

Article

Has Digital Technology Empowerment Enhanced the Resilience of the Industrial Chain and Supply Chain?

Tiantian Gao ¹, Jun Wan ¹ and Jingwen Sun ^{2,*}

¹ Business School, Beijing Normal University, Beijing 100875, China; tiantiangao_bnu@163.com (T.G.); wanjun@bnu.edu.cn (J.W.)

² Postdoctoral Research Station, Institute of Finance and Banking, Chinese Academy of Social Sciences, Beijing 100710, China

* Correspondence: sjw_cass@163.com

Abstract

The new wave of technological revolution and industrial transformation has created unprecedented opportunities for enhancing the resilience of manufacturing, industrial, and supply chains. Using panel data from 31 Chinese provinces covering the period 2004–2022, this study develops a comprehensive indicator system to measure dual-chain resilience and examines the impact of digital technology empowerment on its development. The results show that digital technology empowerment significantly enhances dual-chain resilience (coefficient = 0.286, $p < 0.01$), and the findings remain robust across a series of endogeneity and robustness tests. Mediation analysis shows that digital technology empowerment enhances dual-chain resilience through two complementary mechanisms: factor reallocation and scale expansion. Heterogeneity analysis further reveals that the benefits of digital technology empowerment differ across industrial characteristics and supply-chain positions, with downstream spillover effects (coefficient = 0.321, $p < 0.01$) substantially exceeding upstream effects (coefficient = 0.083, $p < 0.05$). Enterprise heterogeneity analysis reveals that the resilience gains from digital technology empowerment are primarily concentrated among capable firms, regardless of their readiness to adopt digital technologies, suggesting that capability, rather than readiness alone, is the critical determinant of successful digital empowerment outcomes. Moreover, exogenous shocks exert heterogeneous influences on the digital empowerment–resilience relationship, highlighting the buffering role of dual-chain resilience in mitigating external disruptions. These findings enrich the theoretical understanding of how digital technology empowerment strengthens dual-chain resilience and provide policy implications for promoting digital transformation, improving industrial circulation systems, and implementing differentiated digital empowerment strategies.

Keywords: digital technology empowerment; resilience of the industrial chain and supply chain; Industrial Correlation Effect; underpinning; high-quality development



Academic Editor: Giada La Scalia

Received: 12 June 2026

Revised: 30 June 2026

Accepted: 3 July 2026

Published: 10 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Enhancing industrial and supply chain resilience has become a global policy priority, particularly following the disruptions caused by the COVID-19 pandemic [1], Sino–U.S. trade tensions, and the energy crisis triggered by regional conflicts. For example, the U.S. CHIPS and Science Act and the EU Critical Raw Materials Act both seek to reduce supply chain vulnerabilities and strengthen industrial resilience through strategic investment and digital monitoring. These initiatives reflect a growing consensus that supply chain

resilience is not only an issue of economic efficiency but also of national security and social stability [2,3]. Although digital technologies are widely regarded as a key driver of resilience in both developed and emerging economies, evidence on how and under what conditions digital technology empowerment enhances supply chain resilience remains fragmented and context-dependent.

For China, strengthening the resilience of manufacturing, industrial, and supply chains (hereafter, dual-chain resilience) is essential for maintaining smooth domestic economic circulation and achieving high-quality development. Supported by a series of opening-up policies, China's manufacturing sector has become increasingly integrated into global value chains and has steadily moved toward higher value-added segments, following a development path of stabilizing, supplementing, securing, and strengthening industrial chains. However, recent external shocks, including the Sino-U.S. trade tensions and global supply chain restructuring, have interrupted this upgrading process by accelerating regionalization and localization of production networks. Consequently, China faces increasing competitive pressure from both the relocation of labor-intensive industries to developing economies and the reshoring of high-end manufacturing to developed countries, exacerbating the long-standing challenge of being locked into the lower end of global value chains [4].

Despite substantial progress in industrial upgrading, many manufacturing sectors still lack complete and resilient supply chain systems, limiting their ability to withstand and recover from major external disruptions. An evaluation conducted by the Chinese Academy of Engineering in 2019 found that only six of China's 26 representative manufacturing industries possessed a high level of industrial security, indicating that most sectors remain constrained in terms of autonomous and controllable supply chain capabilities. Under the combined pressures of weakening demand, supply-side shocks, and declining expectations, China's traditional manufacturing advantages have shown signs of erosion [5]. Therefore, enhancing dual-chain resilience has become an urgent prerequisite for sustaining industrial competitiveness and promoting high-quality economic development.

Facing profound global technological and industrial transformation, the deep integration of digital technology empowerment with manufacturing has fundamentally reshaped industrial development [6]. Rapid advances in the digital economy have accelerated the adoption of big data, blockchain, cloud computing, artificial intelligence (AI), and other digital technologies, creating new opportunities for enterprise digital transformation and manufacturing upgrading [7]. More importantly, these technologies provide critical support for strengthening the resilience of industrial and supply chains through multiple channels. Big data analytics and AI enable real-time monitoring and predictive early warning of supply chain risks, allowing firms to anticipate disruptions before they occur [8]. Blockchain technology improves traceability and transparency across multi-tier supply chains, reducing information asymmetry and strengthening trust among supply chain participants [9]. Recent studies further suggest that the effectiveness of blockchain applications depends on a balanced combination of technological, organizational, and environmental conditions [10]. In addition, cloud computing and Internet of Things (IoT) technologies facilitate real-time information sharing and coordination across geographically dispersed production networks, mitigating the bullwhip effect and improving responsiveness to demand fluctuations [11,12]. Collectively, these digital capabilities enhance the risk resistance, rapid recovery, autonomous controllability, and competitive advantages of manufacturing, industrial, and supply chains, thereby strengthening dual-chain resilience.

According to publicly available data from the Cyberspace Administration of China, the number of high-tech digital enterprises in China has grown to 400,000, and technology-based small and medium-sized enterprises (SMEs) have reached 454,000. Enterprise R&D investment accounts for more than three quarters of total social R&D investment, and

enterprises participating in or leading national key R&D programs account for nearly 80%. The vitality and digital capabilities of enterprises are constantly improving (<http://politics.people.com.cn/n1/2023/0713/c1001-40034999.html> (accessed on 22 June 2026)). However, at present, the application of digital technologies faces problems such as “fragmentation” and “segmentation” at both the firm and industry levels. Many enterprises focus on their own digital construction while neglecting digital collaborative development with external parties. In particular, due to dual-chain resilience issues, the transmission of industrial linkages between upstream and downstream is not smooth, making the bullwhip effect increasingly prominent. This makes it difficult for digital technology applications to achieve the “ $1 + 1 > 2$ ” goal at the dual-chain level [13]. Against this background, it is necessary to analyze the impact and transmission mechanisms of digital technology empowerment on the dual-chain resilience of China’s manufacturing industry from the perspective of industrial linkages, so as to provide a reference for guiding enterprise digital technology empowerment and improving dual-chain resilience.

This paper explores the impact and mechanisms of digital technology empowerment on dual-chain resilience. Its marginal contributions are threefold. First, it empirically examines dual-chain resilience from an economic perspective, expanding relevant pathways in the digital economy context. Unlike most existing studies, which either take a management approach or offer theoretical discussions, this paper provides empirical evidence, offering reference value for both digital technology empowerment and industrial and supply chain theories. Second, it constructs a manufacturing dual-chain resilience indicator system, helping to understand China’s current state and historical evolution of dual-chain resilience, and thus supplementing the newly proposed policy concept of “industrial and supply chain resilience.” Third, it offers macro-level and micro-level optimization ideas for improving digital technology empowerment policies and dual-chain resilience. The study finds that digital technology empowerment generates spillover effects through upstream and downstream linkages, with downstream effects being more pronounced. Moreover, due to firm heterogeneity, both government and enterprises should pursue digital technology empowerment “prudently.”

The remainder of this paper is organized as follows. Section 2 presents the literature review and research hypotheses. Section 3 describes the research design. Section 4 reports the empirical results. Section 5 discusses the findings. Section 6 concludes and offers policy implications.

2. Literature Review and Research Hypotheses

2.1. The Connotation of Dual-Chain Resilience

Before analyzing the mechanisms linking digital technology empowerment and dual-chain resilience, it is necessary to clarify the concepts of industrial chain and supply chain. The supply chain, from a micro perspective, enhances efficiency from raw materials to final products through inter-enterprise collaboration. The industrial chain, from a meso perspective, improves industry and regional competitiveness via industrial ecosystems and economic networks [14]. The two are interconnected through a chain network that links micro product supply chains, supply chain collections, meso industrial linkages, and meso industrial and supply chains. With theoretical advances, scholars have attempted to integrate them. The supply chain facilitates the smooth operation of the industrial chain by coordinating multiple organizations, while the industrial chain allocates resources across sectors and provides institutional guarantees for the supply chain. Thus, they converge at the meso level, jointly forming a new economic organization that integrates value formation, social division of labor, process coordination, resource allocation, spatial temporal-layout, and efficiency.

Due to domestic and international instability, the security of industrial and supply chains has risen to the national level, shifting development philosophy from “efficiency” alone to both “efficiency” and “security.” Song and Yang (2022) defined dual-chain resilience as the ability to withstand major risks and recover quickly, even becoming stronger [15]. Shi and Lu (2023) viewed it as the ability to prevent breakage, maintain stability, adjust after shocks, and achieve chain upgrading [16]. Tao et al. (2023) defined it as restoring market linkages to a normal or better state after shocks [13]. The Research Group on Economic Security of Renmin University of China (2023) drew on capital circulation theory [17]. Other scholars decomposed resilience into autonomy, controllability, high digitalization, innovation, high added value, fairness, and smooth circulation [8,18,19]. Aligning with the dual circulation pattern, this paper defines dual-chain resilience as the ability to “stabilize,” “supplement,” “strengthen,” and “control” the chain when facing domestic and international shocks (See Figure 1). It includes four capacities: risk resistance (fundamental support), rapid recovery (dynamic supplement), leading competitiveness (driving industrial upgrading and breaking low-end lock-in), and autonomous controllability (core aspiration). dual-chain resilience thus serves as an “underpinning” guarantee for economic development, helping China avoid the middle-income trap and prevent forced economic downgrading.

