# *Research on the Mechanism and Path of Digitalization Driving the Supply Chain Resilience of Pharmaceutical and Health Industry*

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**ABSTRACT**

Against the backdrop of frequent global public health emergencies and a complex, volatile international trade environment, the stability and security of the pharmaceutical and healthcare industry supply chain have become a critical component of national strategic security. This paper explores how digital technologies can enhance the resilience of the pharmaceutical and healthcare supply chain, systematically analyzing its underlying mechanisms and implementation pathways. The study concludes that digitalization significantly improves the supply chain's predictability, adaptability, and resilience through four key mechanisms: information transparency, intelligent processes, data-driven decision-making, and network collaboration. The proposed implementation pathways include: establishing a comprehensive data-sharing platform across the entire supply chain, deepening the application of artificial intelligence and Internet of Things (IoT) technologies, developing flexible supply chain network models, and establishing a robust digital governance framework. This research aims to provide theoretical references and practical guidance for relevant enterprises and policymakers.

**Keywords:** digitalization; healthcare industry; supply chain resilience

## 1 Introduction

The pharmaceutical and healthcare industry is a strategic sector vital to national economy, public welfare, and security. The stability, efficiency, and safety of its supply chain directly impact public health and the robustness of the healthcare system. In recent years, amid global geopolitical turbulence, frequent public health emergencies, and increasingly complex international trade environments, the vulnerabilities of traditional pharmaceutical and healthcare supply chains have become increasingly apparent. Issues such as disruptions in raw material supply, production halts, logistics bottlenecks, and inadequate information flow are becoming commonplace. These challenges not only affect the accessibility of pharmaceuticals and medical devices but also pose severe tests to the emergency response capabilities of healthcare systems worldwide. Consequently, enhancing the resilience of pharmaceutical and healthcare supply chains has emerged as a focal point of concern for industry, academia, and policymakers.

Meanwhile, digital technologies represented by big data, artificial intelligence, the Internet of Things, and blockchain are reshaping the global industrial landscape with unprecedented depth and breadth. Digitalization not only enhances efficiency and optimizes costs, but more crucially, it provides revolutionary tools and paradigms for addressing supply chain uncertainties and strengthening system adaptability through real-time data

collection, transparent sharing, and intelligent analysis across the entire supply chain. Systematically embedding digital capabilities into all aspects of the pharmaceutical and healthcare industry supply chain—ranging from R&D, production, distribution, consumption to regulation—is seen as an inevitable choice to overcome the pain points of traditional supply chains, such as rigidity, fragmentation, and slow responsiveness, and to build a more resilient, agile, and sustainable modern supply chain system.

However, current research on digital empowerment of supply chains predominantly focuses on macro-level theoretical frameworks or general analyses. For the pharmaceutical and healthcare industry—a sector characterized by high specialization, stringent regulation, and unique ethical requirements—the specific mechanisms driving supply chain resilience through digitalization and systematic implementation pathways still require in-depth exploration. Existing practices also face challenges such as fragmented technology adoption, persistent data silos, and underdeveloped collaborative governance mechanisms, which constrain the full realization of digital potential. In light of these issues, this study aims to thoroughly analyze the logical relationship between digital technologies and supply chain resilience in the pharmaceutical and healthcare industry. It systematically elucidates the core mechanisms of digital empowerment and proposes development pathways that combine foresight with practicality. The findings are intended to provide theoretical references and practical guidance for building secure, reliable, and efficient resilient supply chain systems in China and globally.

## 2 Literature Review

Amid growing global economic uncertainties, enhancing supply chain resilience has become a critical strategy for businesses to tackle challenges and maintain competitiveness, particularly in the healthcare industry where efficient supply chain operations directly impact public health and social stability. The rapid advancement of digital technologies in recent years has created unprecedented opportunities for corporate supply chain management. Through digital transformation, companies can not only improve operational efficiency but also significantly strengthen their ability to withstand external shocks and achieve rapid recovery. Academic research primarily focuses on the following aspects.

