeably distant from the practical needs of blood centers. Future directions should therefore prioritize the integration of mathematical modeling with empirical data and human-based decision frameworks, allowing models to become more realistic, validated, and context-sensitive. Within the paper, this interpretation is extended through a multi-layered knowledge development cycle covering theoretical, methodological, and practical dimensions to clarify how the dominance of quantitative paradigms affects each level. At the theoretical level, the prevalence of computational methods has led to an algorithmic and model-oriented body of knowledge that is precise, quantifiable, and replicable. Nonetheless, this emphasis has limited the incorporation of behavioral, managerial, and social perspectives into the discourse. The field consequently needs a quantitative–qualitative integration paradigm that bridges numerical modeling with managerial and decision-support reasoning, advancing the literature from descriptive optimization toward strategic governance. At the methodological and practical levels, the focus on optimization tools has generated operationally applicable approaches for network design, facility location, and resource allocation. However, since only 38% of the studies include case-based validation, the gap between modeling and field application persists. This finding underscores the need for practice-driven modeling, where empirical validation and contextual adaptation strengthen the relevance and reliability of analytical outcomes in real healthcare environments. Finally, at the theoretical development layer, the predominance of computational paradigms has entrenched the paradigm of "optimized resilience," often neglecting the human, social, and ethical dimensions of the BSC. This has resulted in a conceptual divide between physical network resilience and institutional or human resilience. Addressing this imbalance requires a multidimensional theoretical expansion linking mathematical models with behavioral decision-making theories, social sustainability principles, and health equity considerations. In conclusion, while the prevalence of quantitative modeling has brought structural coherence and analytical rigor to the field, it also opens an opportunity for transition toward a hybrid and intelligent paradigm, where hard modeling techniques and soft managerial dimensions complement one another to enable a more holistic, effective, and context-aware understanding of blood supply chain resilience.

The present review reveals a critical deficiency within the literature on blood supply chain management: the absence of field validation and real-world empirical studies. Despite their mathematical sophistication, many optimization and simulation models remain highly theoretical and fail to align with the dynamic realities and operational constraints of blood transfusion centers. As a result, these models often lack reliability for practical application. This gap has serious implications across multiple levels of decision-making operational, policy, and emergency planning all of which depend on the timely, resilient, and safe functioning of blood networks. At the operational level, the lack of empirical validation demonstrates that existing optimization frameworks rarely capture the variability and logistical constraints experienced by real blood service organizations. Consequently, there is an urgent need for context-specific decision-support tools capable of predicting and optimizing system performance under crisis conditions such as donor shortages, distribution disruptions, or pandemics. The findings offer a foundation for developing smart allocation platforms and AI-based decision-support systems that can enhance operational efficiency and reliability in blood service institutions. At the policy level, the scarcity of field data limits policymakers' understanding of how resilience-building strategies perform in practice. This results in policy decisions lacking empirical justification, for example in designing backup contracts, locating blood storage centers, or allocating resources during emergencies. The study therefore recommends integrating real operational data into optimization frameworks to promote evidence-based policy making enabling more informed, data-driven decisions in national blood management systems. For emergency planners, the absence of real-world validation undermines the predictive capacity of theoretical models in large-scale crises such as pandemics or disasters. Without calibration from actual logistical and crisis data, such models cannot reliably guide emergency blood redistribution or timing of response strategies. Accordingly, the research emphasizes combining mathematical modeling with realistic crisis scenarios and operational data to create predictive resilience models that support more effective crisis-response planning in health and relief agencies. Overall, the study's revised conclusions highlight that the lack of real-world validation is not only a scientific gap but also a systemic challenge that affects the effectiveness, safety, and public trust in blood supply networks. Bridging this divide through empirical studies and data-driven model calibration can directly enhance the reliability and resilience of blood supply systems ultimately safeguarding patient lives.

Overall, this research provides a clear picture of a dynamic and vital research field that seeks to combine the precision of mathematical models with operational and crisis considerations for saving human lives. The findings suggest that the prevailing paradigm is a shift toward designing integrated, intelligent, and multi-objective networks that simultaneously pursue resilience, sustainability, and efficiency. Based on the findings of this study, future research can focus on addressing the identified gaps:

(1) Development of Dynamic and Predictive Models: Leveraging Artificial Intelligence (AI) and long-term data analysis to develop dynamic and predictive models can be the next step beyond the current static optimization models.

(2) Integration of Social Sustainability Metrics: Incorporating metrics of social sustainability such as equity in blood access and fair treatment of donors as an objective alongside resilience and economic sustainability, is an essential and nascent area.

(3) Conducting Comparative Field Studies: Performing comparative field studies to test the effectiveness of the proposed models in different geographical-cultural contexts and under real crisis scenarios.

(4) Exploring Novel Technologies: Investigating the role of emerging technologies like Blockchain for transparency and complete traceability of blood from the donor to the patient, which can pave promising research avenues for increasing the reliability of this critical chain.

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**Corresponding author**
Mohammad Reza Fathi can be contacted at: reza.fathi@ut.ac.ir