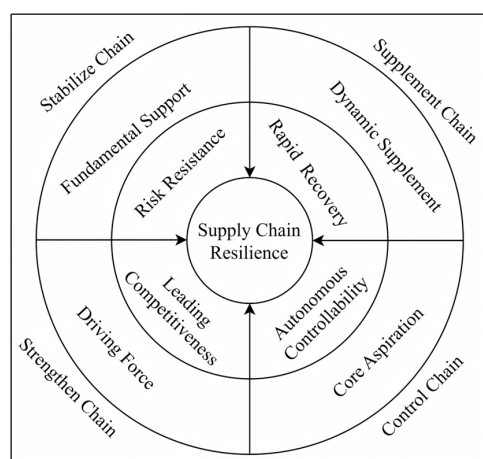


Figure 1. Analysis of The Connotation of Dual-Chain Resilience.

2.2. Research Hypotheses

Currently, there is a notable gap in both theoretical and empirical research directly linking digital technology empowerment to dual-chain resilience. While existing studies have extensively examined digital technology development from macro and meso perspectives, including its relationship with digital tools [20], copyright [21], high end equipment manufacturing [22], and economic development [23], and from micro perspectives focusing on firm definition [1], new product development performance [24], and organizational flexibility [25], the literature on resilience has primarily addressed its connotation, definition, and mechanisms from a management standpoint [8,26,27]. What remains under researched is a systematic empirical investigation, from an economics perspective, of how digital technology empowerment affects the resilience of industrial and supply chains, particularly through mediation channels and heterogeneous pathways. The specific focus of this paper is to fill this gap by providing econometric evidence using provincial-level panel data, identifying the mediating roles of factor reallocation and scale effects, and examining heterogeneity across industries, chain positions, and firm types.

Digital technology empowerment leads the transformation of the manufacturing industry and supply chains, redefining the new development path of manufacturing. First, digital technology has the characteristics of inclusiveness, interconnectivity, and innovation.

It breaks down the intangible boundaries formed by the division of labor and geographical location, reduces information asymmetry in transactions, eliminates the “information island” effect, alleviates the “bullwhip effect,” and improves the response speed, information use efficiency, and enterprise communication costs of industrial and supply chains when facing shocks, thereby promoting dual-chain resilience. Second, the development of digital technology has given rise to new business models and new industrial formats. These new industries and models accelerate the leading competitiveness of industrial and supply chains, driving technology-driven dual-chain resilience development in manufacturing. On the other hand, digital technology empowerment can fully release the potential in the development of the manufacturing industry and supply chains, producing a “ $1 + 1 > 2$ ” synergistic effect, accelerating early warning along the chain, reducing the transmission of various shock risks along the chain, and enabling rapid recovery. Finally, the popularization of digital technology facilitates a more intelligent and refined division of labor in the manufacturing industry and supply chains, promotes the reconstruction of the dual-chains, reduces resource redundancy in each link, and achieves technological and innovation upgrading of the manufacturing industry and supply chains, thereby solving existing bottlenecks such as “stranglehold” issues.

However, existing studies have primarily focused on the productivity and efficiency benefits of digital transformation, while relatively little attention has been paid to whether digital technology empowerment enhances the resilience of manufacturing, industrial, and supply chains. This study addresses this gap by examining the resilience effects of digital technology empowerment from the perspective of dual-chain resilience. Based on this, this paper proposes the following hypothesis.

H1: *Digital technology empowerment has a significant positive effect on dual-chain resilience.*

Digital technology empowerment can enhance dual-chain resilience through factor reallocation and scale effects. The factor reallocation effect, referring to the reorganization of factors and resources, better serves dual-chain resilience. As countries pursue high-end specialization in global value chains, manufacturing production links become crucial. Countries optimize comparative advantages by reallocating factors, replacing old patterns with fast responding digital services and concentrating resources on their strengths, thereby promoting dual-chain resilience [28]. Industrial and supply chains include natural resources, labor, technology, and capital, which classify manufacturing into resource, labor, technology, and capital-intensive types. Digital technology empowerment accelerates the shift from resource and labor-intensive industries to capital and technology intensive ones, enhancing the autonomous, controllable, and leading competitive capabilities of industrial and supply chains. This expands both the production possibility frontier and the innovation technology frontier. Enterprises use new technologies to develop, produce, and circulate goods, improving efficiency and reducing risks. Digital technology empowerment thus creates a sustainable cycle of “technological progress, industrial development, and technological progress,” ultimately enhancing dual-chain resilience.

The scale effect, including internal and external components, refers to the expansion of enterprise functions and scope over time, covering production, circulation, and sales [29]. Digital services and technologies reduce activity costs through improved resource utilization, creating economies of scale and expanding the production possibility frontier. Moreover, enterprise and industry agglomeration can strengthen themselves and generate positive spillovers, reducing costs, increasing information exchange, and improving efficiency via technology and infrastructure sharing, thereby shortening dual-chain response times. However, agglomeration may also cause problems such as environmental pollution and resource misallocation [30]. Digital technology empowerment can mitigate these issues

by increasing agglomeration and linkage within regions, enabling rational resource allocation, and fostering complementarity among factors, thus generating positive spillovers. Based on this, this paper proposes the following hypothesis.

H2: *Digital technology empowerment promotes the enhancement of dual-chain resilience through two mechanisms: factor reallocation effects and scale effects.*

The industrial chain and supply chain form a networked chain structure, and each part is interconnected. The position in the chain has heterogeneous effects on dual-chain resilience. Industrial linkages can be reflected in technological cooperation, production logistics, and other aspects among interconnected entities [31]. Specifically, from a forward linkage perspective, digital technology empowerment in upstream industries, namely the development and use of digital technologies, can enhance dual-chain resilience through factor reallocation effects and scale effects. For downstream industries, the impact on dual-chain resilience occurs through the input of intermediate goods [32]. Based on the “cooperative matching” effect, if upstream industries use digital technologies to improve efficiency, downstream enterprises will also undertake digital technology changes, breaking through existing technologies to catch up with upstream efficiency. Similarly, digital technology empowerment in downstream industries also generates positive feedback to upstream industries [33]. If downstream enterprises improve efficiency through digital technology empowerment, upstream enterprises will adjust their corresponding behaviors accordingly, providing products or services that embed more digital technology empowerment. Based on this, this paper proposes the following hypothesis.

H3: *The impact of digital technology empowerment on dual-chain resilience varies by chain position, with downstream industries having a greater influence on upstream industries.*

From a strategic risk management perspective, digital transformation in industrial enterprises involves not only technological upgrading but also the capability to identify, assess, and mitigate transformation-related risks. Recent studies on economic security suggest that the resilience of industrial systems depends on firms’ ability to manage cybersecurity threats, data governance challenges, and technology adoption risks throughout the digital transformation process [34,35]. Beyond technology availability, the effectiveness of digital technology empowerment is increasingly recognized as being contingent upon firms’ organizational capabilities, resource endowments, and institutional support. Ekhsan et al. demonstrate that successful digital technology acquisition and deployment require not only access to digital technologies but also sufficient absorptive capacity and organizational readiness [36]. Similarly, enterprise digital transformation is constrained by firms’ digital readiness to adopt digital technologies and their capability to effectively integrate and utilize them [37,38]. This capability-based perspective provides an important explanation for why the resilience benefits of digital technology empowerment may differ substantially across enterprises.

Based on differences in digital readiness and capability, enterprises can be classified into four stylized types. Type I enterprises exhibit both high digital readiness and strong digital capability. Type II enterprises demonstrate relatively high digital readiness but limited capability because of constraints in technological resources, financial support, or organizational resources. Type III enterprises exhibit both low digital readiness and limited capability, making digital transformation less likely in the short term. Type IV enterprises possess relatively strong implementation capability but comparatively lower readiness to pursue further digital transformation, often relying on existing operational models and accumulated competitive advantages. Rather than representing fixed organizational

characteristics, these four types describe enterprises' relative levels of digital readiness and implementation capability. Figure 2 presents the conceptual framework of the four enterprise types. The profit curve represents the net returns from digital technology empowerment after accounting for the associated implementation costs rather than conventional accounting profits. Because enterprises differ in their digital readiness and capability, the effectiveness of digital technology empowerment is expected to vary systematically according to enterprises' digital readiness and digital capability, leading to heterogeneous resilience outcomes.

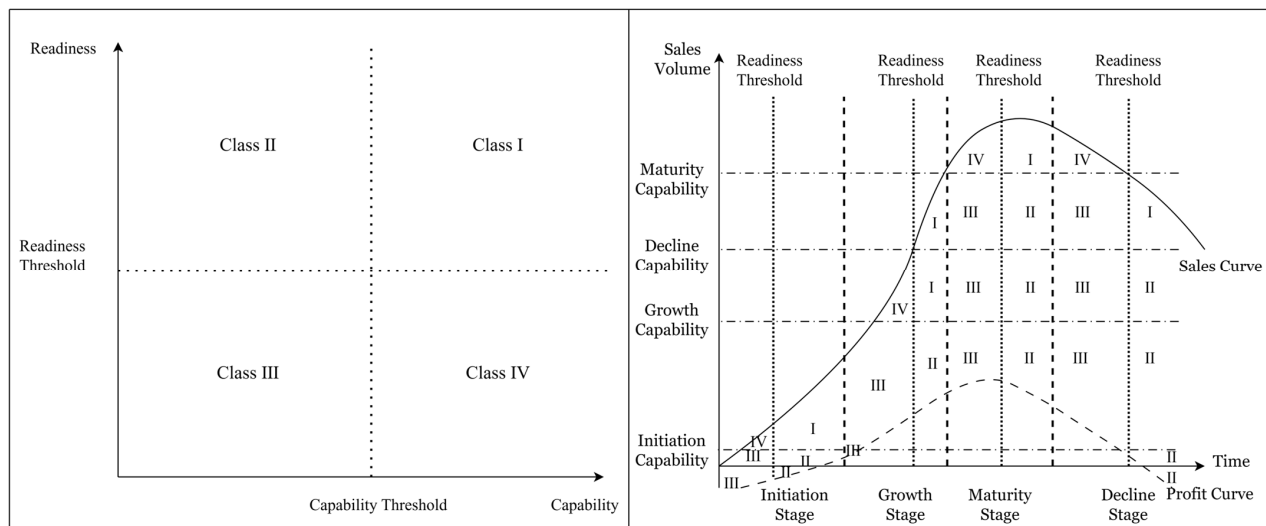


Figure 2. Enterprise Typology Based on Digital Readiness and Capability. The vertical dashed lines indicate the boundaries between different stages of the enterprise life cycle.