### (1) Overall Impact of Digital Transformation on Supply Chain Resilience

Supply chain resilience refers to the ability of a supply chain to maintain stable operations in the face of external shocks, including resilience against shocks, rapid recovery, and adaptability to changes. In the pharmaceutical and healthcare industry, supply chain resilience is particularly crucial for ensuring drug supply and responding to public health emergencies. With the development of digital technologies, enterprises can enhance supply chain resilience by optimizing supply chain management, improving information transparency, and enhancing collaborative efficiency. Cao Yi et al. (2025) studied the impact of supply chain digitalization on corporate resilience based on sample data from listed companies in China from 2007 to 2023. The research found that supply chain digitalization can significantly improve corporate resilience, primarily by alleviating financing constraints, enhancing information transparency, and improving collaborative innovation levels [1].

Similarly, Guo Zhifang et al. (2025) focused on the perspective of supply chain optimization and explored the impact of digital transformation on corporate exports. Their study revealed that digital transformation can significantly enhance corporate export resilience, mainly through improving supply chain innovation quality, enhancing supply chain collaborative efficiency, and strengthening supply chain stability [2]. Additionally, Su Peng and Li Ziying (2025) constructed a multi-period difference-in-differences model to investigate the impact of supply chain digitalization on corporate performance. They found that supply chain digitalization can significantly promote corporate performance growth, primarily through a tripartite micro-level empowerment mechanism involving unimpeded information transmission, improved capital flow, and talent aggregation [3].

### (2) Specific Applications of Digital Technology in the Pharmaceutical Supply Chain

The application of digital technologies not only enhances supply chain efficiency but also improves transparency and collaborative capabilities, thereby strengthening supply chain resilience. In the pharmaceutical and healthcare industry, digital technology plays a particularly critical role as it directly impacts drug safety and accessibility. Han Xiaoyu and Deng Yu (2020) investigated the application of digital technologies in supply chain finance, highlighting that digital upgrades can address issues such as low adoption rates of online applications, complex processes, and incomplete credit data in traditional supply chain finance. They proposed that technologies like 5G, artificial intelligence, big data, and the Internet of Things (IoT) could be leveraged to build a more robust digital supply chain finance system [4]. Luo Junmei et al. (2025) conducted a dual-case study using JD Health and Alibaba Health as examples to explore the mechanism of digital technology coupling in the digital transformation of pharmaceutical supply chains. Their research revealed that digital technology coupling fosters dual capabilities—agile response and collaborative innovation—forming a dynamic capability system for digital supply chain restructuring [5]. Additionally, Zheng Xuemei and Zou Fenju (2025) analyzed the impact of the digital economy on manufacturing supply chain resilience from three perspectives: information flow, capital flow, and logistics. Their findings demonstrated that the digital economy enhances supply chain resilience by ensuring information transparency, efficient capital circulation, and optimized logistics [6].

### (3) Challenges and Countermeasures of Digital Transformation

While digital transformation has demonstrated significant effects in enhancing supply chain resilience, practical implementation still faces challenges such as technological barriers, talent shortages, and data security issues. These problems are particularly prominent in the pharmaceutical and healthcare industries, as they directly impact drug safety and accessibility. Su Peng and Li Ziyin (2025) investigated the impact of supply chain digitalization on corporate performance, finding that the promoting effect of digitalization is positively moderated by government support, but exerts an inverse regulatory effect on corporate governance levels. This indicates that enterprises need to balance internal and external factors when advancing digital transformation [3]. Yuan Yehu and Wu Duanduan (2025) developed a multi-stage model of corporate digital transformation to study its impact on supply chain

resilience. Their research revealed that digital transformation significantly enhances supply chain resilience, with varying effects across different stages, and that it improves resilience through information spillover and knowledge spillover [7]. Additionally, Zheng Xuemei and Zou Fenju (2025) analyzed the impact of the digital economy on manufacturing supply chain resilience from three perspectives: information flow, capital flow, and logistics. They found that the digital economy can enhance supply chain resilience by ensuring information transparency, capital circulation, and logistics efficiency [6].

