

REVIEW ARTICLE

Resilience strategies for healthcare supply chains: Lessons from global crises and future directions

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Abstract

Healthcare supply chains are critical infrastructures that ensure the availability of medicines, medical devices, and essential consumables for patient care. However, recent global crises, including the COVID-19 pandemic, geopolitical conflicts, and natural disasters, have exposed significant vulnerabilities in their structure and functioning. This paper provides a narrative review of resilience strategies in healthcare supply chains, highlighting lessons learned from past disruptions and exploring approaches to strengthen preparedness for future challenges. Key themes discussed include supplier diversification, inventory optimization, digitalization and real-time data sharing, local sourcing, and collaborative partnerships across public and private stakeholders. Particular attention is given to the role of risk management frameworks, predictive analytics, and sustainable practices in enhancing flexibility and responsiveness. Despite a growing body of literature, existing reviews often remain thematically narrow, crisis-specific, or fail to integrate sustainability and equity dimensions, limiting their applicability for future system-wide preparedness. By integrating technological innovation with organizational and behavioral strategies, this review aims to contribute to the development of robust supply chain systems that can withstand future global shocks.

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1. Introduction

Healthcare supply chains form the backbone of modern health systems, ensuring that medicines, medical devices, and essential consumables are delivered where and when they are needed.¹ Their seamless functioning directly influences the quality, accessibility, and continuity of patient care. However, recent global crises have exposed the fragility of these systems. The COVID-19 pandemic, for example, revealed critical bottlenecks in the supply of personal protective equipment, ventilators, and vaccines.² Geopolitical conflicts and trade restrictions have further disrupted the flow of raw materials and finished products, while natural disasters continue to cause sudden, unpredictable supply disruptions.³

These events highlight the pressing need to strengthen the healthcare supply chain resilience. In this context, resilience is understood not merely as the ability to recover from disruptions but also as the capacity to anticipate risks, adapt dynamically to shocks, and maintain essential services under adverse conditions. Unlike traditional supply chain models that prioritize efficiency and cost reduction, resilient systems aim for flexibility, redundancy, and adaptability.

The objective of this review is to synthesize current knowledge on resilience strategies in healthcare supply chains, drawing lessons from past crises and identifying opportunities for innovation. Particular emphasis is placed on supplier diversification, inventory optimization, digitalization, real-time data sharing, local sourcing, and collaborative partnerships. Moreover, the review considers the role of risk management frameworks, predictive analytics, and sustainable practices in building supply chains that are not only robust but also future-ready.

While several previous reviews have examined healthcare supply chain resilience—often focusing on isolated dimensions such as inventory management, digitalization, or pandemic-related disruptions—most studies adopt a fragmented perspective or are limited to specific crises or high-income settings. In contrast, the present review provides a comprehensive and integrative synthesis that bridges multiple dimensions of resilience, including structural, technological, organizational, and sustainability-oriented strategies.

Additionally, unlike prior reviews that primarily describe resilience mechanisms, this study advances the field by proposing a conceptual roadmap that connects digital intelligence, local adaptability, collaborative governance, and sustainability within a unified framework. Particular emphasis is also placed on equity and low-resource contexts, which remain underexplored in existing literature. By combining lessons from diverse global crises with forward-looking strategies, this review aims to move beyond descriptive analysis toward a more holistic and actionable framework for future healthcare supply chain resilience.

By consolidating insights from global experiences and highlighting persistent gaps, especially in low-resource contexts, this paper seeks to provide a conceptual roadmap for designing healthcare supply chains that are adaptive, collaborative, and sustainable. Strengthening these critical infrastructures is vital to ensure preparedness for future shocks and to safeguard the resilience of health systems worldwide.

For clarity, key concepts used throughout this review

are defined as follows. Resilience in healthcare supply chains refers to the capacity to anticipate, absorb, adapt to, and recover from disruptions while maintaining the continuity of essential services. This extends beyond simple recovery to include proactive preparedness and adaptive transformation.

Redundancy is understood as the intentional incorporation of additional capacity, resources, or alternative options, such as multiple suppliers or buffer stock, to ensure system functionality in the event of disruptions. While redundancy enhances robustness, it may come at the expense of efficiency and cost.

Sustainability refers to the ability of healthcare supply chains to operate in a manner that meets present needs without compromising future generations, integrating environmental, economic, and social dimensions. In this context, sustainability is closely linked to resilience, as long-term system viability depends on both adaptive capacity and responsible resource use.

1.1. Search strategy and selection approach

This study is a narrative (non-systematic) review aimed at providing a conceptual and integrative synthesis of resilience strategies in healthcare supply chains. Unlike systematic literature reviews that follow structured protocols such as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), this review adopts a thematic and interpretative approach, focusing on integrating evidence across multiple domains, including risk management, digitalization, and sustainability.

A targeted literature search was conducted using databases such as PubMed, Scopus, and Web of Science, focusing on studies published in recent years addressing healthcare supply chain resilience. Keywords included combinations of “healthcare supply chain,” “resilience,” “risk management,” “predictive analytics,” and “sustainability.”

Relevant articles were selected based on their conceptual relevance, methodological rigor, and contribution to key themes. Priority was given to recent studies, high-impact journals, and papers addressing global crises such as the COVID-19 pandemic.

Given the narrative nature of this review, no formal inclusion/exclusion criteria or PRISMA flow diagram were applied. Instead, the objective was to provide a comprehensive and integrative overview rather than an exhaustive systematic synthesis.

2. Vulnerabilities in healthcare supply chains

Healthcare supply chains are uniquely complex due to

the diversity of products, strict regulatory requirements, and the critical importance of timeliness in delivering life-saving goods. Despite their central role, global crises in recent decades have revealed deep vulnerabilities that threaten the continuity of care and the system's resilience.

