frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 02 October 2024
DOI 10.3389/fsufs.2024.1439593

Check for updates

OPEN ACCESS

EDITED BY
Isabelle Piot-Lepetit,
INRAE Occitanie Montpellier, France

REVIEWED BY
Jingsuo LI,
Qingdao Agricultural University, China
Mamun Habib,
Independent University, Bangladesh

*CORRESPONDENCE
Huiming Jiang
huimingj@jlau.edu.cn

RECEIVED 28 May 2024
ACCEPTED 06 September 2024
PUBLISHED 02 October 2024

CITATION
Chang J, Jiang H, Liu J and Li M (2024) How the digital economy enhances the grain supply chain resilience in China: exploring the moderating effects of government innovation-driven.
Front. Sustain. Food Syst. 8:1439593.
doi: 10.3389/fsufs.2024.1439593

COPYRIGHT
© 2024 Chang, Jiang, Liu and Li. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

How the digital economy enhances the grain supply chain resilience in China: exploring the moderating effects of government innovation-driven

Jinrui Chang[1], Huiming Jiang[1]*, Jianbo Liu[1] and Mingyang Li[2]

[1]College of Economics and Management, Jilin Agricultural University, Changchun, China, [2]College of Economics and Management, Changchun University of Technology, Changchun, China

Introduction: Ensuring food security in the new development paradigm urgently requires increasing the grain supply chain resilience. In order to clarify how can significantly enhance grain supply chain resilience, to demonstrate the relationship between the digital economy, government innovation-driven and grain supply chain resilience is necessary. To specify how the government can effectively perform its macro-regulatory functions, the government innovation-driven is reflected by government innovation-driven planning and government innovation-driven investment, respectively.

Methods: The data of 31 provinces in China from 2011 to 2021 have been used. The panel fixed effects model, moderating effects model and threshold effects model have been selected to analyze.

Results: Digital economy has a stronger enhancement effect on grain supply chain resilience; Government innovation-driven has an increased moderating effect on digital economy enhance grain supply chain resilience; The enhancement effect of digital economy and the moderating effect of government innovation-driven are differentiated between China's functional zones of grain production; And the threshold effect of government innovation-driven planning shows a process of digestion and absorption, which accumulating to 0.018 will emerge a multiplier effect. Government innovation-driven investment is higher than 0.026, which can have a promoted moderating effect.

Discussion: To expand the depth of integration of the digital economy, accurately government innovation-driven, the focus should be on attracting innovative talent, who can construct the perpetual motion machine mode of "external promote + internal drive," so as to strengthen the robustness of the grain supply chain.

KEYWORDS

grain supply chain resilience, digital economy, government innovation-driven, moderating effects, threshold effects

1 Introduction

At this stage, guaranteeing sustainable food security is essential. Exogenous risks, which are triggered by frequent perturbations in uncertainty (Chang and Jiang, 2023) such as geopolitical conflicts, natural disasters, and the COVID-19 pandemic, coupled with endogenous risks such as lower grain price-response elasticity, led to a double whammy to the sustainability of the grain supply chain (GSC). China's No. 1 central document for 2024 emphasized "Improving the grain production and enhancing the grain regulation capability," reflecting how maintaining a sustainable grain supply is the foundation of food security under the international and domestic double cycle. The rural survey conducted in China indicates that during the COVID-19 pandemic, the grain market experienced significant price fluctuations. The average sales prices for wheat, rice, corn, and soybeans rose year-on-year in 2020 by 1.83, 9.40, 20.22, and 8.62%, respectively (Wei et al., 2022). The constraints of temporary supply in the grain market have led to a rush for rice and hoarding of flour in the market, which has triggered panic consumption among the population. The phenomenon indicates the vulnerabilities due to the low circulation efficiency and the loose connection between subjective functions within GSC. Under the new development paradigm featuring dual circulation, the domestic market as the mainstay in China is becoming more essential. In order to guarantee the high-quality output of the grain industry, strengthening GSC resilience has become the main grip (Sharifi et al., 2024).