To empirically examine these firm-level differences using provincial-level panel data, we adopt an aggregation approach. Enterprise types are first identified at the firm level according to their digital technology empowerment indicators relative to the sample mean. Firm-level classifications are then aggregated to the provincial level by calculating the weighted average digital technology empowerment of each enterprise type, where the weights correspond to the number of firms belonging to each type within a province-year. This approach follows established studies linking micro-level heterogeneity to aggregate outcomes [39]. The underlying premise is that enterprises with higher digital readiness and stronger digital capability are more likely to translate digital technology empowerment into stronger regional dual-chain resilience through industrial linkages and regional production networks. Although this aggregation strategy cannot fully capture within-province firm heterogeneity, it provides an appropriate empirical approach for examining whether regional differences in enterprise composition are associated with variation in dual-chain resilience.

Moreover, existing studies have largely explained heterogeneous digital transformation outcomes using observable firm characteristics such as firm size, ownership, or industry type, whereas the roles of enterprises' digital readiness and implementation capability remain underexplored. To address this gap, this study classifies enterprises according to their readiness and capability and examines whether these differences shape the resilience effects of digital technology empowerment. Accordingly, we propose the following hypothesis:

H4: *The effect of digital technology empowerment on dual-chain resilience is expected to vary across enterprise types, with enterprises possessing stronger digital capability more likely to realize resilience gains from digital technology empowerment.*

The overall research framework of this paper is as follows (Figure 3).

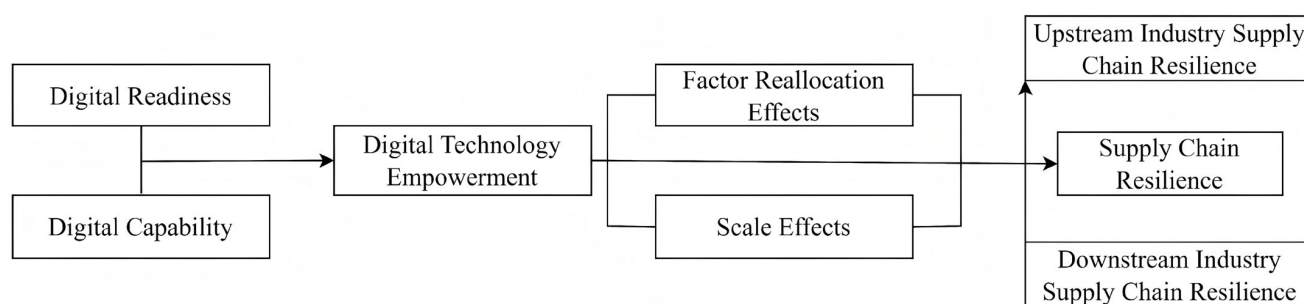


Figure 3. Overall Research Framework.

3. Materials and Methods

3.1. Data Source

The study uses panel data for 31 Chinese provinces covering the period 2004–2022. The data were compiled from multiple authoritative sources, including the China Macroeconomic Database, China Economic Net Statistical Database, China Statistical Yearbook, the Ministry of Finance of China, the Ministry of Ecology and Environment of China, and the Publicity Department of the Central Committee of China. Missing observations were supplemented using linear interpolation. All econometric analyses were conducted using Stata 17.0 (StataCorp LLC, College Station, TX, USA).

To mitigate the influence of outliers, all continuous variables were winsorized at the 1% level in both tails. This threshold is widely adopted in panel data studies in economics and management because it effectively reduces the influence of extreme observations while preserving sample variation [40]. By comparison, a 5% threshold may excessively compress the tails of the distribution and attenuate the estimated coefficients. As a robustness check, we also applied 2% and 5% winsorization thresholds, obtaining qualitatively identical results.

Table 1 reports the descriptive statistics of the main variables. The relatively large standard deviations of dual-chain resilience (resilience) and the Herfindahl–Hirschman Index (hhi) indicate substantial regional heterogeneity in industrial resilience and industrial concentration across Chinese provinces. By contrast, the remaining variables, including localization rate (national), enterprise profitability (profit), enterprise innovation capability (inno), industry factor intensity (element), labor quality (labour), Market concentration (hhi), economic development level (ecodev), and infrastructure support (infra), exhibit relatively moderate dispersion, suggesting comparatively stable distributions within the sample. Overall, the distributions of the explanatory and control variables are within reasonable ranges, providing a suitable basis for subsequent econometric analysis.

Table 1. Descriptive Statistics.

Variables	Observations	Mean	SD	Min	Max
resilience	589	10.568	8.634	0.011	31.472
digital	589	39.892	5.369	17.617	50.383
national	589	8.440	6.549	0.050	31.389
profit	589	13.828	7.255	0.466	33.400
inno	589	10.636	3.659	1.221	18.439
element	589	10.661	7.062	0.050	33.800
labour	589	14.617	6.893	0.222	28.522
hhi	589	49.915	14.172	1.416	85.241
ecodev	589	12.916	8.147	0.054	28.829
infra	589	15.791	7.401	0.059	31.713

3.2. Variable Description

3.2.1. Core Dependent Variable

Dual-chain resilience (resilience). Following Li et al. (2015) and Yu and Chen (2022), this study defines dual-chain resilience as the ability of manufacturing industrial and supply chains to withstand external shocks, recover rapidly, maintain autonomous controllability, and sustain long-term competitiveness under domestic and international market disruptions [41,42]. Based on this definition, we construct a comprehensive evaluation system comprising 4 dimensions, 8 sub-dimensions, and 16 indicators, following the principles of scientificity, representativeness, comprehensiveness, and feasibility [41,42]. Several indicators, such as market share, the number of Fortune Global 500 firms, and total manufacturing output, may appear to reflect industrial scale or competitiveness rather than resilience itself. However, resilience theory suggests that these indicators capture key dimensions of a system's ability to absorb, withstand, and recover from external shocks [43]. Within this framework, market share reflects an industry's recovery capacity by indicating its ability to regain a competitive position following disruptions. The presence of Fortune Global 500 firms serves as a proxy for the stabilizing role of core enterprises within industrial and supply-chain networks. Such firms typically possess diversified supplier networks, greater bargaining power, and stronger resource mobilization capabilities, enabling them to buffer external shocks and enhance systemic resilience [44,45]. Likewise, total manufacturing output proxies the buffering capacity of an industrial system by reflecting the redundancy and resource reserves available during periods of disruption, which are widely recognized as essential components of engineering and ecological resilience [46,47]. Accordingly, these indicators capture resilience-related characteristics beyond simple measures of industrial performance.

The indicator system is weighted using the entropy weight method, as reported in Table 2. Risk resistance (39.6%), rapid recovery (31.2%), and autonomous controllability (19.4%) receive substantially larger weights than leading competitiveness (9.8%).

Table 2. Evaluation Indicator System and Entropy Weights of China's Dual-chain Resilience.

Dimensions	No.	Domain Layer	Sub Indicator	Weight	Indicator Explanation	Attribute
A: Risk Resistance (0.396)	A1	Risk Prediction Capability (0.253)	Supply side prediction	0.235	Producer Price Index (PPI)	+
			Demand side prediction	0.018	Consumer Price Index (CPI)	+
	A2	Risk Resistance Capability (0.143)	Inventory clearing capacity	0.134	Difference between finished goods and total inventory of industrial enterprises	+
			Industrial foundation	0.009	Total manufacturing output value	+
B: Rapid Recovery (0.312)	B1	Industrial Efficiency (0.202)	Production efficiency	0.174	Manufacturing labor productivity	+
			Output capacity	0.028	Total profit of industrial enterprises	+
	B2	Recovery Capability (0.110)	Adjustment capacity	0.026	GDP energy consumption per unit	−
			Unemployment rate	0.084	Ratio of unemployed to total employed population	−

Table 2. Cont.

Dimensions	No.	Domain Layer	Sub Indicator	Weight	Indicator Explanation	Attribute
C: Autonomous Controllability (0.194)	C1	Autonomy Capability (0.079)	Share of innovative enterprises	0.058	Ratio of high tech manufacturing enterprises to total manufacturing enterprises	+
			Industrial output value ratio	0.021	Ratio of industrial output value to secondary industry output value	+
	C2	Controllability Capability (0.119)	Current asset turnover rate	0.082	Difference between total current assets and total assets of industrial enterprises	+
			Degree of import dependence	0.037	Ratio of import value to total import and export value of industrial enterprises	–
D: Leading Competitiveness (0.098)	D1	Leading Capability (0.019)	Market share	0.010	Ratio of manufacturing exports to world total exports	+
			Number of Fortune Global 500 enterprises	0.009	Number of Fortune Global 500 enterprises	+
	D2	R&D Capability (0.075)	R&D capital flow	0.052	R&D expenditure of industrial enterprises	+
			R&D talent flow	0.023	Full time equivalent of R&D personnel in industrial enterprises	+

Note: The sub-indicator “adjustment capacity” is measured by GDP energy consumption per unit, reflecting the ability of industries to adjust their energy intensity and production structures in response to external shocks or policy changes. A lower value indicates more efficient energy use and greater structural adjustment capacity. This specification helps ensure that the resilience index primarily captures the capacity to resist and recover from external shocks rather than competitive performance alone. At the sub-dimension level, risk prediction capability, industrial efficiency, risk resistance capability, controllability capability, and recovery capability each receive entropy weights exceeding 10%, suggesting that these dimensions contribute most to the overall resilience index. Using this indicator system, we calculate the dual-chain resilience index for all Chinese provinces during 2004–2022. The resulting index captures substantial regional variation in manufacturing resilience and provides the basis for the subsequent empirical analysis.