2.1. Lessons from the COVID-19 pandemic

The COVID-19 pandemic underscored severe weaknesses in global healthcare supply chains. Overdependence on limited suppliers and manufacturing hubs created bottlenecks, particularly in the supply of personal protective equipment, ventilators, and diagnostic tests.^{4,5} Lockdowns and border restrictions further disrupted global logistics, leading to delays in the delivery of raw materials and finished products. The crisis highlighted the risks of "just-in-time" inventory models, which, while cost-efficient, left many healthcare providers without critical stock during peak demand.⁶

2.2. Geopolitical conflicts and trade disruptions

Geopolitical tensions, such as trade wars, sanctions, and armed conflicts, have added new layers of uncertainty.⁷ The concentration of pharmaceutical ingredient production in a few countries makes supply chains vulnerable to political decisions, export bans, and regulatory shifts.⁸ Such dependencies pose risks not only for high-income nations but particularly for low- and middle-income countries, which often lack local manufacturing capacity and rely heavily on imports.^{9,10}

2.3. Natural disasters and climate-related risks

Natural disasters, including hurricanes, earthquakes, and floods, frequently disrupt healthcare supply chains by damaging infrastructure, halting production, and delaying transportation.¹¹ The increasing frequency of climate-related events amplifies these risks, raising concerns about long-term sustainability. Localized disasters can have global ripple effects when key suppliers or transport hubs are affected.¹² These disruptions often propagate across global supply networks, amplifying their impact beyond the immediate geographic area and affecting critical supply availability.¹³

2.4. Structural and systemic weaknesses

Beyond crisis-specific disruptions, systemic issues contribute to fragility. These include:

- Fragmentation of supply networks, with limited coordination among stakeholders.¹⁴
- Lack of transparency and real-time data, which hinders visibility across the supply chain.¹²
- Overreliance on efficiency-driven models, prioritizing cost savings over redundancy and preparedness.¹⁵

- Inequities in access, particularly in low-resource settings, where shortages are more acute, and recovery is slower.¹⁶

Taken together, these vulnerabilities reveal that healthcare supply chains are highly exposed to external shocks. Addressing these weaknesses requires a paradigm shift from efficiency-centered models to resilience-oriented frameworks that integrate technological innovation and organizational strategies. To better illustrate the range of disruptions and weaknesses exposed by recent global crises, [Table 1](#) summarizes the main types of shocks affecting healthcare supply chains, along with their associated impacts and vulnerabilities. This comparative view highlights how crises, whether biological, geopolitical, environmental, or systemic, converge to reveal common fragilities, such as overreliance on limited suppliers, inadequate risk planning, and insufficient coordination among stakeholders.

3. Resilience strategies in healthcare supply chains

In response to the vulnerabilities revealed by global crises, a variety of resilience strategies have been proposed and implemented across healthcare supply chains. Unlike efficiency-driven models that prioritize cost reduction, resilience-oriented approaches emphasize redundancy, flexibility, adaptability, and collaboration.¹⁷ These strategies aim to ensure continuity of supply under stress while also fostering long-term sustainability and equitable access.

Building resilient supply chains requires both structural adjustments, such as diversifying supplier networks and localizing production, and technological innovations, including predictive analytics and digital monitoring systems.¹⁸ Organizational and behavioral aspects, such as cross-sector collaboration and workforce adaptability, are equally essential.

3.1. Supplier diversification

One of the most frequently highlighted strategies for strengthening resilience is supplier diversification.¹⁹ Dependence on a limited number of vendors or geographic regions creates systemic risks, as disruptions in one area can cascade globally. For example, the heavy reliance on a handful of countries for active pharmaceutical ingredients was a critical vulnerability exposed during the COVID-19 pandemic, when export restrictions and production slowdowns led to widespread shortages.⁴

Supplier diversification mitigates such risks by spreading procurement across multiple regions and vendors, thereby reducing reliance on any single source. This approach can be operationalized through:

- Multi-sourcing arrangements, ensuring redundancy and flexibility in procurement.
- Regional balancing, combining global suppliers with local or regional alternatives.
- Dual sourcing of critical products, particularly for life-saving medicines and medical devices.

While diversification enhances robustness, it also introduces challenges. Managing multiple suppliers may increase costs and complexity, requiring robust governance mechanisms and transparent communication. Furthermore, in low-resource settings, the limited availability of alternative suppliers can restrict the feasibility of this approach.^{3,20}

Overall, supplier diversification is not a universal remedy but a foundational component of resilient healthcare supply chains. Its effectiveness is maximized when combined with other strategies, such as inventory optimization and digital monitoring, which together create a more adaptive and responsive system.

3.2. Inventory optimization

Inventory management is another critical lever for enhancing the resilience of healthcare supply chains.³ Traditionally, many health systems have adopted just-in-time models to minimize storage costs and improve efficiency. However, the COVID-19 pandemic revealed the fragility of this approach, as sudden surges in demand quickly depleted supplies of personal protective equipment, diagnostic reagents, and essential medicines.⁶

Resilient supply chains require a shift toward just-in-case or hybrid inventory models that balance efficiency with preparedness. This involves maintaining buffer stocks of critical items, supported by risk-based assessments of likely shortages. Strategic stockpiling at national, regional, or hospital levels has been shown to mitigate supply interruptions during emergencies, provided that systems are in place to ensure proper rotation and prevent wastage.^{21,22}

Key approaches to inventory optimization include: Risk-adjusted stockpiling, where product criticality, usage patterns, and disruption likelihood determine inventory levels; Dynamic inventory management, using predictive analytics and demand forecasting to align stock levels with real-time needs; Decentralized storage models, which distribute reserves across multiple locations to reduce vulnerability to localized disruptions; Vendor-managed inventory, where suppliers take responsibility for maintaining agreed stock levels at healthcare facilities.²³

Nevertheless, stockpiling and buffer strategies present challenges. They require significant financial investment,

infrastructure for climate-controlled storage, and governance to prevent misuse or inequitable distribution. Overaccumulation also risks product obsolescence, particularly for items with short shelf lives.

