

Article

The Mechanism and Spatiotemporal Variations in Digital Economy in Enhancing Resilience of the Cotton Industry Chain

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Abstract

In the era of the digital economy, enhancing the resilience of industrial chains is a core task in building a modern industrial system. This paper views the cotton industrial chain as a system composed of multiple segments and entities, aiming to explore how the digital economy drives the collaborative evolution of the chain's constituent elements, organizational structure, and overall functions, ultimately enhancing its resilience to respond to shocks and adapt to changes. The study focuses on the cotton industrial chain, systematically analyzing the mechanisms and spatiotemporal characteristics of the digital economy's impact on its resilience, aiming to provide theoretical support and practical pathways for constructing a secure, efficient, and sustainable cotton industrial chain. Based on panel data from nine provinces in China's three major cotton-producing regions from 2013 to 2022, the study uses the entropy method to measure the technological innovation vitality and the resilience of the cotton industrial chain, employing a semi-parametric panel model to empirically test the systemic association between them, and utilizing a mediation effect model to identify the roles of market information utilization and the scale of planting in this relationship. The findings indicate the following: (1) The development of the digital economy significantly enhances the resilience of the cotton industrial chain and exhibits an inverted U-shaped nonlinear relationship. (2) The digital economy enhances the overall resilience and synergy of the cotton industrial chain through two key pathways: improving the technological innovation vitality and increasing the level of planting scale. (3) The influence of the digital economy on the resilience of the cotton industrial chain shows geographical heterogeneity, with the order being "Yangtze River Basin cotton areas > Northwest Inland cotton areas > Yellow River Basin cotton areas." The impact of the digital economy on the resilience of the cotton industrial chain also exhibits temporal heterogeneity, with "2013–2017 > 2018–2022." From the perspective of system optimization, future efforts should focus on constructing regionally differentiated collaborative mechanisms, improving the integrated platform for market information services, strengthening incentives for large-scale planting policies, enhancing the digital literacy of practitioners, and conducting skills training, in order to strengthen the overall resilience and sustainable evolution of China's cotton industrial chain.

Keywords: digital economy; resilience of the cotton industrial chain; mediating effects; spatiotemporal differences

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1. Introduction

The resilience of the industrial chain refers to the comprehensive attributes demonstrated by the system in withstanding, adapting to, and recovering from external shocks and internal disturbances, as well as maintaining the critical functions and structural integrity of the system. In recent years, affected by the evolution of regional economic development [1] and systematic adjustments in agricultural industrial structure [2], the cotton planting area in China has declined from 5.11 million hectares in 2003 to 3 million hectares in 2022, showing an overall downward trend [3]. At the same time, influenced by factors such as climate change and international trade barriers, the cotton industrial chain faces unprecedented challenges [4]. Against this background, enhancing the ability of the cotton industry to withstand various risks and shocks has become an urgent priority in system governance and policy design.

With the rapid development of information technology, the digital economy has become a key force driving the transformation of agricultural modernization, profoundly reshaping the structure and function of agricultural systems, and gradually emerging as the core driving force for promoting high-quality agricultural development. According to the “Research Report on the Development of China’s Digital Economy (2024),” data shows that in 2023, the scale of China’s digital economy reached 53.9 trillion yuan, accounting for 42.8% of the GDP [5]. The systematic development of the digital economy provides strong technological support and innovative momentum for the cotton industrial chain, driving its evolution towards a more flexible, cooperative, and resilient modern industrial chain system [6].

Existing research indicates that the digital economy influences the operational efficiency and resilience of agricultural industrial chain systems through various mechanisms. Its effects are primarily manifested in optimizing the decision-making mechanisms and execution efficiency of various links in the industrial chain through digital technology. The agricultural supply chain, as a complex organizational system [7] encompassing multiple links including production, processing, and distribution, has seen its digital transformation become a key pathway for enhancing overall performance. The integration of artificial intelligence technologies with intelligent systems, machine learning, and advanced analytical tools has enabled data-driven decision-making, predictive modeling, and operational automation [8], thereby directly enhancing the responsiveness and operational accuracy of the supply chain system. Such direct effects are manifested in the integrated application of precision agriculture technologies within agricultural production subsystems, exemplified by automated smart farms reliant on sensor networks and remote sensing systems [9], which significantly reduce operational costs and optimize resource allocation efficiency.

The empowering effect of the digital economy on industrial chain systems is also reflected in breaking down information barriers and reducing transaction costs within the system. Blockchain technology establishes an immutable distributed data-sharing mechanism, creating a trusted interaction structure among multiple stakeholders [10,11], which is crucial for enhancing the information transparency of agricultural product supply chains. In the cotton industrial chain, enhanced information transparency helps alleviate information asymmetry between upstream and downstream entities, enabling production decisions to better respond to market demand fluctuations and reducing resource misallocation due to market misjudgments, thereby strengthening the entire industrial chain system’s adaptability and resilience in the face of external price shocks.

The assessment of industrial chain resilience is fundamental for accurately identifying vulnerable links and effectively formulating enhancement strategies. In the field of agricultural systems, related evaluation studies have gradually evolved from a single eco-

conomic dimension in the early stages to a multidimensional system framework that encompasses resistance capability, recovery capability, and adaptability. Notably, significant progress has been made in the research of evaluation systems in the field of the cotton industrial chain. Zhang et al. (2024), based on resilience theory, constructed a systematic evaluation index system for the resilience of the cotton industrial chain from four dimensions: resistance capability, renewal capability, recovery capability, and government support [12]. In terms of evaluation methods [13,14], comprehensive assessments based on the entropy method are widely applied in agricultural industrial chain research. Additionally, the introduction of GIS spatial analysis technology enables researchers to explore the spatial evolution characteristics of industrial chain resilience, providing visual tools for identifying spatial heterogeneity within the system.

With industrial development, the optimization and extension of the cotton industrial chain have become a research hotspot, particularly through practices in major producing areas like Xinjiang [15], where scholars have proposed various industrial chain expansion models. These studies generally point out that a short industrial chain is a significant constraint on value addition in Xinjiang's cotton industry system and propose pathways to enhance overall competitiveness through the expansion, optimization, and integration of the industrial chain. In recent years, with the development of the digital economy, the digital transformation of the cotton industrial chain has begun to attract attention [16]; however, there is still a lack of systematic research and empirical testing in this area.

Existing research has certain limitations in the following aspects: Firstly, most studies focus on analyzing the indirect impact mechanisms of the digital economy on industry chains, but research on its direct effects remains insufficient, especially in the cotton industry chain, which lacks systematic and comprehensive empirical support. Meanwhile, existing research predominantly concentrates on agriculture as a whole, without in-depth consideration of specific agricultural products like cotton, thereby neglecting the interactions among various links in the cotton industry chain under the influence of the digital economy. Furthermore, the impact of internal and external factors on the relationship between the digital economy and the resilience of the cotton industry chain has not been adequately discussed. The aforementioned research gaps urgently require further systematic studies to achieve a clearer understanding of the effects and mechanisms of the digital economy on enhancing the resilience of the cotton industry chain. Secondly, studies on the assessment of industrial chain resilience, particularly specialized and quantitative evaluations concerning cotton as an important economic crop, are still lacking, and no systematic evaluation framework has yet been established. Furthermore, existing findings often rely on qualitative analyses or case study methods, while empirical tests based on panel data are relatively insufficient, making it difficult to comprehensively reveal their impact mechanisms. Finally, existing studies have insufficiently addressed the regional heterogeneity in the impact of the digital economy on the resilience of the cotton industrial chain, limiting the formulation and implementation of differentiated regional policies.

This study is the first to operationally define and quantitatively analyze the cutting-edge concept of “industrial chain resilience” within the cotton industry, systematically examining the direct effects of the digital economy on it and its regional heterogeneity, thereby breaking through the previous qualitative analysis paradigms that focused on technological applications or single segments. This provides new theoretical perspectives and empirical evidence for understanding the risk resistance capacity of agricultural industrial systems. Methodologically, an innovative semi-parametric panel model is employed, allowing for a more flexible and robust capture of the potentially complex non-linear relationships between the digital economy and industrial chain resilience without presupposing a specific functional form. Compared to traditional linear assumption models, this approach can more accurately reflect the intrinsic connections between the two,

enhancing the reliability of the research conclusions and the theoretical explanatory power. Through the mediation effect model, key transmission pathways through which the digital economy affects the resilience of the cotton industrial chain are identified and validated. This analysis delves from “whether it affects” to “how it affects,” revealing its underlying mechanisms, thus theoretically constructing a logical chain from “digital technology empowerment” to “enhancing industrial chain resilience,” which constitutes an important complement to the existing theoretical framework. By conducting empirical tests on the heterogeneity of different cotton regions, significant regional differences in the impact of the digital economy are revealed. This finding not only enriches the theoretical understanding of regional differentiation influenced by technology in industrial economics, but more importantly, it provides a solid theoretical basis and data support for formulating location-specific and precisely effective regional industrial chain policies.

2. Theoretical Analysis and Research Hypotheses

2.1. *The Impact of the Digital Economy on the Resilience of the Cotton Industrial Chain*

This study is based on the collaborative characteristics of the cotton industrial chain across its upstream, midstream, and downstream segments, systematically analyzing the impact mechanisms of the digital economy on its resilience.

2.1.1. Empowerment Mechanisms of the Digital Economy on the Resilience of the Cotton Industrial Chain

(1) Enhancing the Resilience Capability of the Industrial Chain. The digital economy relies on the dual drivers of “technology empowerment” and “model innovation” to promote the evolution of the industry chain from a traditional rigid structure to a flexible intelligent system [17]. Upstream: The digital economy constructs a cotton field “digital twin” system through the Internet of Things (IoT) and remote sensing technologies, focused on precision production and risk hedging mechanisms based on data elements. Its economic value is reflected in two core aspects: From the production perspective, this system achieves comprehensive digitalization of agricultural production processes, effectively reducing information asymmetry between producers and the natural environment, greatly enhancing both production efficiency and resource utilization efficiency. From the perspective of risk management, digital production data provide verifiable objective evidence for agricultural insurance, facilitating precise pricing and efficient claims settlement for agricultural insurance products, and enhancing the ability of upstream production processes to withstand natural risks and market fluctuations. Midstream: Digital supply chain platforms create a bilateral market with diverse participant involvement. On one hand, the platform reduces search costs, negotiation costs, and compliance monitoring costs for both supply and demand sides through centralized information processing and sharing. On the other hand, the platform achieves precise matching and dynamic adjustment of supply and demand through big data analysis, significantly reducing the risks of inventory backlog and capacity surplus. Downstream: The blockchain traceability system is not merely an anti-counterfeiting technology; it runs throughout the entire process of credit formation and value transformation by reducing information asymmetry, optimizing incentive compatibility, and reconstructing governance models. First, the decentralized and immutable characteristics of blockchain transform the entire process information of cotton production, processing, and logistics into traceable and verifiable digital signals, effectively reducing consumers’ information discernment costs, alleviating information asymmetry between supply and demand sides, and laying the foundation for brand credit construction. Second, the system establishes a market-based incentive mechanism of “quality for price,” directly linking quality signals to market pricing, forming a positive

incentive cycle of “quality enhancement—credit strengthening—value premium.” Finally, the blockchain creates a decentralized credit governance system, significantly reducing the costs and timeframes for credit certification, thereby enhancing the stability and credibility of the credit system.

(2) Restructuring the Renewal Capability of the Industrial Chain. The essence of the digital economy is “data-driven,” reconstructing the value creation logic of the industrial chain. Upstream: Demand-Side Data Guiding Supply-Side Structural Reforms [18]. Accurately conveying downstream market value signals to upstream segments to guide the allocation of production factors toward high value-added areas is the core mechanism for achieving agricultural supply-side reforms. Midstream: Flexible Manufacturing and Service Extension. Manufacturers are no longer merely production units; they have transformed into service-oriented manufacturing entities that can quickly respond to fragmented orders, as well as undertake customized services for downstream brand owners. Downstream: Community Operation and Value Co-creation. The digital profiling and social media analysis in the downstream segment carry the economic implications of “user operation” and “community economy.” Brands, through continuous interaction with consumers, not only accurately identify trends but also invite consumers to participate in reverse customization of products and value co-creation.