3.2.2. Core Explanatory Variable

Digital technology empowerment (digital). Following Bai and Zhang (2021), this study measures digital technology empowerment using the digital innovation dimension of the digital economy [48]. Digital innovation captures the technological foundation of digital transformation by reflecting the generation and diffusion of core digital technologies, making it an appropriate proxy for the degree of digital technology empowerment. Specifically, the index is constructed from five indicators that capture both digital innovation and digital infrastructure: the logarithm of the number of granted 5G technology patents, granted industrial Internet patents, granted e-commerce patents, Internet users, and websites. These indicators jointly reflect the technological innovation and digital infrastructure that underpin digital technology empowerment. The inclusion of both innovation-oriented and infrastructure-oriented indicators reflects the view that digital technology empowerment depends not only on the creation of digital technologies but also on the diffusion and accessibility of digital infrastructure. To ensure comparability across indicators, all variables are

first normalized and then aggregated into a composite digital technology empowerment index using the arithmetic mean method with equal weights. Detailed definitions of all indicators are reported in Table 3.

Table 3. Sub Indicators of Digital Technology Empowerment.

Variable	Indicator	Observations	Mean	Data Resource
Digital Innovation	Logarithm of granted patents for 5G technology	589	5.486	China Statistical Yearbook, China Economic Network Database
	Logarithm of granted patents for industrial internet	589	15.070	
	Logarithm of granted patents for e commerce	589	1.277	
	Logarithm of number of internet users	589	8.576	
	Logarithm of number of websites	589	1.505	

3.2.3. Mediating Variables

First, following the approach of Guo et al. (2022), this study uses the upgrading of industrial structure (upgrading) as a proxy for factor reallocation effects in the regression, measured specifically by industrial value added [31]. Following Wang (2022), relative capital intensity (intensity) is used to measure factor endowment intensity [49]. Second, following Dai and Yang (2022), the total number of employees in the manufacturing industry in a province is used to measure internal scale effects (size) [18]. Industrial diversity (Tvariety) is used to measure external scale effects. Industrial diversity is measured using the entropy weight method to calculate the employment share of a certain industry in a certain region. After derivation and decomposition (see the original footnote for the formula), it includes related diversification level (Rvariety) and unrelated diversification level (Uvariety). The former indicates the diversification level of sectors with strong industrial linkages, while the latter indicates the diversification level of sectors with weak industrial linkages.

3.2.4. Other Control Variables

Referring to existing studies on industrial chain resilience and supply chain resilience [5,10], this paper selects the following control variables. (1) Localization rate (national), measured by the proportion of state-owned enterprises to the total number of enterprises in each region. (2) Enterprise profitability (profit), measured by the logarithm of the total profits of industrial enterprises above the designated size. (3) Enterprise innovation capability (inno), measured by the logarithm of the number of invention patents granted to industrial enterprises above the designated size. (4) Industry factor intensity (element), measured by the ratio of industrial capital stock to the number of employees. (5) Labour quality (labour), measured by the logarithm of the number of students enrolled in regular higher education institutions, which serves as a proxy for regional human capital. (6) Market concentration (hhi), represented by the Herfindahl–Hirschman Index. (7) Economic development level (ecodev), measured by the ratio of industrial value added to regional GDP. (8) Infrastructure support (infra), measured by the logarithm of highway mileage.

3.3. Model Construction

Due to substantial missing data at the enterprise level, this paper attempts to investigate the impact of digital technology empowerment on dual-chain resilience at the provincial level, establishing the following regression model:

$$resilience_{it} = \alpha_0 + \alpha_1 digital_{it} + \alpha_2 controls_{it} + \varepsilon_{it} \quad (1)$$

Here, $resilience_{it}$ is the core dependent variable, representing dual-chain resilience. i and t denote province and year, respectively. $digital_{it}$ is the core explanatory variable, representing digital technology empowerment. $controls_{it}$ represents industry level and provincial level control variables. α_1 and α_2 are the variable coefficients, and ε_{it} is the random error term.

4. Results

4.1. Benchmark Regression

Table 4 reports the benchmark regression results based on Equation (1). Column (1) presents the baseline estimation without control variables or province and year fixed effects, whereas Column (2) incorporates all control variables together with province and year fixed effects. Across both specifications, the coefficient on digital technology empowerment (digital) remains positive and statistically significant. After controlling for observable characteristics and fixed effects, the estimated coefficient is 0.286 ($p < 0.01$), providing robust evidence that digital technology empowerment is positively associated with dual-chain resilience. Therefore, Hypothesis H1 is supported.

Table 4. Benchmark Regression Results.

Variable	(1) Resilience	(2) Resilience
digital	0.641 *** (0.0594)	0.286 *** (0.0342)
national		0.0974 ** (0.0442)
profit		0.115 ** (0.0586)
inno		0.749 *** (0.0652)
element		0.121 *** (0.0307)
labour		0.264 *** (0.0495)
hhi		0.0181 * (0.00937)
ecodev		0.750 *** (0.0430)
infra		0.272 *** (0.0441)
constant		1.559 (1.696)
Province fixed	No	Yes
Year fixed	No	Yes
Observations	589	589
R ²	0.6734	0.9397

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The same applies to all subsequent tables.

The estimated effect is not only statistically significant but also economically meaningful. Specifically, a one-standard-deviation increase in digital technology empowerment is associated with a 1.535-unit increase in the dual-chain resilience index, equivalent to approximately 14.5% of its sample mean, indicating that improvements in digital technology empowerment are associated with substantial gains in regional dual-chain resilience. Among the control variables, variables capturing industrial foundations (localization rate and industry factor intensity), enterprise characteristics (profitability and innovation capability), and regional development conditions (labor quality, economic development, and infrastructure support) all exhibit significantly positive coefficients. These findings suggest that both firm-level capabilities and regional economic conditions play important supporting roles in strengthening dual-chain resilience. Market concentration (hhi) is also positively associated with dual-chain resilience, although the estimated effect is comparatively smaller. Overall, the control variables behave largely as expected, providing additional support for the empirical specification.

4.2. Robustness Test

To examine whether the benchmark findings are sensitive to alternative variable definitions, model specifications, and potential endogeneity concerns, we conduct a series of robustness tests. Specifically, we replace both the dependent and core explanatory variables with alternative measures, perform sensitivity analyses using different weighting schemes, address potential endogeneity through an instrumental-variable approach, and further examine the stability of the results under exogenous shocks.

4.2.1. Replacing Variables

Because both the dependent variable and the core explanatory variable are composite indices, we first examine whether the benchmark results are robust to alternative measurements. Specifically, we replace the dual-chain resilience index with two alternative measures and substitute the digital technology empowerment index with an alternative indicator of digital economy development. Following Song (2023), we employ a counterfactual measure based on industrial productivity growth as an alternative proxy for dual-chain resilience [50]. Because the original indicator was developed to measure agricultural resilience, we modified the variable definitions and calculation procedure to better reflect the characteristics of manufacturing, industrial, and supply chains. Thus, we revise the formula as follows.

$$\left(\Delta E_r^{t+k}\right)^E = \sum_{i=1}^n g_N^{t+k} E_{ir}^t \quad (2)$$

Here, g_N^{t+k} is the national industrial production contraction or expansion rate, and E_{ir}^t is the industrial productivity of region i at time t , also representing the turning point of decline and recovery. The counterfactual difference is used to measure dual-chain resilience.

$$Newresilience = \frac{\left(\Delta E_r^{contraction}\right) - \left(\Delta E_r^{contraction}\right)^{expected}}{\left|\left(\Delta E_r^{contraction}\right)^{expected}\right|} \quad (3)$$

Here, $\Delta E_r^{contraction}$ is the actual change in industrial productivity, and $\left|\left(\Delta E_r^{contraction}\right)^{expected}\right|$ is the counterfactual change. The value of dual-chain resilience ranges between -1 and 1 , with values closer to 1 indicating stronger resilience.

The resulting alternative resilience index is then substituted into the benchmark regression. As reported in Table 5, the coefficient of digital technology empowerment remains positive and statistically significant, indicating that the benchmark findings are

robust to alternative measurements of the dependent variable. As an additional robustness check, we reconstruct the dual-chain resilience index using principal component analysis (PCA). Unlike the entropy weight method, which determines indicator weights according to information entropy, PCA extracts the dominant variation contained in the original indicators through dimensionality reduction. The benchmark results remain qualitatively unchanged, indicating that the estimated relationship is not sensitive to the weighting method used to construct the resilience index.

Table 5. Robustness Checks: Alternative Indicators.

Variables	(1) Replacing Dependent Variable	(2) Replacing Measurement Method	(3) Replacing Core Explanatory Variable	(4) Equal Weights	(5) Industry Level Test
	Newresilience	PCAreilience	Resilience	Equalresilience	Traderesilience
digital	0.849 *** (0.0361)	0.647 *** (0.0385)		0.251 *** (0.0370)	0.188 *** (0.0270)
Newdigital			0.520 *** (0.0351)		
Control	Yes	Yes	Yes	Yes	Yes
Observations	589	589	589	589	760
R ²	0.8591	0.7362	0.7380	0.9410	0.4681

Note: Robust standard errors are in parentheses. *** $p < 0.01$. The industry-level robustness test employs an alternative industry-year panel consisting of 40 manufacturing industries observed from 2004 to 2022 (760 industry-year observations).

As an additional robustness check, we replace the core explanatory variable with an alternative measure of digital technology empowerment to examine whether the benchmark findings are sensitive to variable specification. Following Zhang and Wang (2023), digital technology empowerment is proxied by the level of digital economy development, which is constructed from three dimensions: internet development, digital transaction development, and informatization development [51]. The resulting alternative indicator (Newdigital) is substituted into the benchmark model, and the results are reported in Table 5. The estimated coefficient remains positive and statistically significant, indicating that the positive relationship between digital technology empowerment and dual-chain resilience is robust to alternative operationalizations of the core explanatory variable. These results provide additional support for the robustness of the benchmark findings and further validate Hypothesis H1.

To further examine the sensitivity of the resilience index to the weighting structure, we reconstruct the index by assigning equal weights to the four resilience dimensions (Column (4), Equalresilience). The stability of the estimated coefficient after reweighting also suggests that the benchmark findings are not driven by the relatively lower weight assigned to the competitiveness dimension in the entropy-based index. The reweighted index is then used as the dependent variable in the benchmark regression. Digital technology empowerment continues to exert a positive and statistically significant effect (coefficient = 0.251, $p < 0.01$), with an estimated magnitude close to that reported in the benchmark specification. These results indicate that the main findings are not driven by the specific weighting scheme adopted in constructing the resilience index.