Ultimately, inventory optimization is about achieving a delicate balance: ensuring sufficient redundancy to withstand shocks without compromising efficiency or sustainability.²³ When combined with digital monitoring and collaborative planning, optimized inventory systems can provide both security in crises and efficiency in stable periods.

3.3. Digitalization and real-time data sharing

Digital transformation is increasingly recognized as a cornerstone of resilient healthcare supply chains.²⁴ The ability to track, analyze, and share data in real time enhances visibility across the supply network, reduces uncertainty, and enables proactive responses to disruptions. During the COVID-19 pandemic, supply chain blind spots, such as a lack of transparency on available stock levels and shipment delays, significantly hindered the timely allocation of critical resources.^{25,26}

Digital technologies such as blockchain, Internet of Things (IoT) sensors, cloud-based platforms, and artificial intelligence (AI) provide powerful tools to address these challenges. For example:

- Blockchain systems can improve traceability and trust by creating tamper-proof records of product origin, movement, and quality.²⁷
- IoT-enabled tracking allows real-time monitoring of inventory levels, shipment status, and environmental conditions (e.g., temperature control for vaccines).²⁸
- AI and machine learning algorithms enhance demand forecasting and predictive analytics, enabling decision-makers to anticipate shortages and adjust procurement strategies.²⁹
- Cloud-based platforms facilitate data integration across multiple stakeholders, supporting collaborative planning and resource sharing.³⁰

Digitalization also supports equitable allocation, as real-time data can guide decision-makers in prioritizing the distribution of scarce resources to the areas of greatest need.³¹ Furthermore, simulation tools and digital twins of supply networks can be employed to model potential disruptions and test response strategies before crises occur.³²

However, challenges remain in implementing digital solutions. These include interoperability issues between different systems, cybersecurity risks, high upfront investment, and disparities in digital infrastructure

between high- and low-resource settings. Without adequate governance and capacity building, digitalization risks deepening inequities rather than resolving them.^{33,34}

Despite these barriers, integrating digital technologies into healthcare supply chains is a critical step toward building transparent, adaptive, and proactive systems. When aligned with robust data governance frameworks, digitalization not only improves operational efficiency but also strengthens resilience to future global shocks.

3.4. Local sourcing and manufacturing

Another resilience strategy gaining prominence is the localization of sourcing and manufacturing.³⁵ Heavy dependence on globalized supply chains, while cost-efficient, has made healthcare systems highly vulnerable to international disruptions such as export bans, shipping delays, and geopolitical conflicts.³⁶ The COVID-19 pandemic clearly demonstrated this vulnerability when international restrictions on the export of personal protective equipment, vaccines, and active pharmaceutical ingredients created widespread shortages across countries with little or no domestic production capacity.³⁷

Local sourcing involves prioritizing procurement from domestic or regional suppliers, thereby reducing reliance on distant markets and complex logistics. Similarly, local manufacturing capacity—whether for essential medicines, medical devices, or consumables—can serve as a critical buffer during crises. Examples include national initiatives to produce ventilators and vaccines domestically during the pandemic, which reduced exposure to international supply volatility.^{3,38}

Key advantages of local sourcing and production include:

- Shorter lead times, improving responsiveness to surges in demand.
- Reduced transportation risks, lowering dependency on vulnerable trade routes.
- Improved supply security, particularly for essential or life-saving goods.
- Potential economic benefits, including job creation and regional industrial growth.

However, local manufacturing also presents challenges. Establishing production facilities requires substantial financial investment, regulatory alignment, skilled labor, and long-term commitment. Furthermore, small-scale or fragmented local production may lack the economies of scale and technological sophistication of global suppliers, potentially increasing costs.³⁹

To balance these trade-offs, hybrid models are emerging that complement global supply chains with regional

hubs. Such approaches aim to combine the efficiency of international trade with the resilience of localized production. Partnerships between governments, local industries, and global companies are particularly critical to making these initiatives sustainable.³

Overall, local sourcing and manufacturing strengthen the self-reliance and adaptability of healthcare supply chains, especially during global crises. When strategically integrated with supplier diversification and digital tools, they form a core component of a more balanced and resilient system. To highlight the strategic trade-offs, [Table 2](#) contrasts global and local sourcing models, showing how each contributes differently to cost, risk, and resilience considerations.

3.5. Collaborative partnerships

Collaboration across stakeholders is a cornerstone of resilient healthcare supply chains. No single actor—whether a government, healthcare provider, or private company—can independently guarantee supply continuity during crises. Building strong, trust-based partnerships across public and private sectors, as well as across borders, enhances coordination, resource sharing, and collective problem-solving.^{40,41}

During the COVID-19 pandemic, numerous examples illustrated the importance of collaboration. Public-private partnerships enabled the rapid scale-up of testing, vaccine development, and distribution.^{42,43} International organizations facilitated resource pooling and information exchange, while regional consortia negotiated collective procurement of medicines and vaccines to improve bargaining power and equity in access. At the local level, collaboration between hospitals, community organizations, and logistics providers ensured the timely delivery of critical supplies despite transportation bottlenecks.⁴⁴

Key forms of collaborative partnerships include:

- Public-private partnerships: Joint initiatives between governments and private manufacturers/logistics companies to increase production capacity and strengthen distribution networks.⁴⁵
- Inter-organizational networks: Collaborative arrangements among healthcare providers, non-governmental organizations, and suppliers to pool resources and share risks.⁴⁶
- Cross-border collaboration: Regional and international consortia that enable joint procurement, harmonized regulatory frameworks, and coordinated crisis responses.⁴⁷
- Community engagement: Involving local organizations and civil society in last-mile delivery and awareness campaigns to ensure equitable distribution.⁴⁸