## 3 The Connotation and Challenges of Supply Chain Resilience in the Pharmaceutical and Healthcare Industry

Building a resilient supply chain has become an effective strategy for the pharmaceutical and healthcare industry to address uncertainties and ensure public health safety. Compared with traditional industries, the supply chain in the pharmaceutical and healthcare sector exhibits unique characteristics: its end products directly impact life and health, with nearly stringent requirements for quality, safety, and timeliness; its processes span research and development, production, distribution, and end services, featuring a long chain and high degree of specialization; simultaneously, it is subject to extremely rigorous and continuously evolving global and regional regulatory oversight. The stable operation of this complex system is not only a matter of economic efficiency but also a significant social responsibility. However, profound changes in the current international environment, the impact of technological revolutions, and the challenges posed by public health emergencies have increasingly magnified the inherent vulnerabilities of this system. The concept of resilience needs to be re-examined, and the challenges it faces now present new systemic and multidimensional features. A thorough analysis of the essence of resilience and identification of core challenges serve as the logical starting point and practical basis for subsequent discussions on digital empowerment mechanisms and pathways.

### (1) Core Connotation of Supply Chain Resilience

Supply chain resilience refers to the comprehensive capability of a supply chain system to anticipate, adapt, respond, and recover to its original operational state, or even achieve upgrades and transformation, when facing internal and external disturbances, disruptions, or pressures. This concept transcends the traditional scope of risk resistance, emphasizing the system's dynamic adjustment and continuous evolution capabilities. In the pharmaceutical and healthcare industry, supply chain resilience holds particular significance. Since pharmaceutical products are directly linked to human life and health, any disruption or delay in their supply chain may severely impact public health security. Therefore, the resilience of the pharmaceutical and healthcare industry supply chain is not only reflected in ensuring the continuous supply of drugs and medical devices but also in maintaining quality and safety across the entire chain, cost control, and efficiency optimization.

Specifically, the resilience of the pharmaceutical and healthcare industry supply chain encompasses four key dimensions: First, visibility, which refers to the transparency and real-time traceability of information across all supply chain segments. Visibility enables enterprises to fully grasp the dynamic processes from raw material procurement, production,

warehousing, distribution to end-use, allowing timely identification of potential risks and rapid response. For instance, through IoT technology and blockchain systems, companies can achieve comprehensive monitoring of critical indicators such as drug temperature and humidity, ensuring quality and safety during transportation and storage. Second, agility, which denotes the supply chain's ability to swiftly respond to and adapt to external environmental changes. Pharmaceutical market demand exhibits high uncertainty and suddenness, particularly during public health emergencies when demand may surge explosively within short periods. Agile supply chains can rapidly adjust supply strategies through flexible production, dynamic inventory management, and flexible logistics allocation to meet urgent market needs. For example, during the early stages of the COVID-19 pandemic, some companies achieved rapid production increases and supply of protective materials by swiftly adjusting production lines. Third, collaboration, which involves information sharing, resource integration, and coordinated actions among supply chain participants. The pharmaceutical and healthcare industry supply chain involves multiple stakeholders including raw material suppliers, manufacturers, logistics service providers, medical institutions, and regulatory authorities. Enhanced collaboration can effectively reduce efficiency losses and risk accumulation caused by information asymmetry. Through digital platforms and collaborative mechanisms, all parties can achieve synchronized demand forecasting, inventory management, and emergency response, forming a collective force to address sudden challenges. Fourth, redundancy refers to a supply chain's capacity to maintain buffer resources at critical junctures. Strategic redundancy measures — such as multi-source procurement, safety stock, and backup production capacity — can provide alternative solutions when primary supply chains are disrupted, ensuring operational continuity. However, such redundancy requires careful cost-risk balancing to avoid resource wastage. In the pharmaceutical and healthcare sectors, diversifying sourcing of key raw materials and core technologies is particularly vital, as it effectively mitigates supply chain disruptions caused by geopolitical tensions and trade conflicts.