4.2.2. Robustness Check Using Industry-Level Resilience

As an additional robustness check, we examine whether the benchmark findings remain stable when dual-chain resilience is measured at the industry level rather than the provincial aggregate level. Industry-level resilience provides an alternative perspective on dual chain resilience by capturing sectoral variation in the capacity to withstand and recover from disruptions, complementing the provincial-level analysis. Following the measurement approach of Chen (2022), we construct an industry-level resilience index

for 40 manufacturing sectors using data from 2004 to 2022 (Traderesilience) [52]. This industry-year panel serves as an alternative dataset to test whether the main findings hold at the sectoral level [52]. According to the China Statistical Yearbook, 42 industrial sectors are classified as industrial enterprises above the designated size. Owing to data availability, 40 manufacturing industries are retained in the final sample. The regression results are reported in Table 5 Column (5). The coefficient of digital technology empowerment remains positive and statistically significant when the alternative industry-level resilience measure is employed. This consistency indicates that the benchmark findings are robust to alternative levels of measurement and suggests that the positive association between digital technology empowerment and dual-chain resilience is not driven by the specific construction of the baseline resilience index.

4.2.3. Endogeneity

Although the benchmark regressions include province and year fixed effects together with a comprehensive set of control variables, potential endogeneity may still arise from reverse causality, omitted variables, and measurement error. To further strengthen the identification of the estimated relationship, we employ an instrumental-variable (IV) approach. Following the Bartik shift-share approach [53,54], we construct a Bartik-style instrument by interacting the digitalization level of India's manufacturing sector with the historical number of Internet users per capita in each Chinese province in 2000, the earliest year for which consistent data are available ($\text{India_dig} \times \text{Internet_2000}$). The interaction generates province-specific variation in exposure to global digitalization trends while remaining predetermined with respect to subsequent provincial dual-chain resilience.

The validity of the instrumental variable relies on both relevance and the exclusion restriction. Regarding relevance, provinces with higher historical Internet penetration were better positioned to absorb and benefit from global digital technology diffusion, making them more responsive to external digitalization trends. This argument is also consistent with the technology diffusion literature, which emphasizes that regional infrastructure conditions shape the capacity to effectively adopt and utilize digital technologies, thereby influencing the benefits that regions derive from digital transformation [55]. Moreover, the shift-share interaction design follows the widely adopted Bartik framework, in which regional exposure to common external shocks generates plausibly exogenous variation across locations [54,56].

The exclusion restriction requires that India's manufacturing digitalization affects provincial dual-chain resilience in China only through domestic digital technology empowerment rather than through alternative channels. This assumption is plausible because India's digital transformation is unlikely to generate province-specific effects on China's manufacturing resilience directly. Instead, any common global technology shocks, international supply-chain adjustments, or worldwide digitalization trends are absorbed by year fixed effects, while province fixed effects and regional control variables account for persistent regional heterogeneity. Consequently, the identifying variation is primarily driven by differences in provinces' exposure to external digitalization trends rather than by local resilience conditions. Although the exclusion restriction cannot be tested directly, the strong first-stage relationship together with conventional identification diagnostics provides empirical support for the validity of the proposed instrument [57].

Table 6 Column (1) reports the IV estimation results. The first-stage coefficient is positive and statistically significant, indicating that the instrument is strongly correlated with digital technology empowerment. The Kleibergen Paap rk LM statistic rejects the null hypothesis of underidentification ($p < 0.05$), while the Cragg Donald Wald F statistic (132.37) substantially exceeds the Stock Yogo critical value, indicating that the instrument

is not weak. Although no instrumental-variable strategy can completely eliminate all endogeneity concerns, these diagnostic tests substantially strengthen the credibility of the benchmark estimates.

Table 6. Robustness Checks: Endogeneity Issues and Exogenous Shocks.

Variables	(1) Endogeneity Issue		(2) Exogenous Shock	
	First Stage	Second Stage	Financial-System Shocks	Trade-Related Shocks
	Digital	Resilience	Resilience	Resilience
India_dig × Internet_2000	0.412 *** (0.0891)			
digital		0.804 *** (0.1584)	0.261 *** (0.0328)	0.261 *** (0.0328)
Shock Dummy			(absorbed)	(absorbed)
FinanceCrisis * digital			0.160 * (0.0907)	
Friction * digital				0.456 *** (0.1389)
Marginal effect of digital in shock period			0.421 *** (0.0964)	0.717 *** (0.1427)
Controls	Yes	Yes	Yes	Yes
LM statistic		5.6532		
Wald P		0.0000		
Wald F		(132.37)		
Observations	589	589	589	589
R ²	0.5823	-	0.7859	0.4664

Note: Robust standard errors are in parentheses. *** $p < 0.01$, * $p < 0.1$. Shock dummy variables are absorbed by year fixed effects and are not separately reported. Marginal effects are calculated as $(\beta_{\text{digital}} + \beta_{\text{interaction}})$ for the shock period, with standard errors computed using the Delta method.

4.2.4. Exogenous Shocks

To further assess the robustness of the benchmark findings under major external disturbances, we examine two representative exogenous shocks during the sample period: the 2008 global financial crisis and the escalation of the Sino–U.S. trade friction in 2018. These events capture two distinct sources of disruption to manufacturing, industrial, and supply chains, namely financial-system shocks and trade-related shocks. Specifically, dummy variables are constructed for each event, taking the value of 0 before the occurrence of the shock and 1 thereafter. These dummy variables are interacted with digital technology empowerment and incorporated into the benchmark regression.

The estimation results are reported in Column (2) of Table 6. The interaction terms are positive and statistically significant, indicating that digital technology empowerment plays a stronger resilience-enhancing role following major external shocks. Moreover, the estimated effect is larger under the Sino–U.S. trade friction than under the global financial crisis. A plausible explanation is that trade frictions directly disrupt production networks, intermediate goods supply, and cross-border industrial linkages, whereas financial crises primarily affect firms through financing constraints and macroeconomic uncertainty. Consequently, digital technologies become particularly valuable in improving information sharing, production coordination, and supply-chain adaptability when manufacturing systems face trade-related disruptions.

These findings suggest that digital technology empowerment not only enhances dual-chain resilience under normal conditions but also strengthens the capacity of manufacturing, industrial, and supply chains to withstand and adapt to major external shocks. This

evidence further supports the robustness of the benchmark results and provides additional support for Hypothesis H1.

4.3. Mechanism Analysis

To better understand how digital technology empowerment enhances dual-chain resilience, we examine two potential mechanisms suggested by the theoretical framework: the factor reallocation effects and the scale effects. Following Jiang (2022), we employ a mediation analysis to test whether digital technology empowerment improves dual-chain resilience by facilitating more efficient resource allocation and expanding production scale [58]. Columns (1) and (2) of Table 7 present the mediation results for the factor reallocation effects. Digital technology empowerment significantly promotes industrial upgrading and improves factor allocation intensity. When these mediators are incorporated into the benchmark regression, both remain positively and significantly associated with dual-chain resilience, while the coefficient of digital technology empowerment declines but remains significant. These results indicate that digital technology empowerment enhances dual-chain resilience partly by facilitating industrial upgrading and improving the efficiency of factor allocation. More efficient allocation of capital, labor, and technological resources enables manufacturing industries to respond more effectively to external disruptions, thereby strengthening the resilience of industrial and supply chains.

Table 7. Mechanism Analysis Results.

Variable	Factor Reallocation Effects		Scale Effects		
	(1) Upgrading	(2) Intensity	Internal	External	
			(3) Size	(4) Rvariety	(5) Uvariety
Digital Technology Empowerment → Mediator					
digital	0.165 *** (0.0441)	0.225 *** (0.0410)	0.170 * (0.0956)	0.100 *** (0.0264)	0.025 (0.0381)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	589	589	589	520	240
R ²	0.3096	0.4887	0.1815	0.7153	0.8454
Mediator → Dual-chain Resilience					
digital	0.251 *** (0.0351)	0.248 *** (0.0356)	0.243 *** (0.0362)	0.261 *** (0.0339)	0.280 *** (0.034)
mediator	0.184 ** (0.0821)	0.196 ** (0.0873)	0.231 *** (0.0714)	0.152 ** (0.0682)	0.045 (0.0537)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	589	589	589	520	240
R ²	0.4413	0.3410	0.2218	0.7305	0.8499

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The same applies to all subsequent tables.

Columns (3)–(5) report the mediation results for the scale effects. Digital technology empowerment significantly promotes internal scale expansion and related diversification, both of which exhibit significant positive mediation effects. By contrast, unrelated diversification is neither significantly influenced by digital technology empowerment nor significantly associated with dual-chain resilience. This finding suggests that digital technologies primarily strengthen resilience by deepening production networks and reinforcing linkages within related industries rather than by expanding into unrelated sectors. Such related expansion facilitates resource sharing, knowledge spillovers, and supply-chain coordination, whereas unrelated diversification generates relatively limited resilience benefits. These results indicate that the scale effects constitute an important transmission channel through which digital technology empowerment enhances dual-chain resilience.

Taken together, the mediation results suggest that digital technology empowerment enhances dual-chain resilience through two complementary pathways: efficiency-enhancing mechanisms (factor reallocation) and capacity-expanding mechanisms (scale expansion). These findings provide a more comprehensive explanation for the benchmark results and offer empirical support for Hypothesis H2.

4.4. Heterogeneity Analysis

4.4.1. Heterogeneity Analysis Based on Differences in Digital Technology Utilization Across Industries

The effectiveness of digital technology empowerment may vary with the extent to which digital technologies have been integrated into industrial production. To examine this heterogeneity, industries are first classified into high- and low-utilization groups according to their digital technology utilization rates. Following the logic that new products embody firms' digital technologies and innovation outcomes, digital technology utilization is measured by the ratio of new-product profits to production costs for industrial enterprises above the designated size. A higher ratio indicates that digital technologies have been more effectively translated into commercially valuable production activities. Based on this criterion, 17 industries are classified as low-utilization industries (e.g., coal mining), while 23 industries are classified as high-utilization industries (e.g., instrument and meter manufacturing). To further explore whether technological characteristics matter within digitally lagging sectors, the low-utilization group is subsequently divided into high-technology and low-technology industries.