The benefits of collaborative partnerships are substantial: improved information sharing, better allocation of scarce resources, and enhanced flexibility in response to disruptions.⁴⁹ However, effective collaboration requires overcoming challenges such as misaligned incentives, competition for scarce resources, and a lack of trust between stakeholders. Governance frameworks, transparency mechanisms, and legal agreements are critical to ensure accountability and sustainability.⁵⁰

Ultimately, collaborative partnerships represent more than crisis-response mechanisms—they are long-term enablers of trust, transparency, and shared resilience. When integrated with supplier diversification, inventory optimization, and digitalization, they create a networked ecosystem capable of withstanding future global shocks.

4. Risk management and predictive approaches

Risk management is fundamental to building resilience in healthcare supply chains. Unlike reactive strategies that address disruptions only after they occur, risk management frameworks emphasize proactive identification, assessment, and mitigation of potential threats. By systematically analyzing vulnerabilities, organizations can develop contingency plans that reduce exposure to shocks and ensure continuity of essential services.^{51,52}

4.1. Risk management frameworks

Risk management frameworks provide structured approaches for identifying, assessing, and mitigating disruptions in healthcare supply chains. While several frameworks have been adapted from general supply chain management, their application in healthcare contexts reveals both strengths and important limitations.

Common approaches include risk identification and mapping, which systematically categorize potential disruptions such as pandemics, supplier failures, geopolitical instability, and natural disasters. These methods are valuable for improving visibility of vulnerabilities; however, they often rely on static risk registers that may not capture rapidly evolving or cascading risks characteristic of global crises.⁵³

Risk assessment models, such as Failure Mode and Effects Analysis and Hazard and Operability Studies, are widely used to prioritize risks based on likelihood and severity. These tools offer structured and transparent evaluation processes, making them suitable for clinical and operational environments. Nevertheless, they are often criticized for their reliance on expert judgment, which may introduce subjectivity and variability across contexts.⁵⁴ In

addition, these models tend to assess risks in isolation, limiting their ability to account for interdependencies within complex supply networks.⁵⁴

Business continuity planning and disaster preparedness frameworks focus on defining response strategies, roles, and recovery pathways.⁵⁵ While these frameworks are essential for crisis response, they are frequently reactive rather than proactive, emphasizing recovery after disruption rather than anticipation and adaptation. Moreover, business continuity planning is often developed at the organizational level, which may lead to fragmentation and poor coordination across the broader supply chain.⁵⁶

International standards, such as ISO 31000, and health-specific guidance from global organizations provide comprehensive principles for risk management. These frameworks promote a systematic, iterative approach that integrates risk identification, evaluation, and monitoring into organizational processes. However, their implementation in healthcare supply chains remains inconsistent. In many cases, these frameworks are applied in a fragmented manner, without full integration into operational decision-making or alignment with digital systems.^{57,58}

A key limitation across existing frameworks is their limited ability to incorporate dynamic and systemic risks, particularly those involving simultaneous disruptions across multiple supply chain nodes.³ Furthermore, most frameworks have been developed and tested in high-income settings, raising concerns about their applicability in low- and middle-income countries, where infrastructure constraints, data limitations, and resource scarcity significantly affect implementation.⁵⁹

To address these gaps, there is growing recognition of the need for integrated, adaptive risk management frameworks that combine qualitative tools with quantitative analytics. Embedding real-time data, predictive modeling, and cross-sector coordination into risk management processes can enhance both anticipatory capacity and responsiveness. Ultimately, effective frameworks must move beyond static assessments toward continuous, system-wide risk monitoring and learning.

4.2. Predictive analytics and scenario planning

The integration of data-driven predictive tools enhances the effectiveness of risk management. Predictive analytics uses historical data, demand patterns, and external indicators (such as epidemiological trends or climate data) to forecast potential supply chain disruptions.^{60,61} However, the effectiveness of these tools depends heavily on data quality, model selection, and contextual applicability.

Predictive analytics in healthcare supply chains can be broadly categorized into descriptive, predictive, and prescriptive analytics. While descriptive approaches provide retrospective insights, their utility for resilience is limited, as they do not support forward-looking decision-making. Predictive and prescriptive approaches offer greater value but require more sophisticated infrastructure and expertise, which may not be available in all settings—particularly in low- and middle-income countries.^{32,62}

Several types of models are used in predictive analytics. Statistical time-series models, such as Autoregressive Integrated Moving Average and exponential smoothing, are widely applied due to their simplicity, interpretability, and relatively low data requirements.⁶³ These models perform well in stable environments with clear temporal patterns. However, their predictive accuracy declines significantly during unprecedented disruptions—such as pandemics or geopolitical crises—where historical data is no longer a reliable predictor of future behavior.

Machine learning models, including random forests, support vector machines, and artificial neural networks, offer improved predictive performance by capturing nonlinear relationships and complex interactions among variables. Deep learning approaches, such as long short-term memory networks, are particularly suited to dynamic, real-time forecasting.^{64,65} Nevertheless, these models are often criticized for their “black-box” nature, which limits interpretability and may reduce trust among decision-makers.⁶⁶ In addition, Machine learning models require large, high-quality datasets and substantial computational resources, making their implementation challenging in resource-constrained settings. Overfitting and lack of generalizability across different healthcare systems also remain significant concerns.⁶⁷

Simulation-based models, including Monte Carlo simulations, system dynamics, and agent-based models, are widely used to explore disruption scenarios and assess system behavior under uncertainty. These models are particularly valuable for stress-testing supply chains and evaluating policy interventions.^{68,69} However, their reliability depends on the assumptions embedded in the model structure, which may oversimplify real-world complexity. Moreover, simulation models can be computationally intensive and require specialized expertise, limiting their routine use in operational settings.⁷⁰

Emerging tools such as digital twins represent a promising advancement, enabling real-time replication of supply chain systems and continuous scenario testing.^{71,72} While these approaches enhance decision-making capabilities, their adoption is still limited due to high implementation costs, integration challenges, and the need

for advanced digital infrastructure.