(3) Accelerating the Recovery Capability of the Industrial Chain. In the face of shocks, the digital economy has enabled dynamic optimization and efficient resetting of resources within the industrial chain. Digital platforms (such as B2B and smart logistics platforms), functioning as “resource dispatch centers,” can rapidly resolve localized supply disruptions by matching alternatives through global networks, transforming the rigid linear structure into a flexible, networked form [19]. At the same time, digital finance leverages accumulated transaction and production data for automated credit assessments and rapid claims processing, providing critical cash flow support for affected nodes [20], effectively preventing systemic collapse and significantly shortening recovery periods.

2.1.2. Nonlinear Constraints and Suppressive Effects in the Empowerment Process of the Digital Economy

Although the digital economy significantly enhances resilience during its development stage, once its development level surpasses a specific threshold, it may encounter the following constraints that lead to diminishing marginal benefits or even suppressive effects:

(1) Diminishing Marginal Returns on Technological Investment and Synergy Bottlenecks: Based on Micro-Subject Funding Constraints and Marginal Decisions. As the level of digitalization increases, technological investment in the industry chain gradually shifts towards the deep integration of advanced technologies and system upgrades. At this point, the marginal cost of technological investment shows an exponential upward trend for several reasons: First, the research, procurement, and deployment costs of advanced technologies are high. Second, in order to achieve technological integration, various entities need to modify existing systems, incurring substantial conversion costs. Third, the increased complexity of technology requires specialized operation and maintenance teams along with talent reserves, further increasing fixed costs. Meanwhile, the marginal returns of technological investment exhibit a diminishing trend [21], with the core constraint being synergy bottlenecks. The lack of uniform data standards, incompatible system interfaces, and differences in technological architecture among various entities lead to significantly diminished integration effectiveness of advanced technologies, preventing the expected improvements in synergy efficiency. When the level of digitalization crosses a critical threshold, the marginal cost of technological investment will exceed the marginal returns. For the core micro-subjects such as smallholder farmers and small to medium-

sized cotton enterprises with limited funding, sustained high digital investment will result in an overcrowding effect. The theoretical model's derivations suggest that at this point, the risk resistance capacity of micro-subjects will significantly decline; when faced with external shocks such as market price fluctuations or natural disasters, they will lack sufficient funds to make adjustments and respond, further weakening the overall resilience of the industry chain.

(2) Increased System Coupling and Rising Vulnerability: Based on Risk Transmission Mechanisms and Threshold Effects of Complex Systems. The development of the digital economy is essentially a process of transitioning the cotton industry chain from a loosely coupled system to a tightly coupled system. At lower levels of digitalization, the connections between different links in the industry chain are relatively loose, and the transmission pathways for localized risks are limited, with both the scope and extent of their impacts being manageable. At this time, the enhancement of system coupling can reduce the degree of information asymmetry, improve synergy efficiency, and thus strengthen the resilience of the industry chain. As digitalization levels rise, the coupling between various links in the industry chain continually strengthens, forming a full-chain data linkage mechanism of “upstream planting—midstream processing—downstream distribution”: The planting data of upstream farmers will directly influence the production scheduling of midstream processing enterprises, while the processing data from midstream will directly determine the inventory strategies of downstream distribution companies. Any localized risk at any link will rapidly propagate through the industry chain, triggering a “domino effect” [22] and significantly increasing the system's vulnerability. Complex systems theory suggests that when coupling exceeds a certain critical threshold, the vulnerability of the system will increase dramatically.

(3) Widening Digital Divide and Structural Imbalance: Based on Differences in Digital Capacities of Industry Chain Entities and the Matthew Effect. The development of the digital economy is characterized by economies of scale and network effects, which has led to a widening digital divide between leading enterprises within the industry chain and smallholder farmers and small to medium-sized cotton enterprises, creating a typical Matthew effect [23]. As digitalization levels rise, the pace of digital technology iteration continues to accelerate, and the application thresholds for advanced technologies also increase. For leading enterprises, they have sufficient funding, complete talent reserves, and strong technological research and development capabilities, allowing them to continually invest in the research and application of digital technologies, reaping the benefits of economies of scale and network effects, and continuously enhancing their digital capabilities and competitive advantages. Smallholder farmers and small to medium-sized cotton enterprises, on the other hand, face constraints such as limited funding, talent shortages, and insufficient technological reserves. They cannot keep pace with the speed of digital technology iteration and can only remain at the application level of basic digital tools, even facing the risk of elimination, ultimately falling into the predicament of “digital marginalization.” When the level of digitalization crosses a critical threshold, the widening digital divide will lead to structural imbalances in the industry chain.

(4) Emergence of New Digital Risk Spillovers: Based on Dynamic Changes in Risk Costs and Externality Effects. The deep application of the digital economy has not only improved efficiency but has also introduced new risks like cybersecurity, data privacy, and platform dependence [24]. As digitalization levels rise, the application scope of digital technologies continues to expand, and the depth of application deepens, leading to a significant increase in the occurrence probability of new digital risks, an ever-expanding impact range, and a substantial rise in management costs. For instance, attacks on upstream agricultural data platforms may threaten farmers' privacy and expose the business strat-

egies of processing and distribution companies. Interruptions to downstream sales platforms will cause operations across the entire chain to come to a standstill. Platform dependence can lead industry chain entities to lose their autonomous decision-making abilities; when a platform encounters failures or adjusts its strategies, the entities will face significant risks. When the level of digitalization crosses a critical threshold, the externality effects of new digital risks will become fully evident, and their management costs and potential losses will outweigh the positive contributions brought by digitalization. Based on this, the following hypothesis is proposed:

H1. *The digital economy has a nonlinear impact on the resilience of the cotton industrial chain.*

2.2. Mechanism Analysis of the Impact of the Digital Economy on Cotton Resilience

2.2.1. Technological Innovation Vitality

The digital economy activates the technological innovation vitality at various stages of the cotton industry chain through the full-chain penetration of data factors and the resource integration functions of digital platforms, from the dual dimensions of “supply of innovation factors—construction of collaborative innovation networks.” This activated innovation vitality is not a static capacity reserve, but rather a dynamic mechanism that runs through the entire process of building resilience in the industry chain via “risk pre-warning—emergency response to shocks—long-term adaptive evolution,” becoming the core mediator driving resilience enhancement.

From the intrinsic logic of innovation activation, the real-time and traceability characteristics of data factors provide precise problem orientation for technological innovation [25]: Real-time data on soil moisture and weather changes in the upstream production process directly drive the R&D of incremental innovations such as precise irrigation algorithms and pest forecasting models. In the midstream distribution process, logistics trajectories and inventory turnover data compel upgrades in technologies such as intelligent warehousing and scheduling systems and dynamic delivery route optimization. This direct connection of “data-innovation” allows technological innovation to break free from randomness and focus on the core needs of risk management and efficiency enhancement in the industry chain. Simultaneously, digital platforms break down geographical and organizational boundaries to construct collaborative innovation networks that include research institutions, production entities, and logistics companies, integrating scattered innovation resources into a scaled collaborative force, thus providing organizational support for emergency innovations following shocks and long-term breakthrough innovations [26].

From the perspective of the dynamic evolution mechanism of resilience, the activated technological innovation vitality promotes the enhancement of resilience in the industry chain through three progressive mechanisms: First, during the risk incubation phase, incremental technological innovations establish a “precise warning—proactive adaptation” mechanism that can transform traditionally passive responses to risks into variables that can be anticipated and intervened in advance. By using technologies such as precise irrigation and green pest control, it can enhance the adaptability of the industry chain to fluctuations in the external environment in advance, thereby reducing the probability and intensity of risk impacts from the outset. Second, during the phase of risk shocks, the collaborative innovation network initiates a “rapid response—resource reorganization” mechanism, allowing diverse innovative entities linked by digital platforms to quickly collaborate. This enables targeted R&D of emergency technological solutions based on the type of shock, shortening the recovery cycle of the industry chain from disruption through rapid reorganization of technological resources, thereby enhancing the system’s resistance

to disturbances. Third, in the recovery and evolution phase following the shock, breakthrough innovations drive the “functional upgrade—value reconstruction” mechanism, the full-chain data insights brought by the digital economy can accurately capture changes in market demand and weaknesses in industry development aftershocks. This drives breakthrough innovations that extend the industry chain towards higher value-added segments, achieving iterative upgrades of industry chain functions and reconstruction of value systems, fundamentally enhancing the long-term adaptability of the industry chain to future changes in uncertainty (Figure 1). Based on this, the following hypothesis is proposed:

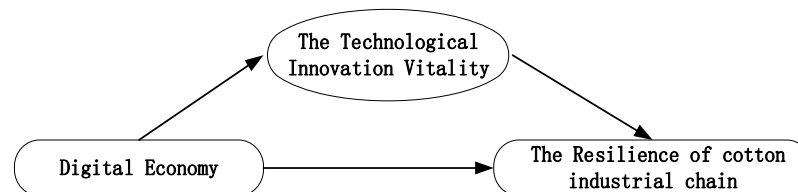


Figure 1. Mediating Effect—Technological Innovation Vitality.

H2. *The digital economy enhances the resilience of the cotton supply chain by boosting technological innovation vitality.*

2.2.2. Level of Planting Scale

The fragmented small-scale farming in the upstream production of the cotton industry chain is essentially a vicious cycle of “weak risk resistance—low technological adaptability—poor supply stability” caused by the decentralized allocation of production factors, which directly hinders the foundational construction of resilience in the industry chain. The digital economy does not merely drive the expansion of planting scale; rather, it transforms decentralized production factors into systematic risk resistance capabilities through a progressive dynamic mechanism of “reducing factor flow costs—cultivating scale operating entities—implementing standardized production—buffering risks across the entire chain,” thereby solidifying the core foundation of resilience in the cotton industry chain.

From the perspective of the mechanism’s starting point, digital technology provides crucial support for the optimized allocation of factors [27]: Digital tools such as online labor platforms and digital land circulation systems significantly reduce the flow costs and matching difficulties of core production factors like rural land and labor by breaking information barriers and simplifying transaction processes, creating the necessary conditions for the concentration of cotton farming towards larger growers, cooperatives, and other new operating entities [28]. This process of factor integration is not merely a matter of scaling up; rather, it represents a systematic reconstruction of the production organization model in the upstream sector of the industry chain, providing an organizational framework for the implementation of subsequent risk resistance mechanisms.

From the perspective of the core chain of dynamic resilience enhancement, scale operation upgrades the resilience of the industry chain through three key mechanisms: First, in the risk prevention phase, scale operating entities, leveraging their advantages in financial resources and technological capabilities, are more likely to adopt and promote standardized advanced technologies, establishing a “precise control—quality stabilization” preemptive guarantee mechanism. Standardized production can effectively avoid fluctuations in the quality of raw cotton caused by non-standard technological applications in smallholder farming, thereby reducing the uncertainty risk of upstream production from the outset. Second, during the risk shock response phase, the “bulk supply—resource co-

ordination” buffer mechanism formed by large-scale planting plays a key role. When facing external shocks such as natural disasters and market fluctuations, scale operating entities can flexibly allocate cross-regional planting resources and adjust production plans, ensuring the continuity of raw cotton supply and avoiding the chain reaction of “single point damage leading to complete supply disruption” typical of smallholder farming, thereby providing stable raw material support for downstream textile and garment manufacturing sectors. Third, in the recovery and evolution phase following shocks, the resource integration capabilities of scale operating entities accelerate the recovery of the upstream sector of the industry chain. Compared to dispersed smallholders, scale entities find it easier to access credit support and technological assistance, enabling them to quickly organize post-disaster recovery and shorten the recovery cycle of upstream production, thus laying a foundation for the recovery of the entire chain (Figure 2). Based on this, the following hypothesis is proposed:

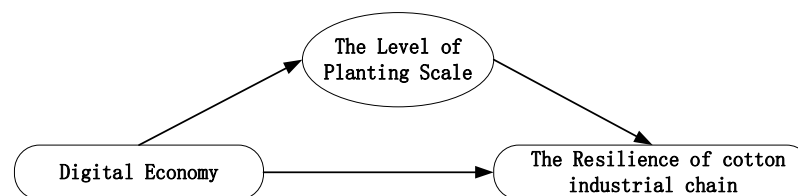


Figure 2. Mediating Effect—the Level of Planting Scale.

H3. *The digital economy enhances the resilience of the cotton industrial chain by increasing the level of planting scale.*

The theoretical analytical framework of this study is shown in Figure 3.