The estimation results are reported in Table 8. Column (4) shows that digital technology empowerment has a positive and statistically significant effect on dual-chain resilience in industries with high digital technology utilization ($\beta = 0.346$, $p < 0.01$). By contrast, Column (1) shows that the corresponding coefficient for low-utilization industries is positive but statistically insignificant ($\beta = 0.310$, $p > 0.10$), indicating that digital technology empowerment alone is insufficient to generate resilience gains where digital technologies are not widely utilized. Further decomposition of the low-utilization group reveals that digital technology empowerment remains positively and significantly associated with dual-chain resilience in high-technology industries ($\beta = 0.337$, $p < 0.01$, Column (2)), whereas the estimated coefficient is close to zero and statistically insignificant in low-technology industries ($\beta = -0.004$, $p > 0.10$, Column (3)).

These findings suggest that the resilience-enhancing effect of digital technology empowerment depends not only on the level of digital technology utilization but also on industries' technological characteristics, with significant resilience gains concentrated in industries possessing either strong digital utilization or stronger technological foundations.

4.4.2. Heterogeneity Analysis Based on Upstream and Downstream Differences Across Industries

Because industrial and supply chains operate through vertically connected production networks, the resilience effects of digital technology empowerment may propagate differently across upstream and downstream segments. Upstream firms mainly provide intermediate inputs and production factors, whereas downstream firms interact more directly with markets and final demand. Consequently, digital technology empowerment may generate heterogeneous resilience effects along the industrial chain.

$$R_{it} = \beta_0 + \beta_{front}digital_front_{it} + \beta_{back}digital_back_{it} + \beta_2controls_{it} + \varepsilon_{it} \quad (4)$$

Here, R_{it} represents the dual-chain resilience of industry j (equivalent to *resilience_{it}* at the industry level), where β_{front} and β_{back} capture the spillover effects of upstream and downstream digital technology empowerment on industry-level dual-chain resilience,

respectively. Following Wang and Dong (2020), we construct indicators of upstream and downstream digital technology empowerment to capture potential spillover effects along industrial linkages [59]. The estimation results are reported in Column (5) of Table 8. Both upstream and downstream digital technology empowerment exhibit positive and statistically significant effects on dual-chain resilience. Specifically, the estimated coefficient for downstream digital technology empowerment is 0.321 ($p < 0.01$), whereas the corresponding upstream coefficient is 0.083 ($p < 0.05$). The downstream effect is therefore approximately four times larger than the upstream effect, indicating substantial heterogeneity in the resilience-enhancing effects of digital technology empowerment across different positions in the industrial chain. The results provide empirical support for Hypothesis H3.

Table 8. Differences in Digital Technology Utilization across Industries.

Variable	Low Digital Technology Utilization			High Digital Technology Utilization	Upstream and Downstream Differences
	(1) Resilience	(2) Resilience	(3) Resilience	(4) Resilience	(5) R
digital	0.310 (0.3930)			0.346 *** (0.0655)	
digital_high		0.337 *** (0.03448)			
digital_low			−0.004 (0.0433)		
digital_front					0.083 ** (0.0327)
digital_back					0.321 *** (0.0769)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	323	247	76	437	558
R ²	0.8047	0.2584	0.4621	0.7705	0.1280

Note: Robust standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$. Columns (1) to (4) classify industries based on their digital technology utilization rate (defined as the ratio of new product profits to costs for enterprises above a designated size), distinguishing low utilization industries (17 sectors) from high utilization industries (23 sectors). Column (5) reports results from Equation (4), where the dependent variable “R” represents the industry level dual-chain resilience (R_{it}), corresponding to resilience_it in the main analysis but measured at the industry level rather than the provincial level.

4.4.3. Heterogeneity Analysis Based on Enterprise Readiness and Capability for Digital Technology Empowerment

To bridge the micro–macro gap, we adopt an aggregation strategy that links firm-level classifications to provincial-level outcomes. Enterprises are first classified into four types according to their digital technology empowerment scores relative to the sample mean. Among large enterprises, those above and below the mean are classified as Type I (Idigital) and Type IV (IVdigital), respectively, whereas among small and micro enterprises, those above and below the mean are classified as Type II (IIdigital) and Type III (IIIdigital). The firm-level classifications are then aggregated to the provincial level using province-weighted averages, following the regional resilience literature, which emphasizes that regional resilience is shaped by the composition of firms within a region [60].

The estimation results are reported in Table 9. Digital technology empowerment is positively and significantly associated with dual-chain resilience for Type I enterprises ($\beta = 0.440$, $p < 0.01$) and Type IV enterprises ($\beta = 0.243$, $p < 0.01$), whereas the estimated coefficients for Type II enterprises ($\beta = 0.208$, $p > 0.10$) and Type III enterprises ($\beta = -0.032$, $p > 0.10$) are statistically insignificant. These results indicate that the resilience-enhancing effect of digital technology empowerment varies across enterprise types and is more evident among enterprises with stronger digital capability. Because formal coefficient comparison

tests are not conducted in this study, the relative importance of enterprise readiness and capability should be interpreted with caution. The heterogeneous patterns observed across the four enterprise types provide empirical support for Hypothesis H4.

Table 9. Four Types of Enterprise Digital Technology Empowerment.

Variable	(1) Resilience	(2) Resilience	(3) Resilience	(4) Resilience
I digital	0.440 *** (0.0615)			
II digital		0.208 (0.3858)		
III digital			−0.032 (0.0411)	
IV digital				0.243 *** (0.0594)
Controls	Yes	Yes	Yes	Yes
Observations	589	589	589	589
R ²	0.8373	0.7790	0.6491	0.7491

Note: Robust standard errors are in parentheses. *** $p < 0.01$.

5. Discussion

The findings suggest that digital technology empowerment enhances dual-chain resilience not simply by improving operational efficiency, but by strengthening the adaptive capacity of manufacturing systems. Consistent with the supply chain resilience literature, resilient industrial systems depend on visibility, flexibility, rapid coordination, and adaptive resource reconfiguration rather than operational efficiency alone [61–63]. While previous studies have primarily emphasized the role of digital technologies in reducing information asymmetry, improving coordination efficiency, and enabling real-time decision making [8,9,11], our findings further demonstrate that digital technology empowerment improves the capacity of industrial systems to absorb, adapt to, and recover from external disruptions. More importantly, the mediation results indicate that factor reallocation and scale expansion operate as complementary mechanisms rather than independent channels. This finding extends the adaptive resilience perspective by showing that digital technologies strengthen resilience through both efficiency-enhancing and capacity-expanding processes, thereby providing empirical support for the theoretical framework proposed in this study [43,46,64].

Heterogeneity results also indicate that the resilience benefits of digital technology empowerment are unevenly distributed across industries. Rather than generating uniform improvements once digital technologies are adopted, their effectiveness depends on industries' ability to integrate and utilize these technologies through complementary organizational capabilities. Industries with higher digital technology utilization exhibit significantly stronger resilience gains, whereas the corresponding effects remain insignificant in industries with weak digital foundations. Likewise, digital technology empowerment continues to improve resilience in high-technology industries but generates limited benefits in low-technology industries. These findings are consistent with the capability-based perspective of digital transformation and absorptive capacity theory, which argues that the returns to technological investment depend critically on firms' ability to recognize, assimilate, and exploit new knowledge [65–68]. They also support recent evidence that digital transformation requires complementary investments in organizational capability, skilled human capital, and institutional support rather than technology adoption alone [68]. Accordingly, our study extends the existing literature by demonstrating that digital technology

empowerment becomes an effective resilience-enhancing strategy only when supported by sufficient technological capabilities and organizational readiness.

The heterogeneous patterns observed across industrial linkages and enterprise types further refine the understanding of how digital technology empowerment generates resilience. The stronger downstream effects suggest that the resilience benefits of digital technologies propagate through production networks rather than remaining confined to individual firms. Because downstream industries are more closely connected to final markets and customer demand, improvements in digital coordination, information sharing, and production scheduling are more readily transmitted throughout the industrial chain. This interpretation is broadly consistent with studies on global value chains and industrial spillovers, which emphasize that firms' positions within production networks shape innovation diffusion and economic outcomes [69,70]. Similarly, the enterprise-level heterogeneity analysis suggests that resilience gains are concentrated among enterprises with stronger digital capabilities. Rather than indicating that digital readiness is unimportant, these findings imply that organizational capability constitutes a necessary condition for converting digital investment into resilience improvements, reinforcing the dynamic capability perspective that competitive advantage depends on firms' ability to continuously integrate, build, and reconfigure internal and external resources [66].

Finally, the robustness analyses reinforce the credibility of the proposed theoretical framework. The consistency of the estimated effects across alternative variable specifications, weighting methods, industry-level measures, and instrumental-variable estimation suggests that the observed relationship is unlikely to be driven by model specification or measurement choices. Moreover, the exogenous-shock analysis demonstrates that digital technology empowerment remains effective under both financial and trade-related disruptions, indicating that digital capabilities contribute not only to routine operational performance but also to adaptive resilience during periods of heightened uncertainty. Similar conclusions have been reported in recent studies examining supply-chain resilience under major external shocks, particularly the COVID-19 pandemic [63,71,72]. These findings suggest that digital technology empowerment should be conceptualized as a resilience-enabling capability rather than merely a productivity-enhancing technology.

Taken together, these findings reconceptualize digital technology empowerment as a resilience-enabling capability rather than merely a productivity-enhancing technology, thereby extending the digital transformation literature beyond efficiency-oriented explanations. They further demonstrate that the resilience benefits of digital technology empowerment depend on complementary organizational capabilities and absorptive capacity, suggesting that technology adoption alone is insufficient to strengthen industrial resilience. More broadly, this study contributes to the emerging literature on industrial resilience by showing that digital technology empowerment, enterprise capability, and industrial network position jointly shape manufacturing dual-chain resilience, highlighting the need to view these factors as complementary rather than independent determinants.