Advanced optimization and simulation models have also been applied to healthcare supply chains during crises. For example, reverse logistics network design models using metaheuristic approaches have been developed to manage COVID-19-related medical waste while minimizing operational and infrastructure costs.⁷³

Overall, no single modeling approach is sufficient to capture the complexity of healthcare supply chains. Hybrid approaches that combine statistical, machine learning, and simulation techniques are increasingly recommended. However, their effectiveness depends on integrating reliable data sources, fostering cross-sector collaboration, and aligning with decision-making processes. Without addressing these systemic challenges, predictive analytics risks remaining underutilized or producing outputs that are not actionable in practice.

4.3. Challenges in implementation

Despite the growing adoption of risk management frameworks and predictive analytics, their implementation in healthcare supply chains remains uneven and often limited in practice. Several structural, technical, and organizational challenges constrain their effectiveness and scalability.

A fundamental barrier is the limited availability and quality of data, which directly affects the performance of both risk assessment frameworks and predictive models.⁷⁴ Numerous healthcare systems rely on fragmented or incomplete datasets, often collected through non-standardized or paper-based processes. This undermines the reliability of statistical forecasting models and reduces the accuracy of machine learning algorithms, which depend on large, high-quality datasets. In addition, the lack of interoperability between information systems restricts real-time data sharing, preventing the full utilization of predictive and prescriptive analytics.^{75,76}

Resource and infrastructure constraints further limit the applicability of advanced models. While statistical approaches such as time-series models may be feasible in low-resource settings, more complex machine learning and simulation-based models require significant computational capacity, technical expertise, and financial investment.⁷⁷ As a result, there is a growing risk of a “digital divide,” in which high-income healthcare systems benefit from advanced analytics, while low- and middle-income countries remain dependent on simpler, less adaptable tools.⁷⁸

Another critical challenge is integrating models into decision-making processes. Even when predictive tools are available, their outputs are not always translated into

actionable strategies.⁷⁹ This gap is often due to limited trust in model outputs—particularly for black-box machine learning models—as well as a lack of alignment between technical teams and decision-makers. Consequently, predictive analytics may remain underutilized or function primarily as a retrospective analytical tool rather than a driver of proactive risk management.

Organizational and governance barriers also play a significant role. Healthcare supply chains are typically fragmented across multiple stakeholders, including public institutions, private suppliers, and logistics providers.^{80,81} This fragmentation complicates the implementation of integrated risk management frameworks and limits the effectiveness of system-wide predictive models. In addition, institutional silos and resistance to change can hinder the adoption of innovative approaches, particularly when they require shifts in established workflows or decision-making structures.⁸²

Finally, many existing models and frameworks exhibit limited adaptability to complex and rapidly evolving disruption scenarios. Predictive models trained on historical data may fail to capture unprecedented events, while risk frameworks often lack mechanisms for continuous updating and learning.^{29,83} This highlights the need for more adaptive, hybrid approaches that integrate real-time data, iterative learning, and cross-sector collaboration.

Addressing these challenges requires not only technological investment but also organizational transformation. Strengthening data governance, improving interoperability, fostering interdisciplinary collaboration, and building analytical capacity are essential steps to ensure that risk management and predictive approaches can be effectively implemented across diverse healthcare settings.

4.4. Toward integrated risk management

The limitations identified in existing risk management frameworks (Section 4.1), predictive models (Section 4.2), and their implementation (Section 4.3) highlight the need for a more integrated, adaptive approach to risk management in healthcare supply chains. Rather than relying on isolated tools or static frameworks, effective risk management requires aligning qualitative and quantitative methods within a continuous, system-wide process.

An integrated approach combines structured risk assessment frameworks (e.g., Failure Mode and Effect Analysis, business continuity planning) with data-driven predictive and simulation models, enabling both identification of vulnerabilities and anticipation of future

disruptions.⁸⁴ This integration enables organizations to move beyond reactive strategies toward proactive, anticipatory decision-making. However, such integration is not merely technical—it requires coordination across organizational levels and stakeholders, as well as alignment with operational workflows.⁸⁵

A key feature of integrated risk management is the incorporation of real-time data and dynamic updating mechanisms. Traditional frameworks are often static and periodically revised, whereas resilient systems require continuous monitoring of supply chain conditions.^{86,87} Embedding predictive analytics into routine operations—supported by interoperable digital platforms—can enable early warning systems and faster response times. Nevertheless, this shift introduces challenges in data governance, cybersecurity, and system interoperability that must be carefully managed.⁸⁸

Another critical dimension is the adoption of hybrid modeling approaches that combine statistical, machine-learning, and simulation techniques to capture different aspects of supply chain complexity. While such approaches can improve predictive accuracy and robustness, they also increase model complexity and resource requirements. This raises important questions about scalability and feasibility, particularly in low-resource settings where simpler, more transparent models may be more appropriate.⁸⁹

Importantly, integrated risk management must also address the gap between model outputs and decision-making. Even the most advanced predictive systems are of limited value if their insights are not translated into actionable strategies.⁹⁰ Strengthening this link requires improved communication between technical experts and policymakers, as well as the development of user-friendly decision-support tools that enhance interpretability and trust.