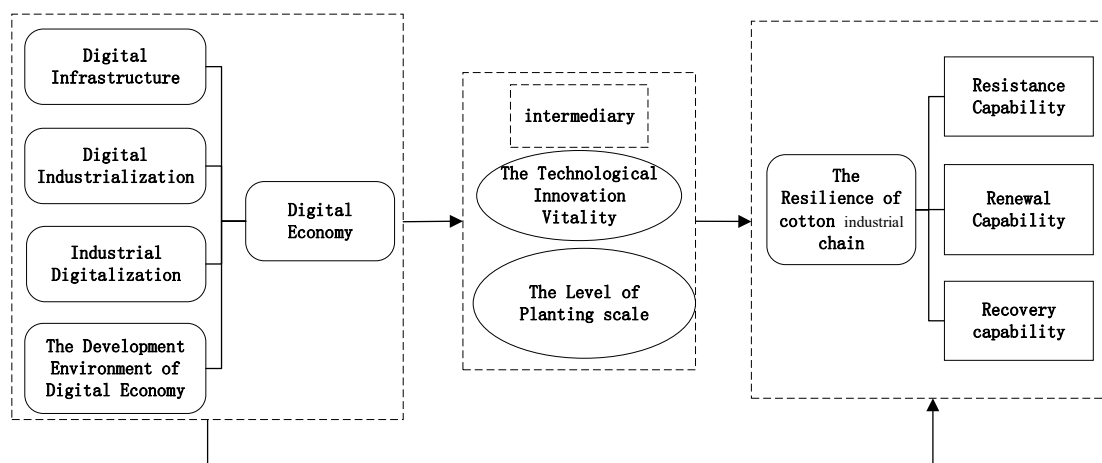


Figure 3. Theoretical Analysis Framework.

3. Results and Analysis

3.1. Measurement of the Digital Economy and the Resilience Level of the Cotton Industrial Chain

3.1.1. Data Sources and Data Processing

Cotton-growing provinces in China include Xinjiang, Gansu, Hebei, Shandong, Shanxi, Henan, Shanxi, Anhui, Jiangxi, Jiangsu, Hunan, and Hubei [29]. Given that the cotton planting area in Shanxi, Shaanxi, and Jiangsu has continuously shrunk in recent years, accounting for less than 0.15% of the national total in 2022, and due to significant missing data on related costs and benefits, these provinces are excluded from the study

[12]. This study selects three major cotton-producing regions: the Northwest Inland Cotton Region (Xinjiang, Gansu), the Yellow River Basin Cotton Region (Hebei, Henan, Shandong), and the Yangtze River Basin Cotton Region (Anhui, Jiangxi, Hubei, Hunan), involving a total of nine major cotton-producing provinces.

The data mainly come from the National Bureau of Statistics official website, the Guotai An database, the “China Statistical Yearbook,” the “China Electronic Information Industry Statistical Yearbook,” the “China Rural Statistical Yearbook,” and the “Peking University Digital Inclusive Finance Index.” For the missing data, this study employs linear interpolation for imputation.

3.1.2. Variable Selection

1. Dependent Variable

This study takes the resilience of the cotton industrial chain as the dependent variable, referencing existing research [30], and selects six primary indicators and twenty secondary indicators from three dimensions: resistance capability, renewal capability, recovery capability to construct an evaluation index system for the resilience level of the cotton industrial chain (Table 1).

Table 1. Cotton Industry Chain Resilience Evaluation Index System.

Dimension	Primary Indicators	Secondary Indicators	Unit	Definition	Attribute
Resistance capability	Foundational endowment	Sown area	1000 hm ²	Cotton sowing area	+
		Cotton production	10,000 tons	The total amount of cotton obtained from planting cotton, including main products and by-products	+
		Total power of agricultural machinery	10,000 kWh	Diesel engine power, gasoline engine power, electric motor power, other mechanical power	+
		Labor cost per mu	yuan	The labor cost of planting cotton	-
		Fertilizer application rate per mu	kg	Amount of fertilizer used to plant cotton	-
		Plastic film usage per mu	kg	Amount of agricultural film used to grow cotton	-
		Cost of pesticide per mu	yuan	Cost of pesticides used in cotton cultivation	-
		Cost of materials and services per mu	yuan	The cost of planting cotton, including both direct and indirect costs	-
		Number of workers per mu	day	Amount of labor required in cotton cultivation	-

		Yarn production	100 million meters	Yarn includes cotton yarn, cotton blended yarn, purified fiber yarn; but does not include cotton thread, substitute fiber yarn, and hand spun yarn	+
		Fabric production	100 million meters	Cloth includes cotton fabric, cotton blend fabric, purified fiber fabric; but does not include substitute fiber fabric or hand-woven fabric	+
		Output value of the main products sold per mu	yuan	Revenue generated from the sale of cotton as main products per acre of land	+
		Cotton yield per acre of main product	kg	Yield of cotton main product per acre of land	+
Resource allocation		Per capita cotton possession	kg/people	The average amount of cotton per person after total production is distributed equally among everyone	+
		Number of employees in the cotton industry chain	people	The sum of employees of listed companies in the cotton industry chain	+
		Cotton industry chain listed companies R&D expenses	10,000 yuan	The sum of research and development expenses of listed companies in the cotton industry chain	+
R&D investment		Number of patents of listed companies in the cotton industry chain	pcs	The sum of patent applications for listed companies in the cotton industry chain	+
		Integration of the cotton industry with the secondary industry	100 million yuan/1000 hm ²	The ratio of the output value of the textile and apparel industry to the cotton cultivation area.	+
Recovery capability	Industrial Chain Integration Capability				

	Integration of the cotton industry with the tertiary industry	100 million yuan/1000 hm ²	The ratio of service sector revenue to cotton cultivation area.	+
Government support	Government subsidies	10,000 yuan	The sum of government subsidies for listed companies in the cotton industry chain	+

(1) Resistance capability

Resilience is the foundational capability of the cotton industry chain to maintain core functions and basic outputs when faced with external shocks, such as natural disasters, market fluctuations, and resource constraints. The selection of indicators should closely align with the two core logics of “foundational endowment” and “buffer capacity,” ensuring that the indicators can directly reflect the material foundation and efficiency level of the industry chain’s risk resistance.

From the perspective of positive indicators related to foundational endowment, the cotton sowing area is a prerequisite for the survival of the industry chain and for resisting risks. A sufficient planting scale can provide stable supply for subsequent processing and sales stages, reducing the impact of production reductions in a single area on the overall industry chain. Cotton production directly reflects the material output capacity of the industry chain; the larger the yield scale, the more ample the buffer space to cope with market demand fluctuations or production losses. The total power of agricultural machinery, as a core indicator of agricultural modernization, directly affects the scale and standardization of cotton planting; advanced machinery can enhance disaster resistance and production efficiency, mitigating the impact of natural risks on yield and is a key support for resisting uncertainties on the production side. From the perspective of negative indicators, measures such as average labor cost per mu, average fertilizer application per mu, average plastic film usage per mu, average pesticide cost per mu, average material service fees per mu, and average working days per mu directly reflect the resource consumption and cost pressures of the cotton planting segment. During periods of market price fluctuations or rising costs, excessively high input costs can compress profit margins of the industry chain and lower its ability to withstand market risks. At the same time, unreasonable investments may lead to long-term risks such as soil degradation and environmental pollution, undermining the sustainable resilience of the industry chain. Setting these indicators as negative can guide the industry chain towards a low-carbon and high-efficiency production model, thereby enhancing long-term resilience.

Buffer capacity, as an extension of resilience, selects yarn production, fabric production, Output value of the main products sold per mu, and Cotton yield per acre of main product as positive indicators. The reason is that yarn and fabric, as core processed products of the cotton industry chain, their output scale reflects the processing and conversion capacity of the industry chain. Adequate processing capacity can absorb upstream cotton output, preventing risks caused by disconnection between planting and processing segments. The average yield and sales revenue per mu are directly related to the profitability and output efficiency of the industry chain. Higher yields and sales revenue can enhance the resilience of growers and enterprises to risks.

(2) Renewal capability

The Renewal capability is the core ability of the cotton industry chain to achieve self-iteration and adapt to changes in the external environment through resource optimization

and technological innovation. The selection of indicators focuses on two dimensions: “resource allocation” and “R&D investment,” aimed at reflecting the dynamic adjustments and long-term development potential of the industry chain.

Among the positive indicators related to resource allocation, per capita cotton possession reflects the distribution efficiency and accessibility of cotton resources. Reasonable resource allocation can ensure balanced resource supply among various segments of the industry chain, avoiding local resource shortages that may constrain the upgrading of the industry chain. The number of employees in the cotton industry chain reflects the human resource support capacity of the industry chain. A sufficient and well-structured labor force is the foundation for the industry chain to achieve technology promotion and model innovation. Especially during the process of digital and intelligent transformation, the reserve of professional talent directly affects the speed and effectiveness of updating and iteration.

Technological innovation is the core driving force behind the updating capacity of the industry chain; therefore, R&D expenses and the number of patents of listed companies in the cotton industry chain are selected as positive indicators. The intensity of the investment in research and development directly determines the innovation potential of the industry chain in areas such as variety improvement, planting technology optimization, and processing technology upgrade. This can enhance the industry chain’s adaptability to environmental changes and market demands. The number of patents is a direct reflection of the results of technological innovation, and the application of patent conversion can drive the industry chain’s transformation from “factor-driven” to “innovation-driven.” Breaking through technological bottlenecks and strengthening long-term competitiveness are key indicators for the industry chain to achieve continuous updates.

(3) Recovery capability

Recovery capability is the ability of the cotton industry chain to quickly return to its original output level and reconstruct its functions after experiencing shocks. The selection of indicators centers around the two cores of “industrial chain integration capability” and “government support,” highlighting the integration efficiency and risk hedging ability of the industry chain.

Industrial chain integration capability is the core support for recovery capacity. Positive indicators include the integration between the cotton industry and the secondary industry, and the integration between the cotton industry and the tertiary industry. The reason is that the ratio of textile and clothing industry output value to cotton planting area reflects the synergy efficiency between upstream planting and downstream processing segments. A higher ratio indicates a closer connection between the planting and processing ends. The stronger the pull of the processing phase on the planting end, when the planting end suffers shocks, the processing end can rapidly assist in the recovery of the industry chain through capacity adjustments and product structure optimization. The integration of the cotton industry with the tertiary industry can provide diversified support to the industry chain through productive services such as logistics, finance, and technology services.

Government support is an important external guarantee for the recovery capacity of the industry chain, with government subsidies selected as a positive indicator. The reason is that government subsidies can provide direct financial support to publicly listed companies in the cotton industry chain. When the industry chain suffers shocks from market downturns or natural disasters, subsidy funds can be used for key areas such as technological transformation, capacity recovery, and employee stabilization, thereby reducing operational pressure on companies. At the same time, subsidy policies can guide social

resources to tilt towards the cotton industry chain, enhance market confidence, and promote the rapid reconstruction of the industry chain, making it an important external driver for enhancing recovery capacity.

2. Key Independent Variable

Based on the connotation of the digital economy and referencing existing research [31], this study selects eight primary indicators and twenty secondary indicators from four dimensions: digital infrastructure, digital industrialization, industrial digitization, and the development environment of the digital economy to measure the level of digital economic development (Table 2).

Table 2. Measurement Indicator System for the Development Level of Digital Economy.