6. Conclusions

This study examines how digital technology empowerment influences the resilience of China's manufacturing, industrial, and supply chains using provincial panel data from 2004 to 2022. The findings provide new evidence that digital technology empowerment should be viewed not only as a driver of digital transformation but also as an important source of manufacturing resilience under an increasingly uncertain global environment. Collectively, these findings provide empirical support for the theoretical framework developed in this study.

Four main conclusions can be drawn from this study, corresponding to the proposed hypotheses. First, Hypothesis H1 is supported. Digital technology empowerment exerts a positive and statistically significant effect on dual-chain resilience ($\beta = 0.286, p < 0.01$), and this relationship remains robust across alternative variable specifications, industry-level analyses, instrumental-variable estimation, and exogenous-shock tests. Second, Hypothesis H2 is supported. The mechanism analysis indicates that digital technology empowerment enhances dual-chain resilience through both factor reallocation effects and scale effects. Specifically, industrial upgrading ($\beta = 0.184, p < 0.05$), capital intensity ($\beta = 0.196, p < 0.05$), internal scale ($\beta = 0.231, p < 0.01$), and related diversification ($\beta = 0.152, p < 0.05$) each serve as significant mediating channels. Third, Hypothesis H3 is supported. The resilience-enhancing effects of digital technology empowerment differ across industrial linkages, with downstream industries exhibiting substantially larger spillover effects ($\beta = 0.321, p < 0.01$) than upstream industries ($\beta = 0.083, p < 0.05$), suggesting that digital transformation generates resilience gains through production-network interactions. Finally, Hypothesis H4 is supported. The resilience benefits of digital technology empowerment vary across enterprise types. Significant positive effects are observed for Type I enterprises ($\beta = 0.440, p < 0.01$) and Type IV enterprises ($\beta = 0.243, p < 0.01$), whereas the effects for Type II and Type III enterprises are statistically insignificant. These findings suggest that digital capability, rather than digital readiness alone, plays a more important role in translating digital technology empowerment into resilience improvements.

These findings carry several practical implications. Rather than adopting a uniform digitalization strategy, policymakers should tailor digital transformation policies to industry characteristics, supply-chain positions, and enterprise capabilities. Consistent with the heterogeneous results, industries with stronger digital technology utilization and technological foundations should be prioritized for advanced digital innovation, data-sharing platforms, and institutional support to further strengthen resilience. By contrast, industries with weaker digital capabilities are unlikely to benefit from digital investment alone. In these sectors, policy should first focus on strengthening complementary capabilities, including digital infrastructure, workforce skills, organizational upgrading, and access to finance, before promoting large-scale digital transformation. Moreover, because the downstream spillover effects are substantially stronger than the upstream effects identified in this study, prioritizing digital capability building in downstream industries may generate broader resilience gains that diffuse throughout manufacturing supply networks.

The enterprise-level heterogeneity results further suggest that policy interventions should distinguish between different combinations of digital readiness and capability rather than simply encouraging digital adoption. For enterprises that are both digitally ready and capable (Type I), policy should emphasize innovation leadership by supporting frontier digital applications, collaborative innovation, and demonstration projects. Enterprises with strong readiness but limited capability (Type II) require capability-building policies, such as technical training, digital consulting, financing support, and access to shared digital platforms, to overcome resource constraints. By contrast, enterprises that possess sufficient capability but remain less digitally ready (Type IV) may benefit more from incentive-based policies that encourage digital adoption through performance evaluation, competitive benchmarking, or market-based mechanisms. For enterprises lacking both readiness and capability (Type III), priority should be placed on strengthening fundamental organizational capabilities before promoting large-scale digital investment. Overall, the results suggest that effective digital transformation policies should prioritize capability building alongside technology adoption, rather than relying on one-size-fits-all digitalization strategies.

Despite these contributions, several limitations warrant consideration. First, owing to data availability, the analysis is limited to Chinese provincial and industry-level data from

2004 to 2022, which may not fully capture post-pandemic industrial restructuring, firm-level heterogeneity, or within-province dynamics arising from the aggregation of enterprise classifications. Second, digital technology empowerment is measured using patent- and internet-related indicators, while certain components of the dual-chain resilience index may partly reflect industrial competitiveness, suggesting that both constructs could be further refined using richer firm-level or survey-based data. Third, although multiple robustness checks, mediation analyses, and instrumental-variable estimation strengthen the credibility of the findings, endogeneity concerns cannot be completely ruled out because the mediation analysis remains correlational and the exclusion restriction of the shift-share instrument cannot be directly tested. Future research could address these limitations by employing more recent and firm-level panel data, richer digitalization measures, policy shocks, or natural experiments for stronger causal identification, and cross-country or nonlinear analyses to further examine the generalizability of the proposed framework.

Author Contributions: Conceptualization, T.G.; methodology, T.G. and J.W.; software, T.G.; validation, T.G.; formal analysis, T.G.; investigation, T.G.; resources, T.G. and J.W.; data curation, T.G.; writing-original draft preparation, T.G.; writing-review and editing, T.G. and J.S.; visualization, T.G. and J.S.; supervision, J.S.; project administration, T.G.; funding acquisition, T.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Beijing Postdoctoral Research Foundation, grant number 20250120.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study are obtained from publicly available sources, including the China Macroeconomic Database, the China Economic Network Statistical Database, the China Statistical Yearbook, the Ministry of Finance of China, the Ministry of Ecology and Environment of China, and the Publicity Department of the Central Committee of China. The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Some data are subject to third-party restrictions and are not publicly accessible; however, the authors can assist with access procedures where permitted.

Acknowledgments: The authors gratefully acknowledge the valuable feedback and constructive suggestions that contributed to the improvement of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. OECD. Global supply chains at work: A tale of three products to fight COVID-19. In *OECD Policy Responses to Coronavirus (COVID-19)*; OECD Publishing: Paris, France, 2022; pp. 1–24. [\[CrossRef\]](#)
2. Taylor, M. The US CHIPS and Science Act of 2022. *MRS Bull.* **2023**, *48*, 874–879. [\[CrossRef\]](#)
3. Hool, A.; Helbig, C.; Wierink, G. Challenges and opportunities of the European Critical Raw Materials Act. *Min. Econ.* **2024**, *37*, 661–668. [\[CrossRef\]](#)
4. Wang, C.; Wang, H. Safety risk characteristics and coping strategies of China's industrial chain. *Economist* **2023**, *45*, 57–67. [\[CrossRef\]](#)
5. Dai, X. International competitiveness of China's manufacturing industry: Measurement based on trade value added. *China Ind. Econ.* **2015**, *322*, 78–88.
6. Institute of Industrial Economics of Chinese Academy of Social Sciences; Shi, D. Industrial stable growth: International experience, realistic challenges and policy orientation. *China Ind. Econ.* **2022**, *407*, 5–26.
7. Xiao, T.; Sun, R.; Yuan, C.; Sun, J. Enterprise digital transformation, human capital structure adjustment and labor income share. *Manag. World* **2022**, *38*, 220–237.
8. Ivanov, D.; Dolgui, A. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Prod. Plan. Control* **2021**, *32*, 775–788. [\[CrossRef\]](#)

9. Kshetri, N. Blockchain and sustainable supply chain management in developing countries. *Int. J. Inf. Manag.* **2021**, *60*, 102376. [CrossRef]
10. Chittipaka, V.; Kumar, S.; Sivarajah, U.; Bowden, J.L.H.; Baral, M.M. Blockchain technology for supply chains operating in emerging markets: An empirical examination of technology-organization-environment (TOE) framework. *Ann. Oper. Res.* **2023**, *327*, 465–492. [CrossRef]
11. Ben-Daya, M.; Hassini, E.; Bahroun, Z. Internet of things and supply chain management: A literature review. *Int. J. Prod. Res.* **2019**, *57*, 4719–4742. [CrossRef]
12. Cao, Q.; Schniederjans, D.G.; Schniederjans, M. Establishing the use of cloud computing in supply chain management. *Oper. Manag. Res.* **2017**, *10*, 47–63. [CrossRef]
13. Tao, F.; Wang, X.; Xu, Y.; Zhu, P. Digital transformation, industrial chain and supply chain resilience and enterprise productivity. *China Ind. Econ.* **2023**, *5*, 118–136.
14. Liu, G. Differences and connections among industrial chain, supply chain and industrial cluster. *Acad. Exch.* **2010**, *12*, 78–80.
15. Song, H.; Yang, Y. Connotation and development path of modernization of China's industrial chain and supply chain. *J. Renmin Univ. China* **2022**, *36*, 120–134.
16. Shi, J.; Lu, D. Research on enhancing the resilience and security level of industrial chain and supply chain [In Chinese]. *Res. Financ. Econ. Issues* **2023**, *2*, 3–13.
17. Research Group on Economic Security; Renmin University of China; Shen, Y.; Chen, R.; Zhu, Y. Research on enhancing the resilience and security level of industrial chain and supply chain: Based on Marx's theory of capital circulation [In Chinese]. *Soc. Sci. Chin. High. Educ. Inst.* **2023**, *2*, 64–158.
18. Dai, X.; Yang, S. Digital empowerment, sources of digital input and green transformation of manufacturing industry. *China Ind. Econ.* **2022**, *9*, 83–101.
19. Wang, J. Research on the co-integration path to enhance the modernization level of industrial chain and supply chain. *J. Zhongnan Univ. Econ. Law* **2021**, *3*, 144–156.
20. Wang, Y.; Yin, Z.; Xing, J. The dredging effect of digital tools on internal circulation bottlenecks: An empirical study based on consumption vouchers relieving merchant difficulties. *China Econ. Q.* **2022**, *22*, 1–20. [CrossRef]
21. Waldfogel, J. Copyright research in the digital age: Moving from piracy to the supply of new products. *Am. Econ. Rev.* **2012**, *102*, 337–342. [CrossRef]
22. Zhang, X.; Song, J.; Shi, L.; Zhang, F.; Wang, W.; Liu, H. High-end equipment digital manufacturing collaboration in the new generation information technology environment. *Manag. World* **2023**, *39*, 190–204.
23. Shi, D. Evolution of industrial development trends under digital economy conditions. *China Ind. Econ.* **2022**, *416*, 26–42.
24. Chi, M.; Ye, D.; Wang, J.; Zhai, S. How can China's small and medium-sized manufacturing enterprises improve new product development performance: Based on the perspective of digital empowerment. *Nankai Bus. Rev.* **2020**, *23*, 63–75. [CrossRef]
25. Yang, Z.; Hou, Y.; Li, D.; Wu, C. The balancing effect of open innovation networks in Chinese enterprises' "dual circulation": Based on the examination of digital empowerment and organizational flexibility. *Manag. World* **2021**, *11*, 184–205.
26. Spieske, A.; Birkel, H. Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic. *Comput. Ind. Eng.* **2021**, *158*, 107452. [CrossRef] [PubMed]
27. Zhu, J.; Ruth, M. Exploring the resilience of industrial ecosystems. *J. Environ. Manag.* **2013**, *122*, 65–75. [CrossRef]
28. Liu, F.; Song, R. The impact of digital technology on regional economic disparity: Based on the test of spatial spillover. *East China Econ. Manag.* **2023**, *37*, 1–10.
29. Zhang, L.; Yao, L. Research on the impact of digital technology empowerment on urban economic resilience: Empirical evidence from 278 prefecture-level and above cities in China. *Manag. J.* **2023**, *36*, 38–59. [CrossRef]
30. Yu, J.; Zhou, X. Bidirectional mutual construction of digital technology application and government innovation: Based on the analysis of digital reform of "three lists" in Zhejiang Province. *Comp. Econ. Soc. Syst.* **2023**, *1*, 133–143. [CrossRef]
31. Guo, D.; Zhou, L.; Chen, L. The impact of digital economy on industrial upgrading and employment adjustment. *Chin. J. Popul. Sci.* **2022**, *210*, 99–110, 128.
32. He, Y.; Tian, J.; Qin, Z.; Chen, Z. Research on the measurement of China's industrial chain resilience from the perspective of production network. *Complex Syst. Complex. Sci.* **2023**, *21*, 21–27. Available online: <http://kns.cnki.net/kcms/detail/37.1402.N.20231103.1135.002.html> (accessed on 23 June 2026).
33. Fang, Y.; Yu, X. The pollution reduction and carbon reduction effects of industrial digitalization: Based on the research perspective of "productivity paradox". *Syst. Eng.—Theory Pract.* **2023**, *44*, 2795–2818. Available online: <http://kns.cnki.net/kcms/detail/11.2267.N.20231102.1350.006.html> (accessed on 23 June 2026).
34. Ivanov, M.; Martseniuk, L.; Angelova, M.; Faifer, S. Strategic risk management of digital transformation in the economic security of industrial enterprises. *Econ. Ecol. Socium* **2025**, *9*, 124–141. [CrossRef]
35. Saeed, S.; Altamimi, S.A.; Alkayyal, N.A.; Alshehri, E.; Alabbad, D.A. Digital transformation and cybersecurity challenges for businesses resilience: Issues and recommendations. *Sensors* **2023**, *23*, 6666. [CrossRef] [PubMed]