Finally, effective integration depends on collaborative governance structures that enable information sharing and coordinated action across stakeholders. Healthcare supply chains are inherently multi-actor systems, and fragmented governance remains a major barrier to resilience.⁹¹ Establishing shared platforms, common standards, and joint risk management protocols can enhance system-wide visibility and responsiveness.

In summary, integrated risk management represents a shift from fragmented, reactive approaches toward continuous, data-informed, and collaborative systems. However, its successful implementation depends not only on technological advancement but also on organizational capacity, governance alignment, and contextual adaptation to different healthcare settings.

5. Sustainability and resilience

Resilience in healthcare supply chains cannot be considered in isolation from sustainability. While resilience emphasizes the ability to anticipate, absorb, and recover from disruptions, sustainability focuses on meeting present needs without compromising future generations' capacity to meet theirs.⁹² Integrating these two dimensions ensures that supply chains are not only capable of withstanding crises but also aligned with long-term social, economic, and environmental goals.

5.1. Environmental sustainability

Healthcare supply chains have significant environmental footprints due to energy-intensive manufacturing, complex logistics networks, and reliance on single-use consumables. Resilience strategies that incorporate green logistics, such as optimizing transport routes, using renewable energy, or adopting eco-friendly packaging, simultaneously reduce vulnerability to energy price shocks and environmental risks.^{93,94} Similarly, localized production and shorter supply chains contribute both to reduced carbon emissions and to improved supply security.

5.2. Circular economy practices

Adopting circular economy principles, including recycling, remanufacturing, and reuse, can enhance resilience by reducing dependency on scarce raw materials and global supply disruptions. For example, reprocessing specific medical devices and recycling critical raw materials help mitigate risks associated with resource scarcity. Closed-loop systems also provide buffers during crises, ensuring the availability of essential goods even when imports are restricted.^{95,96}

5.3. Social and equity dimensions

Sustainability also encompasses social responsibility, particularly in ensuring equitable access to healthcare goods. Resilient and sustainable supply chains must address disparities in resource allocation between high- and low-resource settings.⁹⁷ Strategies such as regional stockpiles, fair procurement practices, and transparent distribution mechanisms ensure that vulnerable populations are not disproportionately affected during crises.

5.4. Aligning resilience with global policy goals

Numerous global frameworks—including the United Nations Sustainable Development Goals and the World Health Organization's initiatives on health system strengthening—stress the interconnectedness of resilience and sustainability.⁹⁸ Embedding sustainability metrics into resilience planning enables healthcare systems to

simultaneously reduce environmental impact, enhance social equity, and improve crisis preparedness.

5.5. Limitations and opportunities

Despite growing recognition, integrating sustainability into resilience planning faces obstacles, including higher initial costs, fragmented policy frameworks, and limited incentives for green innovation.^{17,99} However, the long-term benefits—reduced risk exposure, improved reputation, and alignment with global climate and health goals—far outweigh the barriers. The emerging field of sustainable resilience offers a promising pathway to ensure healthcare supply chains are future-proof in both capacity and responsibility.

While Table 2 focuses on operational and structural characteristics of supply chain models, Table 3 extends the analysis by examining how sustainability and equity dimensions reshape these models toward long-term system resilience.

6. Challenges and gaps

The literature on healthcare supply chain resilience is increasingly diverse in both conceptual and methodological approaches. While a substantial proportion of studies converge on the importance of strategies such as supplier diversification, digitalization, and inventory optimization, differences emerge in terms of implementation approaches, contextual applicability, and reported effectiveness. Furthermore, the evidence base is characterized by a predominance of conceptual and modeling studies, with relatively limited empirical validation, particularly in real-world healthcare settings.

Despite growing recognition of the need for resilience in healthcare supply chains, translating theory into practice remains uneven. Numerous barriers, structural, financial, technological, and organizational, continue to limit the adoption and scaling of resilience strategies across global health systems. Understanding these challenges is crucial for developing targeted interventions that strengthen both preparedness and sustainability.

6.1. Resource and infrastructure constraints

In numerous low- and middle-income countries, healthcare supply chains face chronic underfunding, inadequate infrastructure, and weak logistics systems.¹⁰⁰ Cold-chain networks are often unreliable, warehousing capacity is limited, and transportation systems may be disrupted by conflict or natural disasters. These limitations hinder the implementation of advanced resilience measures such as predictive analytics, digital tracking, or diversified sourcing. Moreover, dependence on donor funding can

make resilience initiatives short-lived and externally driven, rather than structurally embedded.

6.2. Data and information gaps

Reliable, real-time data is essential for decision-making, yet many healthcare systems still rely on fragmented, paper-based reporting. Lack of interoperability between digital platforms prevents effective data sharing among suppliers, governments, and healthcare providers.¹⁰¹ Without accurate visibility into inventory levels, demand forecasts, or transportation status, organizations remain reactive rather than proactive. Data asymmetry also undermines coordination, leading to duplication of efforts or uneven distribution of resources during crises.

6.3. Policy and regulatory barriers

Regulatory misalignment across countries often delays procurement and distribution, especially during emergencies. For instance, varying standards for product certification or customs clearance can create bottlenecks even when supplies are available.¹⁰² The absence of harmonized resilience policies across public and private sectors also hinders coordinated action. Furthermore, most existing regulatory frameworks prioritize cost efficiency and compliance rather than preparedness and adaptability.

6.4. Organizational and cultural challenges

Institutional silos within healthcare organizations often impede collaboration and information sharing. Procurement, logistics, and clinical departments may operate independently, limiting the system's ability to respond holistically to disruptions.¹⁰³ Resistance to change, driven by risk aversion, bureaucratic inertia, or lack of incentives, also slows the adoption of innovative practices. Building a culture of resilience requires leadership commitment, continuous training, and shared accountability across all levels of the supply chain.