Dimension	Primary Indicators	Secondary Indicators	Unit	Definition	Attribute
Digital Infrastructure	Digital platform construction	Number of domain names	ten thousand	The total number of internet domain names that are officially registered and active under the ccTLD system at a specific point in time.	+
		Number of websites	ten thousand	The total number of publicly accessible websites on the internet with independent content and unique domain names.	+
		Optical fiber cable line length	10,000 km	The total physical length of fiber optic communication cables that have been laid and are in service.	+
		Mobile telephone switch capacity	ten thousand	The maximum number of simultaneous user calls or data sessions that the core switching equipment in a mobile communication network can handle per unit of time.	+
	Digital Communication Services	Mobile phone penetration rate	%	The number of mobile telephone subscribers per hundred people in a given geographical area.	+
		Number of mobile phone base stations	ten thousand	Total number of mobile communication base station equipment deployed within a specific geographic area.	+
		Number of internet broadband access ports	ten thousand	Total number of physical or logical ports available for users to access broadband Internet services.	+
Digital Industrialization	Telecommunications industry	Total volume of telecommunications services	100 million yuan	The aggregate value generated by all telecommunications services (including fixed, mobile, data, etc.)	+
		Total volume of postal services	100 million yuan	The aggregate value output of various delivery, financial, and other services provided by postal enterprises.	+

		Number of websites owned by companies	pcs	Number of official websites maintained by or representing the enterprise.	+
	Software and Information Technology Services Industry	Software Business Revenue	100 million yuan	The total revenue generated by software and information technology services enterprises through the sale of software products, the provision of information technology services, and the operation of embedded system software.	+
		Information Technology Services Revenue	100 million yuan	Revenue earned by information technology service enterprises through the provision of various information technology services, including cloud services and big data services.	+
	Digital Finance	Internet Property Insurance Premium Income	million yuan	The total premium income directly generated by property insurance business sold and underwritten by insurance companies through online channels within a specified period.	+
		Internet life insurance premium income	million yuan	Total premiums earned by insurance companies through online channels for the sale of life insurance	+
		Number of financial information service enterprises	pcs	Total number of legal entities engaged in the collection, processing, and dissemination of financial information and related services	+
Industrial Digitalization		The proportion of enterprises engaged in e-commerce transactions	%	The percentage of enterprises in the region that conduct transactions for goods or services via electronic networks such as the internet, relative to the total number of enterprises in the region.	+
	E-commerce	E-commerce sales revenue	100 million yuan	The total revenue generated by a business through the sale of goods and services via the internet or other online transaction methods.	+
		E-commerce purchase amount	100 million yuan	The total amount paid by an enterprise for goods and services procured through the internet or other online transaction methods.	+
Digital Economy Development Environment	Digital talent	Information transmission, software, and information	10,000 people	The number of all employees engaged in information trans-	+

	technology service industry urban unit employment person- nel		mission, software, and infor- mation technology services within urban units and receiv- ing remuneration from their employers at the end of the pe- riod.	
Innovative environ- ment	Fiscal expenditure on science and tech- nology	100 million yuan	The total amount of funds allo- cated by government depart- ments at all levels through fiscal budgets for scientific and tech- nological activities.	+

(1) Digital infrastructure

Digital infrastructure is the “hardware foundation” for the development of the digital economy, serving as a prerequisite for data factor circulation and digital technology application. The selection of indicators focuses on two core elements: “digital platform construction” and “digital communication services,” aimed at comprehensively reflecting the supply capacity and accessibility of infrastructure.

Under the primary indicator of digital platform construction, the number of domain names serves as the core carrier of internet identification resources, and is the fundamental entry point for enterprises and institutions to carry out digital business. Its quantity directly reflects the supply scale of regional digital services and market activity. The number of websites represents the landing carriers of digital content and services; abundant website resources can provide diverse scenarios for various digital economy activities. This is a direct manifestation of the “usability” of digital infrastructure. The Optical fiber cable line length, as the core physical channel for data transmission, determines the rate, stability, and coverage breadth of data transmission. It is a critical hardware foundation supporting large-scale data interactions. The capacity of mobile telephone switches reflects the core processing capability of mobile communication networks. It directly affects the quality of user access and the ability to provide concurrent services to multiple terminals. It serves as an important guarantee for adapting to digital economic activities in the era of mobile internet.

Under the primary indicator of digital communication services, the mobile phone penetration rate intuitively reflects the user coverage level of digital infrastructure. A higher penetration rate means that digital technology reaches more groups and market entities. This lays the foundation for the widespread penetration of the digital economy. The number of mobile phone base stations, as core nodes of mobile communication networks, determines the coverage area and communication quality of mobile signals. This is key to ensuring the accessibility of digital services in remote areas and special scenarios. The number of internet broadband access ports reflects the access capability of fixed networks, providing stable high-speed network support for scenarios such as enterprise office work, industrial internet, and household digital consumption. It is an important complement that balances “mobility” and “fixed” digital demands.

(2) Digital industrialization

Digital industrialization is the core industrial form of the digital economy, directly reflecting the conversion of digital technology into economic value. The selection of indicators focuses on two dimensions: “telecommunication industry” and “software and information technology services industry,” aimed at reflecting the development strength and enabling potential of the digital industry itself.

Under the primary indicator of the telecommunications industry, the total volume of telecommunications services reflects the scale of the telecommunications industry as a

“basic service provider” for the digital economy. Its growth directly reflects the market demand and supply capacity of digital communication services. The total volume of postal services is an important link between the digital economy and the real economy, especially playing a key role in scenarios such as e-commerce logistics and rural digital services. Its scale growth reflects the empowering effect of digital industrialization on the circulation segment. The number of websites owned by companies is a direct indicator of their access to the digital economy and their engagement in online business. This reflects the penetration degree of digital industrialization on the enterprise side. It is also an important manifestation of the market demand for digital services.

Under the primary indicator of the software and information technology services industry, the software business revenue directly reflects the overall scale and profitability of the industry. As the core carrier of digital technology innovation and application, this indicator reflects the comprehensive strength of regional digital technology research and development and service provision. The revenue from information technology services focuses on high-end value-added services such as cloud services and big data services, serving as a key indicator of the transition of digital industrialization toward “high value-added, high-tech content.” Its growth rate reflects the demand potential for the deep integration of digital technology with industries, and also demonstrates the technological support capability of digital industrialization for other industries.

(3) Industrial digitalization

Industrial digitalization is the core path through which the digital economy empowers the real economy, manifested in the deep integration of digital technology with traditional industries. The selection of indicators focuses on two key areas of integration: “digital finance” and “e-commerce,” aiming to reflect the transformation and upgrading effects of digital technology on traditional industry production, circulation, and financial services.

Under the primary indicators of digital finance, the premium income from internet property insurance and the premium income from internet life insurance reflect the achievements of the financial industry in achieving service innovation through digital channels. Digital finance breaks the temporal and spatial limitations of traditional financial services and lowers the service threshold, providing convenient risk protection and financial support to upstream and downstream companies and individual operators within the industry chain. This is a direct manifestation of how digital technology empowers financial services in the real economy. The number of financial information service enterprises reflects the degree of completeness of the digital finance ecosystem. Professional financial information service companies can provide data support, risk assessment, and other value-added services to market entities. This promotes the optimal allocation of financial resources and enhances the enabling efficiency of digital finance for industries.

Under the primary indicators of e-commerce, the proportion of enterprises engaged in e-commerce transactions intuitively reflects the penetration breadth of digital technology in business transaction processes. This reflects the enthusiasm of regional companies to embrace digital transaction models and expand market channels. The sales revenue and purchase amount of e-commerce, respectively, reflect the actual transaction scale of e-commerce from the “sales side” and “procurement side.” This demonstrates the optimization effect of digital technology on enterprise supply chains. The sales side broadens market boundaries, while the procurement side lowers transaction costs and improves efficiency. Together, these two aspects constitute the core value manifestation of industrial digitalization in the circulation segment.

(4) Digital economy development environment

The development environment of the digital economy is an important guarantee for its sustained and healthy growth. The selection of indicators focuses on two core elements: “talent support” and “innovation ecosystem,” aiming to reflect the soft power and sustainable development potential of regional digital economy development.

Under the primary indicator of digital talent, the number of employees in urban units of information transmission, software, and information technology services directly reflects the supply scale of digital talent in the region.

Under the primary indicator of the innovation environment, fiscal expenditure on science and technology reflects the level of government support for technological innovation. The core driving force of the digital economy is technological innovation. The investment of fiscal science and technology funds can provide critical financial support for digital technology research and development, innovation platform construction, and the transformation of scientific and technological achievements. This helps create a favorable ecosystem that encourages innovation and is tolerant of failure, accelerating the iteration and application promotion of digital technologies, injecting long-term momentum into the development of the digital economy.

3. Mediating Variables

This study selects two mediating variables to examine the mechanisms by which the digital economy affects the resilience of the cotton industrial chain: the level of planting scale and the technological innovation vitality. Specifically, referencing the methods of Paula Stoicea et al., this study measures the level of planting scale using per capita cotton planting area [32]; additionally, the logarithm of the number of patent applications granted is used to measure the technological innovation vitality. The rationale is that the number of patents granted directly reflects the output of technological innovation, with its scale indicating both the level of activity in technological R&D and the market value recognition of innovation results. It also effectively captures the ability of market entities to transform R&D investments into technical solutions that possess practical value and commercial potential [33].

4. Control Variables

Considering the relationship between the digital economy and the resilience of the cotton industrial chain, this study selects the following control variables: the level of economic development is measured by the logarithm of regional per capita gross domestic product (GDP); urbanization level is measured by the proportion of urban population to the total resident population at year-end; rural-urban income disparity is expressed by the ratio of per capita disposable income of urban residents to that of rural residents; government support intensity is measured by the proportion of local fiscal expenditure on science, technology, and education to local fiscal budget expenditure; and the level of openness is measured by the ratio of import and export value to regional GDP.

3.1.3. Indicator Measurement

This study employs the entropy method to determine the weights of each indicator and finally calculates the development of the digital economy and the resilience of the cotton industrial chain through weighted summation.

The specific steps are as follows:

1. Create an Evaluation Matrix

$$X = (x_{ij})_{m \times n} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

where i represents the year, j represents the indicator, m denotes the number of sampled observations, n represents the number of indicators, and X represents an $m \times n$ matrix.

2. Data Normalization

The data are processed for dimensionless normalization, applying the range method to reverse indicators and normalizing direct indicators.

After applying the range method, it may result in values of zero; thus, a non-negative translation of all values by 0.0001 units to the right is employed. (Multiple different translation constants were selected for testing within the interval [0.0001, 0.01]. The results indicate that the weight ranking of each indicator remains completely consistent, with very small variations in weight values.)

Normalization method for direct indicators:

$$r_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} + 0.0001 \quad (2)$$

Normalization method for reverse indicators:

$$r_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} + 0.0001 \quad (3)$$

where r_{ij} is the normalized indicator value and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of x across all years for each indicator, respectively.

3. Calculate the Information Entropy Values of Each Indicator

The information entropy value is derived from the following formula:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln p_{ij} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (4)$$

where r_{ij} is calculated based on formulas (2) and (3).

4. Calculate the Weights of Each Indicator

$$w_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (5)$$

where e_j is calculated using formula (4).

5. Calculate the Comprehensive Score Based on Entropy Weights

$$S_j = \sum_{i=1}^n w_j r_{ij} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (6)$$

where w_j is computed using Formula (6), r_{ij} is based on the calculations from Formulas (2) and (3).

Table 3 presents the summary characteristics of the statistical variables.

Table 3. Descriptive Statistics of Key Variables.

Variable	Variable Name	N	Mean	SD	Min	Max
Dependent Variable	Cotton Industry Chain Resilience	90	0.190	0.104	0.067	0.468
Independent Variable	Level of Digital Economy Development	90	0.270	0.176	0.0339	0.810
Mediating Variables	Technological innovation vitality	90	10.649	1.012	8.463	12.743
	Planting scale level	90	0.121	0.288	0.001	0.993
	Level of economic development	90	10.795	0.299	10.071	11.412
	Urbanization level	90	0.548	0.056	0.400	0.650
Control Variables	Urban–rural income disparity	90	2.511	0.343	2.060	3.560
	Government support strength	90	0.196	0.020	0.164	0.242
	Level of openness to the outside world	90	0.130	0.079	0.001	0.373

3.1.4. Analysis of the Measurement Results of Digital Economy Development Level

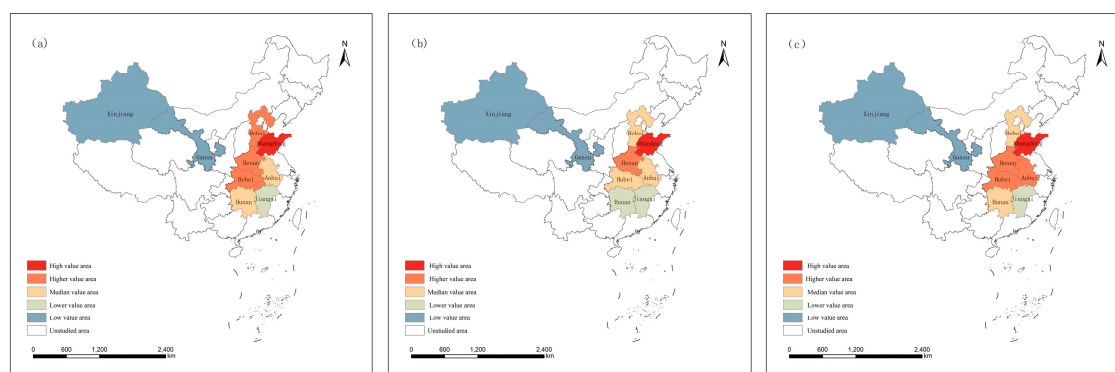
Table 4 presents a detailed display of the digital economy development levels in major cotton-producing provinces from 2013 to 2022. The overall mean shows that the Yellow River Basin cotton region has a higher level of digital economy development compared to

the other two cotton regions. Among these, Shandong Province's digital economy development level is significantly higher than that of other provinces, placing it in a leading position. Although Henan Province ranks second, there remains a considerable gap compared to Shandong's level of digital economy development. Xinjiang and Gansu, located in the Northwest Inland Cotton Region, have not even surpassed a digital economy development level of 0.1, indicating a severe lack of momentum for digital economy development. The digital economy development levels in Hubei, Hunan, and Anhui in the Yangtze River Basin cotton region have all reached 0.2, indicating relatively balanced development; however, Jiangxi lags behind compared to other provinces in the Yangtze River Basin.