36. Ekhsan, M.; Badrianto, Y.; Suwandi, S.; Hermawan, H.; Septiani, A. Strategic human resource capabilities for digital transformation: Linking talent, leadership, competence and readiness to technology adoption. *SA J. Hum. Resour. Manag.* **2026**, *24*, 3327. [CrossRef]
37. Zeng, Y.; Chen, X.; Jin, Z.; Wang, S. The transmission efficiency of targeted reserve requirement ratio policy driven by bank digital transformation: Based on the research of bank scale heterogeneity. *Stud. Int. Financ.* **2023**, *8*, 65–76.
38. Liu, X.; Yang, Y.; Sun, Z. Construction and evolutionary development of enterprise digital capability: Based on a multi-case exploratory study of leading digital enterprises. *Reform* **2022**, *10*, 45–64.
39. Sraer, D.; Thesmar, D. *A Sufficient Statistics Approach for Aggregating Firm-Level Experiments*; NBER Working Paper 2018, No. 24208; NBER: Cambridge, MA, USA, 2018. Available online: <http://www.nber.org/papers/w24208> (accessed on 23 June 2026).
40. Leone, A.J.; Minutti-Meza, M.; Wasley, C.E. Influential observations and inference in accounting research. *Account. Rev.* **2019**, *94*, 337–364. [CrossRef]
41. Li, L.; Cheng, Z.; Liu, J. Research on the “new-type” development and evaluation of China’s manufacturing industry. *China Ind. Econ.* **2015**, *2*, 63–75.
42. Yu, Z.; Chen, W. Competitiveness of China-US digital industries: Measurement, comparison and implications. *Qiushi J.* **2022**, *49*, 72–83.
43. Martin, R.; Sunley, P. On the notion of regional economic resilience: Conceptualization and explanation. *J. Econ. Geogr.* **2015**, *15*, 1–42. [CrossRef]
44. Wang, J.; Chen, Z. Do industrial robots mitigate supply chain risks? Evidence from firm-level text analysis. *Sustainability* **2025**, *17*, 11340. [CrossRef]
45. Lv, W.; Yang, Q.; Li, Y. Digital empowerment and supply chain resilience reconstruction. *Sustainability* **2026**, *18*, 2261. [CrossRef]
46. Holling, C.S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Evol. Syst.* **1973**, *4*, 1–23. [CrossRef]
47. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O’Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.A.; von Winterfeldt, D. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* **2003**, *19*, 733–752. [CrossRef]
48. Bai, P.; Zhang, Y. Digital economy, declining demographic dividend and rights of low- and medium-skilled workers. *Econ. Res. J.* **2021**, *56*, 91–108.
49. Wang, Y.; Fan, Z.; Li, X. Endowment structure, R&D innovation and industrial upgrading. *China Ind. Econ.* **2022**, *414*, 5–23.
50. Song, M.; Liu, X. Research on the mechanism of digital economy empowering agricultural resilience: Based on the mediating effect analysis of human capital. *Jiangsu Soc. Sci.* **2023**, *1*, 103–112.
51. Zhang, G.; Wang, R. How does digital economy development empower high-quality employment of migrant workers. *Chin. Rural Econ.* **2023**, *457*, 58–76.
52. Chen, A. Agglomeration and urban economic resilience in China. *J. World Econ.* **2022**, *45*, 158–181.
53. Bartik, T.J. *Who Benefits from State and Local Economic Development Policies?* WE Upjohn Institute: Kalamazoo, MI, USA, 1991.
54. Goldsmith-Pinkham, P.; Sorkin, I.; Swift, H. Bartik instruments: What, when, why, and how. *Am. Econ. Rev.* **2020**, *110*, 2586–2624. Available online: <https://www.aeaweb.org/articles?id=10.1257/aer.20181047> (accessed on 23 June 2026). [CrossRef]
55. Anderson, J.E.; Toshmatova, M. Infrastructure system obstacles and technology adoption by firms in transition countries. *Comp. Southeast Eur. Stud.* **2024**, *72*, 104–134. [CrossRef]
56. Borusyak, K.; Hull, P.; Jaravel, X. Quasi-experimental shift-share research designs. *Rev. Econ. Stud.* **2022**, *89*, 181–213. [CrossRef] [PubMed]
57. Angrist, J.D.; Pischke, J.S. *Mostly Harmless Econometrics: An Empiricist’s Companion*; Princeton University Press: Princeton, NJ, USA, 2009. Available online: <https://books.google.com/books?id=YSaZEAAAQBAJ> (accessed on 23 June 2026).
58. Jiang, T. Mediating effects and moderating effects in causal inference empirical research. *China Ind. Econ.* **2022**, *5*, 100–120.
59. Wang, Y.; Dong, W. How does the rise of robots affect China’s labor market? Evidence from listed manufacturing companies. *Econ. Res. J.* **2020**, *55*, 159–175.
60. Boschma, R. Towards an evolutionary perspective on regional resilience. *Reg. Stud.* **2015**, *49*, 733–751. [CrossRef]
61. Christopher, M.; Peck, H. Building the resilient supply chain. *Int. J. Logist. Manag.* **2004**, *15*, 1–13. [CrossRef]
62. Sheffi, Y. *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*; MIT Press: Cambridge, MA, USA, 2007. Available online: <https://books.google.com/books?id=5L74DwAAQBAJ> (accessed on 23 June 2026).
63. Ivanov, D.; Dolgui, A. Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *Int. J. Prod. Res.* **2020**, *58*, 2904–2915. [CrossRef]
64. Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Change* **2006**, *16*, 253–267. [CrossRef]
65. Tondro, M.; Jahanbakht, M.; Ozay, D. Enhancing IoT technology acquisition in emerging economies: Insights and recommendations using analytical case study review of IoT startups. *Businesses* **2025**, *5*, 20. [CrossRef]

66. Cohen, W.M.; Levinthal, D.A. Absorptive capacity: A new perspective on learning and innovation. *Adm. Sci. Q.* **1990**, *35*, 128–152. [[CrossRef](#)]
67. Teece, D.J. Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance. *Strateg. Manag. J.* **2007**, *28*, 1319–1350. [[CrossRef](#)]
68. Cirera, X.; Maloney, W.F. *The Innovation Paradox: Developing-Country Capabilities and the Unrealized Promise of Technological Catch-up*; World Bank Publications: Washington, DC, USA, 2017. Available online: <https://books.google.com/books?id=NSG3EQAAQBAJ> (accessed on 23 June 2026).
69. De Backer, K.; Miroudot, S. *Mapping Global Value Chains*; OECD Trade Policy Papers 2013, No. 159; OECD Publishing: Paris, France, 2013. [[CrossRef](#)]
70. Gereffi, G. *Global Value Chains and Development: Redefining the Contours of 21st Century Capitalism*; Cambridge University Press: Cambridge, UK, 2018. [[CrossRef](#)]
71. Craighead, C.W.; Ketchen, D.J., Jr.; Darby, J.L. Pandemics and supply chain management research: Toward a theoretical toolbox. *Decis. Sci.* **2020**, *51*, 838–866. [[CrossRef](#)] [[PubMed](#)]
72. Koren, M.; Pető, R. Business disruptions from social distancing. *PLoS ONE* **2020**, *15*, e0239113. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.