6.5. Equity and access limitations

Global crises have repeatedly exposed inequities in the distribution of healthcare resources. During the COVID-19 pandemic, high-income countries secured large vaccine stocks, while many low-income regions faced prolonged shortages.¹⁰⁴ Such disparities highlight the lack of inclusive resilience frameworks that consider equity as a core dimension. Ensuring fair access to critical supplies requires regional collaboration, transparent allocation mechanisms, and support for local capacity building.

6.6. Research and evidence gaps

Although the literature on supply chain resilience is expanding, empirical evidence, especially in healthcare

contexts, remains limited. Most studies focus on theoretical frameworks or lessons from high-income countries. There is a need for longitudinal, cross-country research that evaluates the effectiveness of resilience interventions, integrates sustainability metrics, and measures the social and economic impacts of disruptions.

6.7. Methodological patterns in the literature

The existing literature on healthcare supply chain resilience exhibits distinct methodological patterns. A large proportion of studies rely on conceptual frameworks, simulation models, and case-based analyses, with relatively limited empirical validation. Modeling approaches, such as optimization, system dynamics, and predictive analytics, are commonly used to simulate disruption scenarios and evaluate resilience strategies. While these approaches provide valuable theoretical insights, their applicability to real-world healthcare systems is often constrained by simplifying assumptions and limited validation.

Empirical studies tend to focus on specific crisis events, particularly the COVID-19 pandemic, and are often restricted to high-income settings. This limits the generalizability of findings across diverse healthcare systems. Furthermore, longitudinal and comparative studies remain scarce, underscoring a lack of understanding of the long-term effectiveness of resilience strategies.

6.8. Strength of evidence

The overall strength of evidence in this field remains uneven. Although there is strong conceptual agreement on key resilience strategies, much of the supporting evidence is derived from qualitative analyses and model-based studies rather than robust empirical research. Controlled or comparative studies are largely absent, and real-world implementation data are limited. As a result, while proposed strategies are theoretically well-supported, their practical effectiveness, scalability, and cost-efficiency require further validation. Strengthening the evidence base will require more empirical, cross-context, and longitudinal research.

In summary, the literature provides a solid conceptual foundation for understanding healthcare supply chain resilience, with clear agreement on key strategic pillars. However, significant gaps remain in empirical validation, cross-context comparisons, and the evaluation of long-term effectiveness. Addressing these gaps is essential to move from theoretical frameworks to actionable, evidence-based practice.

7. Future directions and conceptual roadmap

As global healthcare systems face increasing uncertainty,

Table 1. Vulnerabilities in healthcare supply chains during global crises

Crisis type	Key examples	Impacts on supply chains	Vulnerabilities exposed
Pandemics	COVID-19, H1N1	PPE and ventilator shortages; border closures	Overdependence on few suppliers; “just-in-time” risks
Geopolitical conflicts	Trade wars, sanctions, armed conflicts	Disruption of raw materials and pharmaceutical APIs	Reliance on concentrated production hubs
Natural disasters	Hurricanes, floods, earthquakes	Transport delays, factory shutdowns	Weak infrastructure; lack of contingency planning
Systemic weaknesses	Chronic underfunding, fragmented networks	Unequal distribution; limited visibility	Poor data sharing; lack of redundancy

Abbreviations: APIs: Active pharmaceutical ingredients; COVID-19: Coronavirus disease 2019; H1N1: Influenza A H1N1 (swine flu); PPE: Personal protection equipment.

Table 2. Operational and structural comparison of supply chain models

Dimension	Traditional supply chain	Resilient supply chain	Sustainable-resilient supply chain
Primary goal	Cost efficiency, lean performance	Continuity of operations under disruption	Balanced performance: resilience with long-term system viability
System design logic	Efficiency-driven, optimized for stable conditions	Redundancy and flexibility are built into the system design	Adaptive and flexible design aligned with long-term sustainability goals
Inventory approach	Just-in-time, minimal buffers	Just-in-case and strategic stockpiling	Dynamic, risk-adjusted inventory minimizing waste and obsolescence
Sourcing strategy	Global sourcing based on the lowest cost	Multi-sourcing and geographic diversification	Hybrid sourcing (local–regional–global) with risk and sustainability considerations
Supplier relationships	Transactional, price-focused	Collaborative, risk-sharing partnerships	Long-term partnerships incorporating ethical and sustainability criteria
Technology use	Limited, fragmented systems	Digital tools for visibility and predictive analytics	Integrated digital ecosystems supporting both resilience and sustainability monitoring
Risk management	Reactive, disruption response	Proactive risk identification and mitigation	Integrated, continuous risk management aligned with environmental and social risks
Governance structure	Siloed, organization-centric	Coordinated and collaborative governance	Multi-stakeholder governance with long-term strategic alignment

Table 3. Sustainability and equity integration across supply chain models

Dimension	Traditional supply chain	Resilient supply chain	Sustainable-resilient supply chain
Environmental impact	High carbon footprint; resource-intensive logistics	Moderate impact; limited environmental considerations	Reduced footprint through green logistics, energy efficiency, and eco-design
Resource-use model	Linear (“take–make–dispose”)	Partially optimized resource use	Circular economy approach (reuse, recycling, remanufacturing)
Waste management	Limited focus; high levels of waste	Improved efficiency reduces some waste	Systematic waste minimization and closed-loop systems
Carbon and emissions strategy	Not integrated into decision-making	Considered in limited operational decisions	Actively monitored and embedded in supply chain metrics and planning
Social responsibility	Limited consideration of labor and sourcing ethics	Increasing awareness during disruptions	Ethical sourcing, fair labor practices, and responsible procurement are embedded
Equity in access	Unequal distribution; vulnerable populations are underserved	Improved allocation during crises	Equity-centered design ensures fair and inclusive access across populations.
Local economic impact	Minimal engagement with local economies	Some regional sourcing for resilience	Strong support for local production and capacity building
Long-term system perspective	Short-term cost focus	Medium-term continuity focus	Long-term sustainability, resilience, and societal value creation

from pandemics and geopolitical tensions to climate-induced disasters, the need for resilient, adaptive, and sustainable supply chains has never been more urgent. The lessons learned from recent crises must now evolve into actionable frameworks that guide future preparedness and system-wide transformation. This section outlines emerging directions and proposes a conceptual roadmap for building next-generation healthcare supply chains.