Table 4. Development level of digital economy in major cotton producing provinces in China from 2013 to 2022.

Cotton-Growing Area	Region	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
the Yellow River Basin	Hubei	0.110	0.150	0.201	0.232	0.265	0.305	0.376	0.383	0.359	0.403	0.278
	Anhui	0.089	0.124	0.171	0.213	0.245	0.288	0.350	0.388	0.342	0.359	0.257
	Hunan	0.084	0.107	0.129	0.163	0.194	0.233	0.289	0.334	0.283	0.301	0.212
	Jiangxi	0.046	0.066	0.095	0.101	0.136	0.162	0.201	0.230	0.194	0.212	0.144
the Yangtze River Basin	Shandong	0.320	0.355	0.412	0.491	0.558	0.634	0.670	0.735	0.738	0.810	0.572
	Henan	0.132	0.170	0.221	0.263	0.311	0.365	0.427	0.475	0.389	0.385	0.314
	Hebei	0.115	0.137	0.167	0.201	0.241	0.277	0.335	0.373	0.318	0.323	0.249
Northwest Inland	Xinjiang	0.026	0.035	0.047	0.055	0.060	0.082	0.097	0.117	0.095	0.101	0.071
	Gansu	0.012	0.020	0.034	0.043	0.055	0.069	0.085	0.098	0.075	0.079	0.057

To observe the changes in the digital economy development levels in major cotton-producing provinces from 2013 to 2022 more clearly, Arcmap 10.8 software was used to categorize the digital economy development levels into six categories based on the natural breaks classification method, visualizing the development levels for the years 2013, 2017, and 2022 (Figure 4).



(a) 2013 (b) 2017 (c) 2022

Figure 4. Spatial Distribution of Digital Economy Development Levels in 2013, 2017, and 2022.

In numerical terms, from 2013 to 2022, the high-value area of digital economy development levels remained at one; the higher-value area decreased from three to one in 2017 and then restored to three in 2022; the middle-value area increased from two to three in 2017 and then returned to two in 2022; the lower-value area rose from one to two in 2017 and then dropped back to one in 2022; and the low-value area consistently remained at

two. Overall, the spatial pattern of changes in digital economy development levels was relatively stable.

Specifically, from 2013 to 2022, the digital economy development levels in Xinjiang and Gansu consistently remained in the low-value area; Jiangxi's digital economy development level remained in the lower value area; Hubei and Hunan exhibited fluctuating trends, with Hunan dropping from the middle-value area to the lower value area, and then returning to the middle-value area by 2022, while Hubei declined from the higher-value area to the middle-value area and then rebounded to the higher-value area; Anhui's digital economy development level increased from the middle-value area to the higher-value area; the digital economy development levels in Henan and Shandong remained stable, with Shandong consistently in the high-value area and Henan in the higher value area; and Hebei's digital economy development level dropped from the higher-value area to the middle-value area.

3.1.5. Analysis of the Measurement Results of Cotton Industrial Chain Resilience

The evaluation results of the resilience of the cotton industrial chain from 2013 to 2022 are shown in Table 5. Observing the overall mean reveals that there are small differences in cotton industrial chain resilience levels among provinces in the Yangtze River Basin and the Yellow River Basin, while there is a significant gap in resilience levels in Xinjiang and Gansu of the Northwest Inland Cotton Region. In the Yangtze River Basin, Hubei has the highest resilience level of the cotton industrial chain, showing a clear gap compared with Jiangxi, which has the lowest resilience level in the basin. In the Yellow River Basin, the resilience levels of the cotton industrial chain in Henan and Hebei are nearly comparable to that of Hubei, the highest in the Yangtze River Basin, while Shandong's resilience level is second only to that of Xinjiang.

Table 5. Evaluation Results of Resilience in the Cotton Industry Chain from 2013 to 2022.

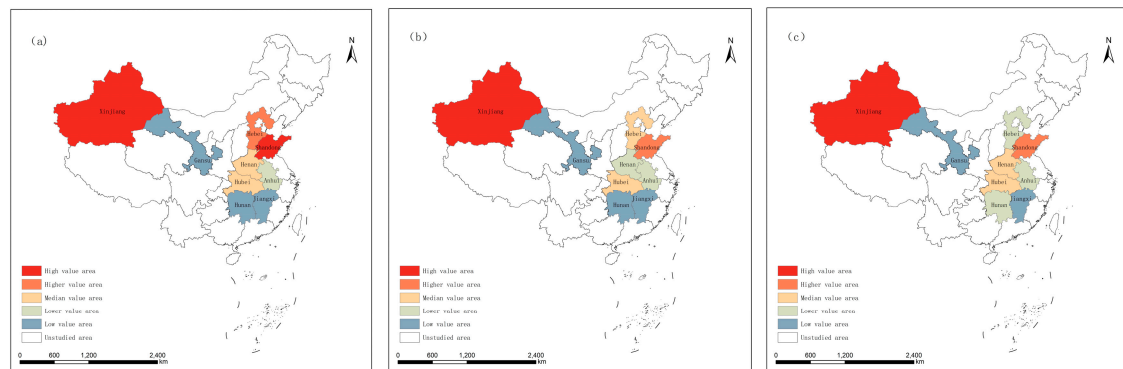
Cotton-Growing Area	Region	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
the Yellow River Basin	Hubei	0.160	0.163	0.169	0.166	0.170	0.189	0.218	0.211	0.252	0.253	0.195
	Anhui	0.117	0.126	0.137	0.152	0.160	0.183	0.184	0.172	0.204	0.203	0.164
	Hunan	0.070	0.071	0.085	0.086	0.103	0.111	0.124	0.130	0.187	0.185	0.115
	Jiangxi	0.084	0.078	0.078	0.083	0.082	0.091	0.098	0.116	0.175	0.096	0.098
the Yangtze River Basin	Shandong	0.272	0.279	0.270	0.271	0.272	0.290	0.303	0.310	0.329	0.336	0.293
	Henan	0.153	0.158	0.156	0.155	0.164	0.171	0.171	0.206	0.262	0.269	0.187
	Hebei	0.173	0.175	0.176	0.169	0.182	0.148	0.147	0.181	0.197	0.206	0.175
Northwest Inland	Xinjiang	0.343	0.359	0.336	0.347	0.416	0.450	0.441	0.451	0.453	0.468	0.406
	Gansu	0.074	0.072	0.068	0.073	0.072	0.071	0.067	0.075	0.079	0.077	0.073

Visualization of resilience levels of the cotton industrial chain for the years 2013, 2017, and 2022 (Figure 5) clearly illustrates the changes in resilience levels among the major cotton-producing provinces in China.

In terms of quantity, from 2013 to 2022, the high-value areas of cotton industrial chain resilience decreased from two to one, the higher-value area remained constant at one, the middle-value area stayed at two, the lower-value area increased from one to three, and the low-value area decreased from three to two. Overall, the resilience level of the cotton industrial chain in China shows a declining trend.

Specifically, the resilience levels of the cotton industrial chain in Xinjiang, Gansu, Jiangxi, Anhui, and Hubei are relatively stable. Xinjiang's resilience level remains in the high-value area, while Gansu and Jiangxi maintain low-value levels. Anhui's resilience level sits in the lower-value area, and Hubei's resilience level stays in the middle-value

area. The resilience level of the cotton industrial chain in Hunan has increased, shifting from the lower-value area to the middle-value area; Hebei's resilience level has fallen from the higher-value area in 2013 to the lower-value area in 2022. Shandong's resilience level of the cotton industrial chain decreased from the high-value area to the higher-value area; Henan's resilience level exhibited fluctuations, dropping from the middle-value area in 2013 to the lower-value area in 2017, before rising back to the middle-value area in 2022.



(a) 2013 (b) 2017 (c) 2022

Figure 5. Spatial Distribution of Resilience in the Cotton Industry Chain in 2013, 2017, and 2022.

3.2. Micro Cases

3.2.1. Case 1: Enhancing Industry Chain Resilience Through “Cotton Farmer Cooperatives + Digital Technology” in Aral City, Xinjiang

Aral City, Xinjiang, as a major production area for high-quality cotton in the country, exemplifies the empowering of industry chain resilience through the collaborative practices of “smart agriculture” and “digital finance” in the digital economy. On the planting side, Aral City vigorously promotes smart agriculture systems. For example, in the cotton fields of Chang’an Town in the Tenth Agricultural Division, farmers can remotely perform one-click irrigation and integrated water and fertilizer operations through the “Tian Xiaor” app on their mobile phones, achieving “farming with a swipe of the phone.” This system integrates field monitoring, intelligent water and fertilizer management, and automated control, allowing growers to monitor cotton moisture levels and pest conditions at any time. In a broader scope of high-standard farmland, IoT technology achieves remote precise monitoring and scientific management of crop growth and the environment by deploying soil moisture sensors and pest monitoring instruments. On the sales and risk hedging side, cooperatives in Aral City have integrated an innovative “order purchasing + futures” digital finance platform. In 2023, supported by the Xinjiang Cotton Futures Public Welfare Special Fund, three local cooperatives, including Jin Hai Cotton Planting Cooperative, participated in a pilot project. This model is centered around leading enterprises, securing the sales and prices of cotton through spot orders on one hand, and providing price risk protection for cooperatives using off-exchange options as a financial tool on the other. The project directly served 45 cotton farmers, covering 18,000 acres of cotton fields, completing the purchase of 7200 tons of seed cotton, and achieving income compensation through off-exchange options.

This practice enhances resilience from three dimensions: First, it enhances the adaptability and recovery capacity of the production segment. The smart agriculture system directly addresses the challenges of regional water resource constraints and labor fluctuations through precise irrigation and fertilization. Farmers no longer need to stay at the fields constantly, reducing the vulnerability of production management to specific

weather conditions and labor availability, thereby enhancing the stability and adaptability of the production system. Second, it strengthens the resistance to risk and stability in the circulation segment. The “order purchasing + futures” model establishes a dual guarantee. Contract farming locks in sales channels, shortens sales cycles, and mitigates the risk of “difficulty in selling”, while the futures financial instruments hedge against market price fluctuation risks, essentially providing “insurance” for farmers’ incomes, thus ensuring their capacity for reproduction. Finally, it promotes synergy and evolutionary capability within the industry chain. This model deepens the benefit connections among “leading enterprises + cooperatives + farmers.” Leading enterprises obtain stable and quality raw material sources through digital platforms, while cooperatives and farmers receive technical and financial support, creating a closely knit industry chain organization characterized by shared risks and shared benefits, thus improving overall collaborative efficiency and the evolutionary capabilities to respond to market changes.

3.2.2. Case 2: Data-Driven Intelligent Transformation of the Entire Industry Chain by Shandong Weiqiao Entrepreneurship Group

Zouping City in Shandong Province focuses on data elements as a critical point, promoting the textile industry to achieve a leap from traditional manufacturing to intelligent, green, and high-end production by building a data foundation, deepening data applications, and revitalizing data assets. Weiqiao Entrepreneurship Group, as a leading enterprise in Zouping’s textile industry, launched the “Digital Weiqiao” strategy in 2018, spending 2–3 years building a corporate data central platform, and installing tens of thousands of sensors on the production lines, which collect real-time, all-encompassing equipment and production data, forming a solid and reliable “data foundation.” Through its self-developed I3.0 intelligent management system, Weiqiao has achieved full-dimensional intelligent management from intelligent order scheduling and quality online control to dynamic cost management, resulting in a 37.5% increase in production efficiency, an 80% reduction in the number of workers, a 21% increase in the comprehensive quality index of semi-finished products, and a reduction of over 40% in overall energy consumption, along with over 20% savings in water consumption. The intelligent spinning factory, which has integrated smart collaboration throughout the entire process, has been selected as a national-level outstanding intelligent factory. In addition, it has built a comprehensive supply chain information platform to achieve visual management from procurement to logistics. Transforming decades of production experience into three major expert knowledge bases: process, quality, and equipment, thus becoming a core data asset for continuous optimization.