Furthermore, the resilience of the pharmaceutical and healthcare industry supply chain emphasizes both foresight and learning capabilities. Foresight refers to the ability to identify potential risks and develop countermeasures through data analysis and scenario modeling, while learning capability denotes the capacity to summarize experiences, optimize processes, and continuously enhance systemic capabilities after disruptions. The integration of these two capabilities enables the supply chain to not only address known risks but also adapt to unknown challenges, transitioning from reactive responses to proactive defense.

### (2) Main Challenges

Although China's pharmaceutical and healthcare industry supply chain has achieved significant progress, it still faces systemic and multi-level challenges in an increasingly complex internal and external environment. These challenges are interwoven, collectively testing the resilience foundation and evolutionary capacity of the supply chain.

First, the complexity of industrial chain structures and information coordination challenges form fundamental constraints. The pharmaceutical and healthcare supply chain spans multiple long-chain segments, including active pharmaceutical ingredient (API) and intermediate production, formulation R&D and manufacturing, commercial distribution, and

medical institution utilization. With numerous upstream and downstream enterprises widely distributed geographically, this multi-level, cross-regional complex structure easily forms "information silos" in the absence of effective digital connectivity. Data from raw material batch information, production progress, inventory status, to logistics trajectories are often confined to internal enterprise systems, making end-to-end real-time sharing and transparent traceability difficult to achieve. This not only results in poor overall visibility of the supply chain but also deprives critical decision-making processes—such as demand forecasting, inventory optimization, and risk alerts—with adequate data support, severely weakening the supply chain's responsiveness and precision.

Secondly, the high uncertainty of demand and forecasting challenges persistently plague industrial operations. The pharmaceutical market demand is not only influenced by long-term demographic changes and shifts in disease patterns, but also prone to drastic fluctuations caused by short-term shocks such as public health emergencies and seasonal epidemics. For instance, during the COVID-19 pandemic, demand for products like ventilators, protective suits, and testing kits exploded exponentially, while the demand patterns for conventional chronic disease medications also underwent significant changes. Traditional forecasting models based on historical data often fail under such extreme scenarios, leading to severe supply-demand imbalances—on one hand, global shortages of critical supplies, and on the other, potential overstocking of certain products. This "bullwhip effect" is amplified step-by-step in long supply chains, exacerbating resource misallocation and waste.

Third, the external dependence on critical resources and geopolitical risks have become increasingly prominent. In the global pharmaceutical industry division of labor, China still exhibits strong import dependence in certain high-end active pharmaceutical ingredients (APIs), core pharmaceutical equipment, biological reagents, and advanced medical devices. For instance, the production of APIs for certain specialty drugs is highly concentrated in a few countries, while the supply chain for core components of high-end medical devices remains relatively fragile. In recent years, the rise of trade protectionism, fluctuations in international relations, and regional conflicts have severely impacted the stability of global supply chains. If this "single point of failure" risk escalates into supply disruptions, it will directly affect the production and supply of related domestic pharmaceuticals, posing a threat to public health security. Building an independent, controllable, and diversified supply system has become an urgent strategic priority.

Fourth, stringent regulatory requirements and full-chain compliance pressures have set higher standards for supply chain management. The pharmaceutical and healthcare industry is vital to life and health, and regulatory authorities in various countries have established extremely strict access and traceability systems, such as China's drug traceability system, the EU's Good Distribution Practice (GDP), and the U.S. Drug Supply Chain Safety Act (DSCSA). These regulations require companies to achieve full lifecycle traceability of products from production to consumption and ensure continuous compliance with storage and transportation conditions (such as cold chains). However, the traditional management model, which relies on paper documents and manual verification, struggles to meet the demands for real-time, accurate, and tamper-proof compliance verification. In cross-border supply chain

scenarios, coordinating regulatory differences across countries further increases operational complexity and compliance costs.