7.1. Integration of digital and physical resilience

Future healthcare supply chains will depend on seamless integration between digital infrastructure and physical logistics. Technologies such as AI, blockchain, and IoT can enhance end-to-end visibility, predictive capacity, and traceability. For example, AI-driven demand forecasting can anticipate surges in essential medicines, while blockchain can secure product authenticity and compliance across borders. However, the goal is not digitalization alone; it is the creation of intelligent, learning systems that continuously adapt to changing risks and conditions.

7.2. Decentralization and local capacity building

The COVID-19 pandemic revealed the fragility of overly globalized supply networks. Building regional manufacturing hubs, strengthening local sourcing, and investing in domestic pharmaceutical production can significantly reduce dependency on single suppliers or distant markets. Future strategies should emphasize regional self-reliance balanced with global cooperation, ensuring redundancy without isolation. Partnerships with local small and medium enterprises also foster socioeconomic development and enhance community-level resilience.

7.3. Collaborative governance and public–private partnerships

Effective resilience requires multi-sectoral collaboration. Governments, international organizations, private suppliers, logistics providers, and healthcare institutions must coordinate through shared platforms and transparent governance mechanisms. Establishing resilience councils or joint command centers can help align priorities during crises and streamline decision-making. Public–private partnerships can accelerate innovation, leverage resources, and scale resilient infrastructure, particularly in low-resource settings.

7.4. Embedding sustainability into resilience planning

The next generation of resilient supply chains must be sustainability-driven by design. Integrating carbon accounting, ethical procurement, and circular economy

principles ensures that short-term crisis responses do not compromise long-term planetary health. Incorporating sustainability indicators, such as emissions reduction, waste minimization, and equitable access, into resilience metrics can align healthcare logistics with broader global goals like the Sustainable Development Goals and Paris Climate Agreement.

7.5. Education, training, and cultural change

Resilience is not solely a function of systems and technology; it is also a product of people and organizational culture. Continuous education and capacity building in supply chain management, data analytics, and emergency preparedness are essential. Leadership programs that promote resilience thinking can cultivate a proactive, learning-oriented culture. Embedding resilience principles in medical, public health, and logistics curricula will ensure that future professionals are equipped to manage uncertainty effectively.

7.6. Conceptual roadmap for the future

Figure 1 presents a conceptual roadmap for resilient and sustainable healthcare supply chains. The model illustrates four interconnected pillars—digital intelligence, local adaptability, collaborative governance, and sustainable practice—supported by an enabling foundation of education and research. Together, these pillars create a dynamic system capable of anticipating disruptions,

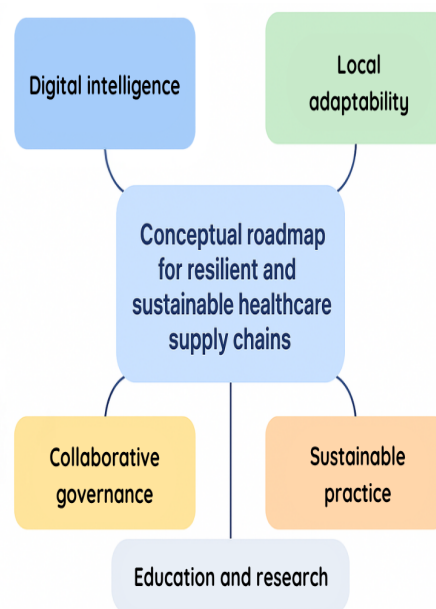


Figure 1. Conceptual roadmap for resilient and sustainable healthcare supply chains. The roadmap integrates digital, organizational, and sustainability dimensions, emphasizing adaptive learning and collaboration across all levels of the healthcare system.

adapting to shocks, and transforming through continuous learning.

7.7. Toward a resilient health future

In summary, the path forward requires a paradigm shift—from fragmented, efficiency-oriented models toward holistic, adaptive systems that value preparedness, inclusivity, and sustainability. By linking technological innovation with ethical and ecological responsibility, healthcare supply chains can evolve into true backbones of global health security.

8. Conclusion

Global crises such as the COVID-19 pandemic, geopolitical instability, and climate-related disasters have exposed critical weaknesses in healthcare supply chains, underscoring the need for resilience as a strategic imperative. This review has synthesized evidence and lessons from past disruptions to identify key resilience strategies, including supplier diversification, digitalization, local sourcing, collaborative partnerships, and integrated risk management frameworks. Together, these elements form the foundation of adaptive systems capable of maintaining continuity of care during uncertainty.

Building resilience, however, requires more than technological innovation; it demands organizational transformation, cross-sector collaboration, and a commitment to sustainability and equity. Future supply chains must integrate environmental responsibility and social inclusion into resilience planning to ensure global health security. Unlike previous reviews that address isolated aspects of supply chain resilience, this study integrates technological, organizational, and sustainability perspectives into a unified framework, offering a more comprehensive understanding of how healthcare systems can prepare for future disruptions.

The conceptual roadmap proposed in this review provides a forward-looking framework that links digital intelligence, local adaptability, collaborative governance, and sustainable practice underpinned by education and research. Embedding these principles across policy, practice, and research agendas will be essential to developing healthcare supply chains that are not only reactive to crises but also proactive, learning-oriented, and future-ready.

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Conflict of interest

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