Weiqiao’s practices have reshaped the resilience of the industry chain from three levels: First, it enhances the self-adaptation and evolutionary capacity of the production system. The intelligent system achieves “one-click smart scheduling,” allowing for quick responses to changes in market orders. The establishment of the expert knowledge base enables the condensation and reuse of production knowledge, driving continuous optimization of processes. This marks an evolution of the industry chain from reliance on human experience to a continuous self-learning and iterative system based on data algorithms, thus equipping it with a strong inherent capacity for renewal. Secondly, it builds operational resilience that is resistant to disturbances and capable of quick recovery. The full-process digital monitoring and predictive maintenance significantly reduce the risks of unplanned downtimes. When fluctuations occur in specific segments, the intelligent scheduling system can quickly adjust production rhythms and logistics paths, avoiding disturbance diffusion, ensuring the stability of overall operations and the capability for rapid recovery. Finally, it strengthens the collaborative and risk-resistance capabilities along the entire chain. The supply chain visualization platform makes the information

between upstream and downstream transparent, enabling earlier detection and response to potential risks in raw materials and logistics. This depth of collaboration extends the resilience of a single enterprise to the resilience of the industry chain network, thereby enhancing the collective capacity of the entire system to respond to external shocks.

3.3. Model Specification

3.3.1. Semi-Parametric Panel Data Model

The core aim of this study is to explore the impact of the digital economy on the resilience of the cotton industrial chain. However, existing economic theories have not provided a clear theoretical function form (such as linear or quadratic) to describe the relationship between the two. The influence of the digital economy may not be a simple linear “input-output” relationship, and its marginal effects may vary depending on levels of development. The advantage of the semi-parametric model lies in its non-parametric component, which can flexibly capture and demonstrate this “data-driven” nonlinear relationship of unknown form without the need to impose a potentially incorrect functional form in advance as with parametric models. The StataMP-64 estimation command `xtsemipar` for the semiparametric panel data model can be directly downloaded and used in Stata software. The following semi-parametric panel data model is constructed in this study:

$$Y_{it} = \beta Z_{it} + g(D_{it}) + \mu_i + \delta_t + \varepsilon_{it}$$

Here, i and t represent provinces and years, Y_{it} respectively; represents the resilience of the cotton industrial chain; Z_{it} represents the control variables; μ_i is the province fixed effect; δ_t is the time fixed effect; ε_{it} is the random disturbance term; β represents the parameters to be estimated; $g(D_{it})$ represents non-parametric estimation of the functional relationship that has not been clearly defined; and D_{it} represents the digital economy.

3.3.2. Mediation Effect Model

A mediation effect model is constructed to empirically test the pathways through which the digital economy affects the resilience of the cotton industrial chain. The specific model is as follows:

$$Y_{it} = \gamma_0 + \gamma_1 D_{it} + \gamma_2 Z_{it} + \mu_i + \delta_t + \varepsilon_{1it}$$

$$M_{it} = \rho_0 + \rho_1 D_{it} + \rho_2 Z_{it} + \mu_i + \delta_t + \varepsilon_{2it}$$

Here, i , t , Y_{it} , Z_{it} , D_{it} have the same meanings as in Equation (1); M_{it} is the mediating variable, which includes the technological innovation vitality and the level of planting scale; μ_i is the province fixed effect; δ_t is the time fixed effect; and ε_{1it} , ε_{2it} are the random disturbance terms for each respective model.

3.4. Mechanisms and Spatiotemporal Differences in Digital Economy Driving the Resilience Improvement of the Cotton Industrial Chain

3.4.1. Multicollinearity Issues

Given the potential strong correlations among variables, this study uses the Variance Inflation Factor (VIF) to test for multicollinearity issues. A higher VIF value indicates more severe multicollinearity among variables, with a common threshold of VIF greater than 10 used to determine the presence of multicollinearity; values below this threshold suggest weak linear correlations that do not constitute significant interference. Table 6 presents the VIF values for the core independent variables and control variables. The results show that all variable VIF values are below 10, indicating that there is no serious multicollinearity in the model, thus making the regression analysis results reliable.

Table 6. Variance Inflation Factor (VIF) for each variable.

Variable	VIF	1/VIF
Level of Digital Economy Development	3.88	0.257906
Level of economic development	7.66	0.130498
Urbanization level	6.77	0.147634
Urban–rural income disparity	2.23	0.447768
Government support strength	3.29	0.303810
Level of openness to the outside world	2.90	0.344531

3.4.2. The Impact of the Digital Economy on the Resilience of the Cotton Industrial Chain

Figure 6 presents the semi-parametric panel data regression results for the impact of the digital economy on the resilience of the cotton industry chain. It can be observed that the relationship exhibits a significant “inverted U-shaped” nonlinear characteristic, which aligns with research hypothesis H1. This finding is consistent with the nonlinear patterns observed by Suo (2022) [34], Wang (2022) [35], Zhao (2025) [36] in their studies on the impacts of the digital economy on total factor productivity, the real economy, and industrial structure upgrading, indicating that the staged bottleneck of digital technology penetration may be a universal economic phenomenon. From the empirical measurement results, the characteristics of the digital economy development stage corresponding to this nonlinear relationship are approximately as follows: Digital infrastructure has been widely disseminated, core business processes have generally completed digital transformation, but the deep integration of data elements and intelligent collaboration have not yet been fully realized. The characteristics of this stage can provide a reference basis for the optimization and adjustment of regional policies.

Analyzing from the perspective of economic mechanisms, the impact effects of digital economy development on the resilience of the cotton industry chain exhibit heterogeneity at different stages, overall presenting a phased empowerment characteristic. In the relatively early stages of digital economy development, its impact is primarily manifested as a significant “empowerment effect.” During this stage, the dissemination and application of digital infrastructure directly resolve issues of information asymmetry, enhancing the transparency of the supply chain and resource allocation efficiency, consistent with the characteristics of concentrated technological dividends observed in the classic “Solow Paradox [37].” Digitalization, as a key dynamic capability, assists cotton farmers and enterprises in expanding markets and optimizing costs, thereby systematically enhancing the adaptability and risk resistance of the industry chain.

As the level of digital economy development continues to rise, its promoting effect on the resilience of the cotton industry chain exhibits marginal changes, leading to the emergence of “structural risks [38]” and “capability threshold effects [39],” which may negate the gains from early empowerment, resulting in a diminished net promoting effect. This is specifically manifested as follows: First, the locking of technological paths and adjustment rigidity: the supply chain develops a deep reliance on the established digital technology system, leading to “path dependence [40]” and “core rigidity [41].” In the face of new market shocks or disruptive technological innovations, large sunk costs and rigid digital processes make it difficult for the system to undergo fundamental adjustments, thereby weakening its “transformational resilience” in responding to discontinuous changes. Second, structural differentiation in the capabilities of entities: the digital capability gap among different entities within the supply chain (large enterprises versus small and medium farmers and cooperatives) rapidly widens. The leading entities enjoy the data scale dividends, while the lagging ones face “digital marginalization” due to resource constraints, and this internal differentiation undermines the overall efficiency and stabil-

ity foundation of the industry chain collaboration. Third, the increase in system vulnerability: while the digital economy enhances the coupling efficiency among various links, it also constructs high-speed transmission channels for risks, making local failures (such as data security incidents and platform interruptions) more likely to trigger systemic disruptions.

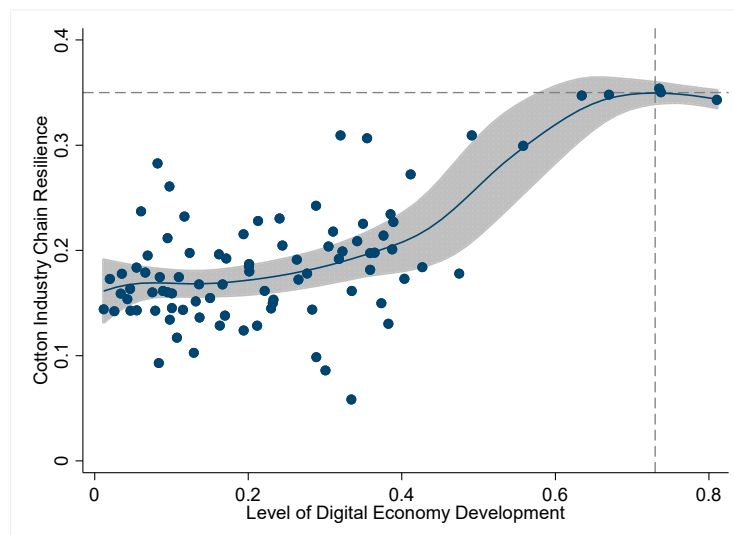


Figure 6. The Relationship Between the Digital Economy and the Resilience of the Cotton Industry Chain.

Table 7 presents the regression results of the semi-parametric panel data for the impact of control variables on the resilience of the cotton industrial chain. As shown in Table 6, the level of economic development, urban–rural income disparity, and industrial structure have significant impacts on the resilience of the cotton industrial chain. (1) The level of economic development is significantly positive at the 1% significance level, indicating that a solid economic foundation positively drives the enhancement of the resilience of the cotton industrial chain. The higher the regional economic development level, the better it leverages regional economic advantages to promote resilience improvement in the cotton industrial chain. (2) The coefficient of urban–rural income disparity is significantly positive at the 10% level, indicating that urban–rural income disparity has a positive promoting effect on the resilience of the cotton industrial chain. The income gap leads to rural outmigration, facilitating land transfer, which is conducive to achieving large-scale operations and enhancing the resilience of the cotton industrial chain. (3) The coefficient of the level of openness is significantly positive at the 1% level, indicating that the level of openness plays an important facilitating role in building the resilience of the cotton industrial chain. Increasing the level of openness significantly promotes the cotton industrial chain in areas such as resource allocation, market diversification, competitive optimization, and collaborative innovation, enhancing overall resilience.

Table 7. Estimation Results of Parameters for Digital Economy and Cotton Industry Chain Resilience.

Variable	Coefficient
Level of economic development	0.254 *** (6.46)
Urbanization level	−0.203 (−1.01)
Urban–rural income disparity	0.070 * (2.50)
Government support strength	0.049 (1.39)
Level of openness to the outside world	1.147 *** (8.32)

N	90
R ²	0.7924
Provinces fixed	Yes
Years fixed	Yes

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses are *t*-values.

3.4.3. Robustness Testing

To enhance the robustness of the regression results, this study introduces the Tobit model and one-period lagged values of the core explanatory variables for robustness testing, with specific results shown in Table 8.

8. Since the resilience indicator of the cotton industrial chain takes values between 0 and 1, it is appropriate to use the Tobit model to handle the limited dependent variable, thus replacing the original model for verification. Column (1) of Table 8 shows that the regression coefficient of the digital economy development level is positive at the 1% significance level, indicating that its promoting effect on the resilience of the industrial chain remains significant, thereby validating the reliability of the conclusion.

9. Considering that the digital economy may have a lagged effect on industrial chain resilience, this study re-regresses the core explanatory variable with a one-period lag. The results in column (2) of Table 8 indicate that the digital economy development level still shows a positive impact at the 1% significance level, further supporting its robustness.

Table 8. Robustness test results.

Variable	Tobit Model	Lagged Core Explanatory Variable
Level of Digital Economy Development	0.341 *** (6.39)	0.375 *** (5.88)
Constant term	1.733 *** (3.21)	1.954 *** (3.18)
N	90	90
Control variables	Controlled.	Controlled.
Provinces fixed	Yes	Yes
Years fixed	Yes	Yes

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses are *t*-values.