Fifth, the practical bottlenecks and cost pressures in technological innovation applications cannot be overlooked. Although digital technologies such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI) provide powerful tools for enhancing supply chain resilience, their practical implementation still faces numerous obstacles. The high cost of technological investment, particularly a heavy burden for small and medium-sized pharmaceutical enterprises; the lack of uniform standards among existing information systems (e.g., ERP, WMS), making integration challenging; the severe shortage of interdisciplinary talents proficient in both pharmaceutical operations and digital technologies; and the critical red lines that must be strictly adhered to in data security and patient privacy protection during technology application. These factors collectively result in the "fragmented" nature of technological applications, making it difficult to develop systematic solutions that cover the entire supply chain.

Finally, the coordination gaps in emergency response mechanisms become glaringly apparent during crises. When confronting major public health emergencies, seamless collaboration among governments, manufacturers, distributors, healthcare providers, and even civil society organizations is essential. Yet current cross-departmental and cross-regional coordination mechanisms remain inadequate, with recurring issues including delayed information sharing, misaligned resource allocation, and inconsistent operational steps. The key challenge lies in establishing a hybrid emergency supply chain system that integrates peacetime and wartime operations, enabling swift transitions from routine operations to emergency responses – a critical step toward enhancing overall resilience.

## 4 The Intrinsic Mechanism of Digitalization in Enhancing Supply Chain Resilience

Digitalization transcends mere technological integration. By deeply embedding itself across all supply chain stages, it catalyzes systemic transformation and enhances resilience through four core mechanisms.

### (1) Enhancing Supply Chain Visibility and Traceability

By deploying IoT sensors, RFID tags, and blockchain technology, pharmaceutical companies can achieve real-time data collection and tamper-proof recording throughout the entire supply chain process — from raw material procurement, production, warehousing, distribution to end-user consumption. This eliminates information silos, creating unprecedented supply chain transparency. Decision-makers can monitor inventory levels, logistics locations, production progress, and environmental parameters in real time, significantly enhancing end-to-end visibility. In the event of quality issues or safety incidents, the blockchain-based traceability system enables rapid identification of problematic links, facilitating precise recall and control measures that dramatically improve crisis response speed and accuracy.

### (2) Enhancing Supply Chain Operational Efficiency and Agility

Artificial intelligence and machine learning algorithms can analyze massive supply chain

data to achieve precise demand forecasting, optimized inventory management, and dynamic logistics route planning. Intelligent warehousing systems (such as AGV robots and automated vertical warehouses) and unmanned delivery technologies reduce reliance on manual labor, improve operational efficiency and accuracy, and ensure basic operations during special periods (e.g., pandemic lockdowns). Industrial internet and flexible manufacturing systems in production enable rapid production line adjustments to meet small-batch, multi-variety order demands, enhancing the supply side's agile response capability.

### (3) Strengthening Risk Early Warning and Scientific Decision-Making

Big data analytics platforms integrate internal supply chain data with external macroeconomic indicators, public sentiment metrics, and logistics data. By leveraging predictive modeling and simulation technologies, they enable early detection and assessment of potential supply chain disruptions. For instance, analyzing global pandemic trends, port congestion data, and weather conditions can help predict delays in raw material supply or logistics disruptions. Data-driven decision support systems provide managers with multi-scenario simulations, assisting them in scientific decision-making regarding supplier selection, inventory strategy formulation, and emergency resource allocation. This approach shifts the focus from reactive responses to proactive risk management.

### (4) Building an Elastic and Open Ecosystem

Cloud computing platforms and industrial internet enable supply chain enterprises, including cross-sector players like logistics providers and financial institutions, to operate within a shared, collaborative digital ecosystem. This networked collaboration facilitates resource sharing (e.g., shared warehousing and transportation capacity), complementary capabilities (e.g., coordinated production), and risk-sharing. When localized disruptions occur, the network can swiftly reconfigure resource flow paths by identifying alternative suppliers or transportation solutions, forming a resilient network structure of "multi-source supply and multi-path distribution." This significantly enhances the system's overall resilience and recovery capacity.