With the development of the internet and internet-related industries, the digital economy (DE) has become an important driving force for sustainability (Ma et al., 2024; Wen and He, 2024). Generally, scholars agree that the DE represents a new technological change and a new impetus for development and that such change and impetus will inevitably upgrade traditional industries (Yang et al., 2023; Abban and Abebe, 2022). As a result, there is a need and possibility for DE to strengthen GSC resilience. Accompanied by the proliferation of digital technology in the agricultural and rural sectors, the mechanization, scaling, and integration of the grain industry empowered by science and technology have accelerated the fusion of new varieties, technologies, and modes. This has contributed to a sustainable cycle of the main functions of GSC. Meanwhile, the DE breaks through the spatial limitations to achieve low-cost and high-circulation of information and channel advantages, thereby eliminating the bullwhip effect of information and business risks. DE can also promote green development of the environment, such as pollutant emissions, energy consumption, and resource utilization (Gu et al., 2023). Facing the complex globalized development environment, it is essential to ensure China's food security by stabilizing domestic self-sufficiency and rationally utilizing international resources. There are fewer existing studies that focus on DE and GSC resilience. Thus, exploring the mechanisms to increase GSC resilience and the interventions to enhance DE incentives for GSC resilience will be beneficial for theoretical and practical relevance. Based on this, the novelties of this study are: (1) articulating and empirically demonstrating how the DE enhances the GSC resilience; (2) introducing government innovation-driven (GI) as the moderating variable and threshold variable, and selecting government innovation-driven planning and government innovation-driven investment as proxies, we explore the efficient path to promote the DE and GSC resilience; and (3) analyzing the heterogeneity of functional zones for grain production, which can precise the policy formulation and boost the GSC resilience toward sustainable food security.

The remaining sections are: Section 2 explains the theoretical analyses and research hypotheses; Section 3 illustrates variable definitions, model construction, and data description; Section 4 provides empirical results; and Section 5 discusses the research's findings and limitations. Section 6 summarizes the conclusion and recommendation.

2 Theoretical analyses and research hypotheses

2.1 Grain supply chain resilience

Currently, strengthening the supply chain in order to withstand possible "Black Swan" incidents is crucial, which coincides with the concept of system resilience. Resilience is defined as the preference of a system to maintain organization after a perturbation. Supply chain resilience is rooted in ecosystems, economics, and risk management research. Yang and Xu (2015) believe GSC resilience demonstrates its ability to robustly and rapidly respond to supply chain disruption resulting from natural disasters and apprehensions toward the upstream member on the profit of the downstream member under the different recovery levels. Identifying the key processes and factors in food supply chains is crucial to improving resilience within food systems (Davis et al., 2021). Based on the findings of other studies, this study defines GSC resilience as the ability to maintain and recover the continuous operation of the GSC subjective functions, such as grain production, unprocessed food grains storage, grain initial processing and precision processing, grain transportation and marketing of grain products following the impact of uncertainties.

To clarify how to optimize resilience scientifically, Tukamuhabwa et al. (2015) reviewed the existing literature and summarized that supply chain resilience can be assessed on four aspects, preparation for a disruptive event; response to an event; recovery from the event; and growth/competitive advantage after the event. Urruty et al. (2016) point out that increasing diversity and adaptive capacity of agricultural systems emerge as key drivers for increasing the ability of agricultural systems to cope with different types of perturbation. FAO (2021) proposes that preventive, anticipative, absorptive, adaptive, and transformative capacities are the key to food supply chain resilience. In order to visualize the evolution of the GSC after being hit by uncertainties, it should also be taken into account the characteristics of the GSC with multiple participants, cross-regions, and multi-links. Zhao et al. (2024) examine the effectiveness across the preparation, response, recovery, and adaption phases of agri-food supply chain resilience through an across-country comparative analysis of the COVID-19 pandemic. Therefore, the GSC's resilience must be assessed from the six dimensions. Prevention capability refers to the robustness of production factor configurations and core infrastructure, aiding in the reduction of pre-existing risks and the avoidance of emerging risks. Prediction capability means to identify and anticipate potential risks and possible shocks in advance, in a timely and accurate manner, through big data and environmental regulations. Absorption capability is a means of an emergency supply and rapid treatment to respond against shocks, absorbing the destructive force of external shocks in order to guarantee the GSC's functions are sustainable and stable. Recovery capability means the stable and sustained operation of the main functions of the GSC, responding efficiently and quickly to grain market changes through systematic industrialization, scale, mechanization, and intensification. The concept of learning capability pertains to the education and research-led driver of the subjects of GSC to self-learn and re-learn, which improves the endogenous dynamics of the system and strengthens the levels of the above-mentioned capacities.