3.4.4. Endogeneity Testing

Although the semi-parametric regression analysis has revealed an inverted U-shaped relationship between the level of digital economy development and the resilience of the cotton industrial chain, this conclusion may be affected by endogeneity issues, particularly, the enhancement of the resilience of the cotton industrial chain may, in turn, promote the application of digital technologies. To mitigate the biases caused by this potential reverse causality, this paper employs two instrumental variables—total length of automobile postal roads and terrain ruggedness—to address potential endogeneity issues within the model. The total length of automobile postal roads, as an important indicator of historical transportation infrastructure, reflects the early conditions for information transmission and material circulation in the region [30]. This historical advantage often persists and transforms into foundational conditions for the development of the digital economy, thus satisfying the criteria for relevance between the instrumental variable and the endogenous variable. At the same time, as a historical infrastructure variable, the total length of automobile postal roads primarily influences the development of the digital economy through path dependency, without directly affecting the contemporary resilience level of the cotton industrial chain, thereby meeting the conditions of exogeneity. Terrain ruggedness, as

a natural geographic condition, directly influences the deployment costs and coverage efficiency of digital infrastructure, satisfying the relevance requirements [42]. Furthermore, as an exogenous geographical variable, terrain ruggedness does not directly affect the resilience of the industrial chain, thus satisfying the exclusivity constraint conditions. It should be noted that terrain ruggedness is cross-sectional data and cannot be matched. Therefore, the interaction terms of terrain ruggedness with the time variable (sample study years) are used as instrumental variables for the digital economy, denoted as IV1 and IV2, respectively.

The results of the 2SLS regression using instrumental variables are shown in Table 9, where the K-P rk LM statistics for both sets of instrumental variables reject the null hypothesis of insufficient identification at the 1% level. The C-D Wald F statistic exceeds the critical value at the 10% level according to Stock-Yogo, indicating that there are no weak instrumental variables, meaning the instrumental variables selected in this study are reasonable and reliable. As shown in columns (2) and (4), after fully considering the endogeneity issues that may result from reverse causality, the estimated coefficient of the digital economy remains significantly positive at the 1% level, consistent with the baseline regression results, further confirming that the digital economy contributes to the enhancement of the resilience level of the cotton industrial chain.

Table 9. Endogeneity test results.

Variable	(1)	(2)	(3)	(4)
	First Stage	Second Stage	First Stage	Second Stage
Level of Digital Economy Development		0.233 *** (0.0802)		0.208 *** (0.0423)
IV1	0.126 *** (0.0181)			
IV2			−0.106 *** (0.0114)	
Control variables	Controlled	Controlled	Controlled	Controlled
Provinces fixed	Yes	Yes	Yes	Yes
Years fixed	Yes	Yes	Yes	Yes
K-P rk LM		19.742 [0.000]		26.112 [0.000]
C-D Wald F		99.272 {16.38}		52.708 {16.38}
N	90	90	90	90
R2		0.530		0.375

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses are t-values.

3.4.5. Exploration of Effect Pathways

This study analyzes the pathways affecting the resilience of the cotton industrial chain, referencing Jiang Ting's (2022) approach to mediating effect testing [43]. The mediating effect test results are shown in Table 10, where column (1) presents the regression results of the core explanatory variable on the resilience of the cotton industrial chain, column (2) shows the regression results of the core explanatory variable on the technological innovation vitality, and column (3) displays the regression results of the core explanatory variable on the level of planting scale.

Table 10. Mediation Effect Test Results.

	(1)	(2)	(3)
	Cotton Industry Chain Re-silience	Technological Innovation Vitality	Planting Scale Level
Level of Digonomy Development	0.169 *** (3.41)	4.995 *** (5.92)	2.938 *** (6.627)
_cons	0.184 *** (15.51)	9.454 *** (46.78)	4.855 *** (45.770)

Control variables	Controlled	Controlled	Controlled
Sobel test		0.049, $p = 0.000$	0.102, $p = 0.000$
Bootstrap test		[0.0141, 0.085]	[0.0516, 0.1532]
Provinces fixed	Yes	Yes	Yes
Years fixed	Yes	Yes	Yes
N	90	90	90
r^2	0.280	0.667	0.126

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses are t-values.

The regression results in column (2) show that the coefficient of the core explanatory variable, the level of digital economy development, is significantly positive at the 1% level, indicating that the advancement of the digital economy effectively stimulates technological innovation vitality. The digital economy significantly reduces the trial-and-error costs and uncertainties associated with technological innovation by establishing a data-driven R&D paradigm: On one hand, technologies such as the Internet of Things and remote sensing monitoring facilitate high-throughput data collection on the production environment and growth processes of cotton, providing rich data support for variety selection and precision agronomy innovation. On the other hand, industrial internet platforms bridge data across the entire “planting-textile-sales” chain, prompting midstream companies to engage in process adaptation R&D based on raw material characteristics and downstream demands, driving the spinning and weaving segments toward greater flexibility and intelligence. This innovation model, which relies on data as a key input factor and platforms as collaborative carriers, not only enhances the efficiency of R&D resource allocation but also gives rise to integrated technological solutions such as smart irrigation systems and blockchain traceability platforms. The sustained vibrancy of technological innovation enhances the resilience of the industrial chain in facing internal and external shocks and its potential for structural reconstruction, providing fundamental motivation for resilience enhancement [44] and validating H2.

The regression results in column (3) show that the coefficient of the core explanatory variable, the level of digital economy development, is significantly positive at the 1% level, indicating that an increase in the level of digital economy development helps to expand the scale of cotton cultivation. The development of the digital economy facilitates the flow of rural labor to cities and the secondary and tertiary industries, allowing idle land to be utilized for large-scale operations. Large-scale cotton cultivation entails the concentration and optimized allocation of production resources, achieving intensive management, utilizing advanced agricultural technologies and digital tools to enhance production efficiency and product quality [45]. At the same time, this can reduce unit costs, enhance market competitiveness, and improve the overall resilience of the cotton industrial chain, thus validating H3.

3.4.6. Heterogeneity Analysis

- Regional Heterogeneity

This study investigates the heterogeneity in the impact of the digital economy on the resilience of the cotton industrial chain across three different major cotton-producing regions. Figure 5 presents the regression results of the core explanatory variables, while Table 11 shows the regression results of the control variables.

From Figure 7, it is evident that there is significant regional heterogeneity in the impact of the digital economy on the resilience of the cotton industrial chain. (1) Yellow River Basin Cotton Region: The development of the digital economy significantly suppresses the enhancement of the resilience of the cotton industrial chain. The mismatch between

transformation costs and organizational capacity means that small and medium-sized cotton enterprises and farmers account for a high proportion in the region, and their limited capital strength makes it difficult for them to bear the high investment and operational costs of digital equipment, while technological investments deplete their elastic resources for coping with market fluctuations [46]. The deficiencies in the data factor market lead to a decline in resource allocation efficiency, with low coverage of agricultural data platforms in the region and inconsistent standards, resulting in distorted data transmission between production and consumption stages. The shortage of digital skills restricts the conversion of technological effectiveness; in the face of an aging agricultural labor force, digital tools have not been effectively integrated into actual production decisions. In summary, constrained by weak foundations, high transformation costs, and insufficient human capital, the digital economy in this region has not effectively empowered the enhancement of industrial chain resilience; instead, it has exacerbated friction and resistance to transformation within the system at this stage. (2) Yangtze River Basin Cotton Region: The development of the digital economy significantly promotes the enhancement of the resilience of the cotton industrial chain. This region has a solid digital foundation and a high degree of integration between information technology and the cotton industry. It has established an efficient supply chain digital management system and decision-making mechanisms, significantly enhancing the responsiveness, adaptability, and stability of the industrial chain, making it a key driving force for resilience enhancement. (3) Northwest Inland Cotton Region: The digital economy has a promoting effect on the resilience of the cotton industrial chain, but this promoting trend is not very pronounced. According to the theory of regional economic and technological gradient transfer [47], this region is still in the early stages of digital development, lacking effective integration pathways, and is constrained by transportation and market conditions; thus, the driving effect of the digital economy on the resilience of the industrial chain has not been fully realized.

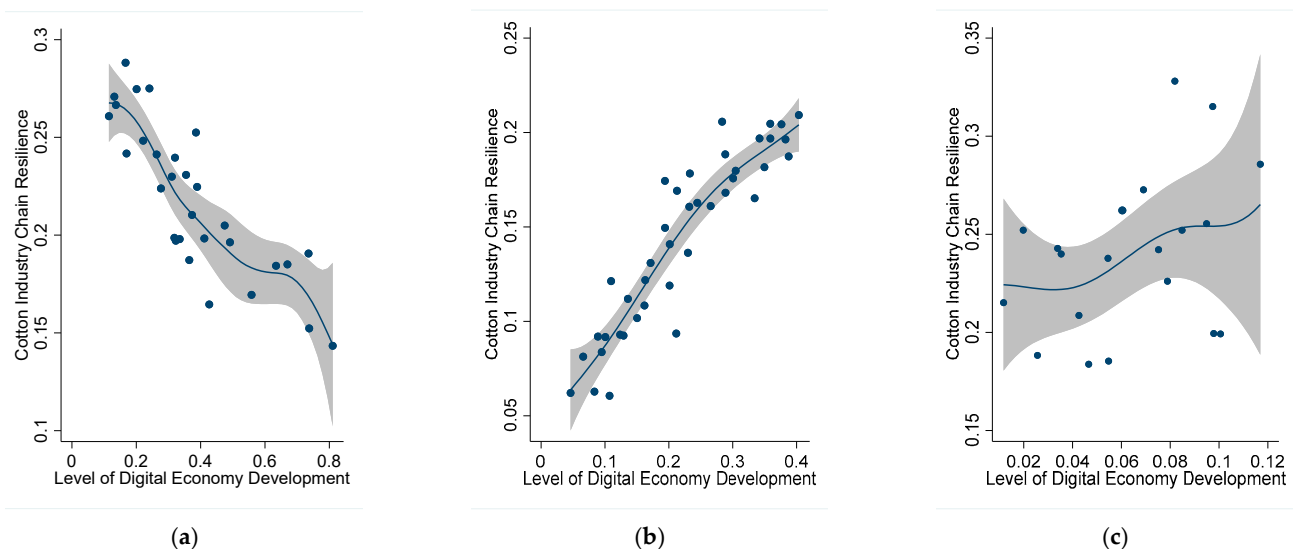


Figure 7. Regional heterogeneity test results. (a) Yellow River Basin Cotton-Growing Region; (b) Yangtze River Basin Cotton-Growing Region; (c) Northwest Inland Cotton-Growing Region.

The spatial heterogeneity regression results of the control variables displayed in Table 11 indicate that the level of economic development, urban–rural income disparity, and openness significantly influence the enhancement of the resilience of the cotton industrial chain. Notably, the effects of economic development level and urban–rural income disparity on the resilience enhancement of the cotton industrial chain in the Northwest Inland Cotton Region are not significant. This may be due to the relatively slow economic

development in this region, leading to insignificant impacts of economic development level and urban–rural income disparity on the resilience of the cotton industrial chain in that area.

Table 11. Test results for heterogeneity of controlled variables.

Variable	Regional Heterogeneity			Time Heterogeneity	
	Yellow River Basin	Yangtze River Basin	Northwest Inland	2013–2017	2018–2022
Level of economic development	0.613 *** (4.32)	0.323 *** (4.03)	0.190 (0.34)	0.154 ** (2.97)	0.276 *** (6.71)
Urbanization level	−0.300 (−1.68)	−1.588 *** (−4.01)	1.225 (0.51)	0.310 (1.74)	−1.033 *** (−3.72)
Urban–rural income disparity	0.264 ** (3.19)	−0.179 ** (−3.10)	0.175 (0.57)	0.086 *** (4.41)	−0.071 (−1.20)
Government support strength	−0.061 (−0.71)	−0.108 ** (−3.19)	−0.044 (−0.34)	−0.011 (−0.33)	−0.051 (0.70)
Level of openness to the outside world	−2.488 * (−2.20)	−1.378 *** (−3.78)	−6.129 *** (−4.14)	−4.976 *** (−13.53)	−4.491 *** (−6.08)
Provinces fixed	Yes	Yes	Yes	Yes	Yes
Years fixed	Yes	Yes	Yes	Yes	Yes

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses are t-values.

• Temporal Heterogeneity

The level of digital economy development and the resilience of the cotton industrial chain evolve over time, suggesting that the impact of the digital economy on the resilience of the cotton industrial chain also exhibits temporal differences. This study divides the sample period into two time frames: 2013–2017 and 2018–2022, to examine the impact of the digital economy on the resilience of the cotton industrial chain during different time periods. Figure 8 presents the regression results of the core explanatory variables, while Table 11 shows the regression results of the control variables.