## 5 Implementation Pathways for Enhancing Supply Chain Resilience in Pharmaceuticals Through Digitalization

### (1) Establishing a Full-Chain Data Sharing and Trustworthy Platform for the Pharmaceutical and Healthcare Industry

Under government guidance and led by leading enterprises, all stakeholders in the pharmaceutical and healthcare industry chain will collaborate to establish a national or regional big data platform for the pharmaceutical and healthcare sector. Unified data standards, interface specifications, and security protocols will be formulated to facilitate compliant sharing of critical data across research, production, distribution, and utilization processes, while safeguarding corporate core trade secrets and patient privacy. The initiative will explore blockchain-based pharmaceutical traceability and regulatory sandbox models to provide foundational support for trustworthy data circulation and value extraction.

### (2) Deepening the Application and Integration of Intelligent Technologies in Key Processes

In manufacturing, we will promote smart manufacturing and digital twin technologies to build intelligent factories. For logistics and warehousing, we will accelerate pilot projects and applications of automated vertical warehouses, smart sorting systems, cold chain logistics monitoring, and drone/vehicle delivery. In retail and services, we will develop smart pharmacies and online medical consultation and prescription flow platforms. We will encourage the application of artificial intelligence in cutting-edge fields such as drug development, clinical trial design, and adverse reaction monitoring, thereby enhancing industrial innovation efficiency and resilience from the source.

### (3) Development of Digital-based Elastic Supply Chain Network Model

Drive enterprises to transition from traditional linear supply chain thinking to dynamic, open supply chain network thinking. Utilize digital tools to map comprehensive supply chain landscapes, identify critical nodes and single-point dependency risks. Proactively develop deep digital connections with key suppliers, and based on platform data, cultivate and certify a group of alternative or substitute suppliers to build a diversified supply system. Explore a distributed intelligent warehousing network of "central warehouses + regional warehouses + front-end micro-warehouses", dynamically adjusting inventory layouts in real-time based on demand data.

### (4) Establish and Improve the Governance and Guarantee System to Adapt to the Development of Digitalization

Refine laws and regulations governing digital supply chains to clarify data ownership, accountability, and privacy boundaries. Strengthen talent development in pharmaceutical digitalization, as interdisciplinary professionals with expertise in both medicine and digital technology are pivotal to successful transformation. Establish a routine cybersecurity protection framework and supply chain disruption emergency drill mechanism. Governments may incentivize enterprises to adopt digital resilience through procurement incentives, financial subsidies, and standard-setting initiatives, while creating cross-departmental collaborative oversight mechanisms for supply chain security.

## 6 Conclusion and Outlook

Digitalization serves as the core driver for enhancing supply chain resilience in the pharmaceutical and healthcare industry. Through four key mechanisms — information transparency, intelligent processes, data-driven decision-making, and network collaboration — it systematically strengthens the supply chain's predictive capacity, adaptability, and recovery resilience. In the future, competition in this sector will not only revolve around products and technologies but also center on the level of supply chain resilience. To advance digital empowerment, all stakeholders in the industrial chain must collaborate and steadily progress along the path of "platform foundation, technological empowerment, network restructuring, and governance support."

It should be noted that digital transformation itself is accompanied by new risks, such as

cybersecurity, data monopolies, and technological dependence. Therefore, in the process of enhancing resilience, it is essential to adhere to the principle of balancing development and security, and to build an inclusive, secure, and trustworthy digital supply chain ecosystem. Looking ahead, with the continuous evolution and integration of digital technologies, the supply chain of the pharmaceutical and healthcare industries will develop in a more intelligent, resilient, human-centered, and sustainable direction, making greater contributions to safeguarding public health and national security.

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