Transformation capability means the application of innovative modes and channels to build high-quality systems, and the scientific adjustment of the GSC structure to avoid continuous disturbance and the danger of being caught in a vicious circle.

2.2 Digital economy and grain supply chain resilience

China's GSC is mainly dominated by traditional and transitional GSC (Song et al., 2019). The grain industry in China is commonly regarded as a production sector consisting mainly of smallholders, and its industrial pattern is dominated by small-sized and medium-sized grain enterprises. This makes it more challenging to improve the quality and efficiency of GSC. DE, with its synergistic, substitution, and penetration effects, has led to new economic forms of economic development and governance modes (Zhang et al., 2023; Bukht and Heeks, 2017). DE is a novel catalyst for improving GSC resilience. To be more specific, productivity with new quality would be formed by digitalizing the subjects of labor, means of labor, and labor forces (Ferguson et al., 2024). Furthermore, the infrastructure of information and telecommunication would see a breakthrough, which breaks the barrier of informational obstruction, improves productivity, matches the grain supply and demand sides, and increases the digital literacy of business subjects. It can effectively bridge the vulnerability of the GSC toward greater efficiency, resilience, inclusiveness, and sustainability (Mboup and Oyelaran-Oyeyinka, 2019).

The DE enhances the GSC resilience in three ways: data element, digital technology, and innovation mode (Miao, 2021). First, the data element has become an important strategic resource, which helps to enhance the prevention and prediction capacities of the GSC. Data elements can accurately simulate grain production space, plan grain chain operations, and alleviate pressure on scarce resources. Data elements, with their multiplication, combined with other elements have the potential to enhance efficiency. Promote the quality and sustainability of resources by using the "data + other elements" mode to build toughness against unforeseen events. Data can help achieve information sharing, avoid the potential "bullwhip effect" of the GSC, and provide effective communication and timely feedback data to improve the system to prevent and predict more scientifically. Second, digital technology has been embedded to enhance the absorption and recovery capacities of the GSC. Grain operations utilize the internet, 5G, artificial intelligence, digital platforms (Singh et al., 2023), and other digital technologies in order to strengthen the GSC's ability to maintain supply in emergencies. Digital technologies are used to replace traditional labor subjects and labor methods, such as seed preparation and precision sowing. Plant protection drones, autopilot systems, AGVs, and intelligent sorting equipment are used to prevent intermittent operations under harmful to health and extreme environments. These technologies strengthen the flexibility of the system when responding to disturbing shocks through mechanization, planning and intelligent production, storage, processing, and consumption. Digital technology has created eco-friendly operations, emphasizing fine production, fine storage and fine processing to promote grain saving and loss reduction. Digital inclusion services assist agricultural enterprises, farmers' professional cooperatives, and smallholders to transform agricultural procurement, production, sales, and other links, which reduces the risk of chain breaks in the GSC. Third, innovation modes have been injected to enhance the learning and transformative capacities of the GSC. The continuous development of scientific and technological research and development (R&D) activities updates the digital equipment, digital products, and digital platforms to enhance the sustainability of GSC. The innovative ideas are applied to all areas of core seed sources for grain cultivation, high-quality fertilizers, arable land quality, water, and energy conservation, as the key driving force for food security and sustainable development of agri-food systems. Growing online channels, such as online stores, big data marketing, and selling goods through livestreaming, drive the digital transformation of smallholders and food processing enterprises. The innovative approach to thinking would inspire the subjects in the grain business. With the help of the ecology of innovation, the digital literacy of subjects would be improved. Smallholders and grain enterprises would practice digital management and participate in e-commerce with a deeper digital awareness and adoption of applications. Hence, the hypothesis is proposed.