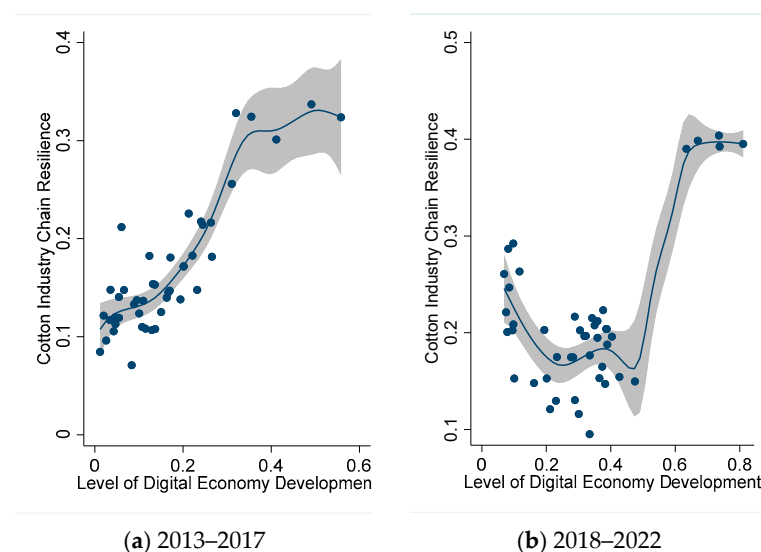


Figure 8. Results of the test for time heterogeneity.

From Figure 8, it is evident that there is significant temporal heterogeneity in the impact of the digital economy on the resilience of the cotton industrial chain. (1) From

2013 to 2017, the digital economy demonstrated a significant promoting effect on the resilience of the cotton industrial chain. During this period, the advancement of the national “Broadband China” strategy and the rapid proliferation of the 4G network significantly improved the coverage of rural information infrastructure, laying the groundwork for the digital transformation of the cotton industrial chain. In the upstream cultivation segment, remote sensing monitoring and sensor technologies began to be applied for assessing soil moisture and pest warnings in cotton fields, helping farmers achieve precise irrigation and disaster mitigation. In the midstream distribution segment, e-commerce platforms gradually opened online trading channels for cotton and cotton products, effectively reducing intermediate distribution costs and improving production-sales matching efficiency. In the downstream sales segment, the improvement of logistics networks and the initial application of traceability technology enhanced consumer trust in the quality of regional brands such as Xinjiang cotton, thus improving market stability. (2) From 2018 to 2022, the impact of the digital economy on the resilience of the cotton industrial chain exhibited a trend of first declining and then rising. The initial decline was mainly due to the unique adaptive challenges faced by various segments of the cotton industrial chain during the digital transformation process: upstream cotton farmers experienced short-term efficiency losses due to insufficient digital skills and investment pressures when transitioning from traditional farming to precision agriculture. Midstream processing enterprises faced issues such as inconsistent data standards and poor production-sales coordination, which affected the scheduling and quality stability of raw cotton. When digital platforms integrated the cotton distribution segment, they led to the exclusion of traditional small-scale ginning factories, thereby somewhat weakening the existing resilient organizational networks within the industrial chain. The subsequent recovery of resilience was attributed to the deep integration and systematic adaptation of digital technologies within the cotton industrial chain, which strengthened the overall resistance and recovery capacity of the cotton industrial chain when faced with natural risks and market fluctuations, propelling its resilience level into a continuous improvement phase.

The temporal heterogeneity regression results for the control variables presented in Table 11 indicate that the levels of economic development, urbanization, urban–rural income disparity, and openness significantly influence the enhancement of the resilience of the cotton industrial chain. Notably, the levels of economic development and openness have significant effects on the resilience enhancement of the cotton industrial chain in both time periods.

4. Discussion

The empirical analysis of this study indicates that the overall impact of the digital economy on the resilience of the cotton industry chain exhibits a significant “inverted U-shaped” nonlinear relationship. This finding reveals the staged nature of the digital empowerment process: in the initial phase, the digital economy mainly enhances the resilience and adaptability of the industry chain by improving information transparency, optimizing resource allocation, and strengthening node collaboration, aligning with the mainstream view worldwide that digital technologies reduce information asymmetry in agricultural supply chains and improve operational efficiency [48,49]. However, as the digitalization process deepens, challenges arising from increased system complexity, elevated technological barriers, and rising transformation costs may inhibit the enhancement of resilience at certain stages. This conclusion is consistent with Zhao’s (2024) [36] findings on the changing marginal effects in the relationship between the digital economy and industrial structure upgrading, collectively highlighting the complexity and staged characteristics of digital economy penetration into the industrial system. At the mechanism level, this study finds that the scale of planting is a key intermediary pathway for the digital

economy to enhance the resilience of the industry chain. This result aligns with the assertion in agricultural transformation theory that “scale is an important carrier for technology adoption and efficiency improvement.” The digital economy creates economically viable conditions for the standardized application of advanced digital agricultural technology by promoting the integration of land circulation and service scale, thereby stabilizing the upstream production base, which is consistent with the optimization directions proposed by Wang and Song (2022) [50] for the Chinese cotton industry. However, this finding also raises a deeper topic for international academic dialog: while promoting scale to obtain digital benefits, how to avoid the potential exacerbation of the “digital divide” and ensure inclusive development for small farmers will be a core balance that policy design and future research need to address [51].

This study still has several areas that could not be fully refined due to limitations of real-world conditions. Firstly, although the entropy method can assign weights based on the objective characteristics of data to avoid subjective biases, and it is widely applied in evaluation research, the method still has inherent limitations, such as difficulties in reducing indicator dimensions and certain requirements for data quality and sample size. Secondly, as the official statistics for core indicators of the digital economy have not yet been fully established, the proxy indicators used in this study, although validated by literature, still struggle to comprehensively capture the multidimensional characteristics of digital economy development. In the future, as the official statistical system is improved, more precise measurement methods can be employed. In evaluating the resilience of the cotton industrial chain, there are methodological challenges in quantifying implicit dimensions such as the resilience of social networks and cultural resilience; although these dimensions significantly influence system resilience, they were not included in this study’s framework due to a lack of a mature measurement system. Furthermore, the impact of extreme external shocks, such as sudden changes in international trade policies, could not be adequately reflected in the empirical model of this study due to their rarity within the sample period and the stability requirements of panel data.

Based on the above discussion, future research could focus on the following areas for further deepening: Firstly, strengthen the collection and analysis of high-frequency data at the city and county levels, combined with spatial econometric methods, to more finely reveal the regional heterogeneity and spatial spillover effects of digital economy impacts. Secondly, explore the construction of a multidimensional evaluation system that includes soft indicators such as social capital and organizational resilience to enhance the comprehensiveness of resilience measurement. Thirdly, regarding the evaluation methods of the indicator system, we will continue to explore, continually attempting to utilize more scientific methods or a combination of various evaluation methods, in the hope of building a more robust comprehensive evaluation system. Finally, focus on the reshaping effect of emerging technologies such as artificial intelligence and blockchain on the governance structure of the cotton industrial chain in the context of rapid iterations of digital technologies. Through continuous deepening of theoretical research and methodological innovation, this study will provide more precise decision-making references for promoting the robust development of China’s cotton industrial chain in the digital era.

5. Conclusions

- (1) There exists a significant nonlinear relationship between the digital economy and the resilience of the cotton industry chain. As the level of digital economy development increases, its promoting effect on the resilience of the cotton industry chain does not remain at a fixed intensity but rather exhibits characteristics of phased changes.
- (2) The mediating effects demonstrate that the technological innovation vitality and planting scale significantly positively influence the digital economy at the 1% level,

indicating that these factors are important mediating channels through which the digital economy affects the resilience of the cotton industrial chain.

- (3) There are spatial and temporal differences in the impact of the digital economy on the enhancement of the resilience of the cotton industrial chain. Spatially, the digital economy significantly positively influences the resilience of the cotton industrial chain in the Yangtze River Basin and Northwest Inland cotton regions but shows a negative impact on the resilience of the cotton industrial chain in the Yellow River Basin. Temporally, from 2013 to 2017, the rapid development of the digital economy concurrently propelled a continuous increase in the resilience of the cotton industrial chain; post 2017, the impact of the digital economy on enhancing the resilience of the cotton industrial chain exhibited a wave-like trend of decline followed by increase.

6. Implications

- (1) Build a regionally differentiated digital collaborative development mechanism.

Based on the regional characteristics revealed by empirical research, establish a precisely tailored differentiated policy framework: For the northwest inland cotton regions, focus on the low efficiency of industry chain collaboration caused by lagging digital infrastructure, set up a special fund for digital infrastructure in the cotton industry, and prioritize support for foundational projects such as 5G network coverage and the deployment of smart agricultural sensors to address the urgent digital needs in irrigation and pest monitoring. For the cotton regions in the Yangtze River Basin, leverage their first-mover advantages in the digital economy to encourage pilot projects for digital technology output, sharing mature resources such as digital planting management systems and market information platforms with the northwest and Yellow River Basin cotton regions to overcome technical barriers hindering the overall resilience of the industry chain. For the cotton regions in the Yellow River Basin, promote transitional support policies for digital transformation, focusing on subsidies for purchasing digital agricultural tools and training in basic data processing, thus connecting the resource advantages of the northwest with the technological advantages of the Yangtze River Basin to build a cross-regional digital collaborative network.

- (2) Establish regionally precise collaborative innovation centers for the industry chain.

Address the differences in digital technology gaps in key areas such as breeding, production, and processing by developing innovation carriers according to regional industrial demand variations: In the northwest inland cotton regions, rely on local research institutions to establish a digital agriculture innovation center for cotton in arid areas, focusing on digital control of water-saving irrigation, digital monitoring for salinity and alkalinity improvement, and tackling the insufficient integration of resilient variety breeding with digital planting technology as a primary direction. In the cotton regions of the Yangtze River Basin, collaborate with universities and leading enterprises to establish a smart processing and brand digital innovation center for cotton, focusing on breakthroughs in intelligent control of cotton spinning processing and digital product traceability technologies, aligning with the advanced industrial foundation of its downstream industry chain. Establish a regional adaptation and transformation mechanism for innovation outcomes, categorizing technical achievements from different centers based on regional adaptability, such as foundational digital technologies applicable to the northwest and advanced intelligent technologies suitable for the Yangtze River Basin, directly connecting to production area demands through a technology promotion specialist system to avoid disconnect between innovation and reality.

- (3) Implement differentiated incentive policies for large-scale planting and digital integration.

Develop incentive measures according to regional development foundations: For the northwest inland cotton regions, given their abundant land resources but relatively low level of digitalization, tie “large-scale planting subsidies” to “digital technology applications,” so that farmers or cooperatives achieving large-scale planting and adopting technologies such as digital irrigation and drone pest control can enjoy additional subsidies; meanwhile, leverage Xinjiang’s agricultural and rural department training system to provide free practical training in digital planting. For the cotton regions in the Yellow River Basin, emphasize support for the “cooperative + digital technology” model, encouraging farmers to form large-scale cooperatives through land equity as a means of generating interest from agricultural venture funds, and construct regional shared digital agricultural service stations to address the high cost of digital technology adoption for small farmers. For the cotton regions in the Yangtze River Basin, implement a digital certification system for large-scale planting, providing tax reductions or brand promotion funding support for large-scale bases that achieve increased yield and optimized quality through digital management, thus strengthening their market orientation towards quality and price while connecting with downstream digital processing links.

(4) Carry out targeted digital literacy enhancement and talent cultivation projects.

Based on the significant differences in digital literacy across different regions and groups, establish a layered and categorized cultivation system: For grassroots farmers in the northwest inland cotton regions, implement a digital agriculture practical skills dissemination program, utilizing Xinjiang’s “Visit, Benefit, and Gather” work mechanism to organize technical personnel to visit villages and households, providing bilingual instruction in Uyghur and Mandarin, focusing on training practical skills such as using smartphone agricultural apps and basic data viewing (e.g., soil moisture levels, market prices). For the heads of cooperatives and large growers in the Yellow River Basin cotton regions, offer advanced courses in digital management, focusing on production data statistics and analysis, and digital cost control, to address the insufficient digital management capabilities of mid-level practitioners. For the technical backbones across the entire industry chain in the Yangtze River Basin cotton regions, collaborate with universities to launch high-end talent cultivation projects in the digital economy of cotton, focusing on training professionals in data analysis, digital platform operations, and simultaneously establish a special fund for digital talent in Xinjiang’s cotton industry to encourage university graduates and technical talents to work in the northwest cotton production area, thus filling the gap for high-end digital talents.

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