> *H1:* DE has positive incentives for GSC resilience.

2.3 Digital economy, government innovation-driven, and grain supply chain resilience

The government, as a synergistic support sector for the stable development of GSC (Ma et al., 2023), plays significant leadership in strengthening and increasing the efficiency of GSC. General Secretary Xi Jinping proposes that "Relying on technology and reform to accelerate the construction of the agricultural powerhouse, we must be prepared to put in efforts, increase investment, and provide long-term and stable support." It has been shown that governments with a strong preference for innovation have led to high-quality industrial development and have had a profound impact on regional innovation activities (Liu and Pan, 2022; Li et al., 2022). The government innovation-driven influences innovation activity through fiscal spending and policy planning. This is an important means of compensating for the externalities of innovation and the shortcomings of capital markets. These findings fully reveal the important role of government macro-measures for the optimization of the DE and GSC resilience. However, it is not clear how government innovation-driven (GI) strengthens the DE's enhancement effect on GSC resilience.

For a long time, all the levels of government in China have implemented catch-up strategies and financial support policies aimed at encouraging technological innovation (Lu and Wang, 2021). Local government spontaneously participates in innovation activities, through the direct strategies of innovation-related policy planning and the financial expenditures on science and technology to support technological progress and R&D. These activities are aimed at breaking through the core technology barriers and preventing the development bottlenecks of enterprises' lack of capital and the mismatch between technology and its practical application. Above all, GI has stabilized the innovation macro-environment of DE-enabled GSC resilience through innovation-driven planning and investment. The government's macro-innovation support has provided a basic guarantee for scientific and technological R&D to overcome the core seed source, the quality and configuration of grain production resource elements, and digitized equipment. Furthermore, the GI strengthens the efficiency of the DE's pathway to GSC resilience through innovative investments in science and technology. The DE has demonstrated the attributes of public goods in the process of re-configuring GSC through data, technology, and innovation. The GI helps to ensure an effective supply of public goods, reduces the financial pressure on in-house research and development, and encourages enterprises to expand their production and operations. Finally, the strategies of GI in regional differentiation for assistance, which solve the existing weakness during DE, empower GSC's resilience. With the help of operational subsidies, investment promotion, talent introduction, and other innovative initiatives, we can drive the digital transformation of farmers' cultivation and grain enterprises' acquisition, production, processing, and marketing. This will assist the regional DE and GSC resilience synergistic development.

It is worth emphasizing that, in the process of optimizing the GSC resilience, the impact of GI on the DE is not static, especially in the dual-track system of government and market resource allocation in China. During the different conditions and stages, the positive and negative impacts generated by the GI exist in a dynamic game (Shi et al., 2024). Considering the potential "trap effect" and negative impact of GI on the DE, it is important to clarify the best moderating effect of government. The "invisible hand" and the "visible hand" should be utilized to form a pattern by innovation-driven in which the government and the market complement and promote each other, so as to provide lasting impetus for food security and the sustainable development of agri-food system in line with current China's national conditions and grain situation. Therefore, the other hypothesis is proposed.

> *H2:* GI has a positive moderating effect on DE to strengthen GSC resilience, and there is a threshold effect of GI.

Through these analyses, we have found that the conceptual framework reflects the logic between the DE, GI, and GSC resilience, which is mapped in Figure 1. Furthermore, it is also used to clarify the subsequent empirical analyses.

3 Research designs

3.1 Variable definitions

3.1.1 Explained variable

GSC resilience: For a more scientific evaluation, the GSC is decomposed into five distinct segments, namely grain production, unprocessed food grains storage, grain initial processing and precision processing, grain transportation, and marketing of grain products. GSC resilience is to be assessed through the following six dimensions. The prevention capability focuses on the stability of the core functions of the grain supply chain; the prediction capability focuses on the functionality of effectively ensuring market-based supply; the absorption capability focuses on the regional grain supply chain to maintain emergency grain supply; the recovery capability focuses on the efficiency of production and the degree of mechanization; and the learning capability focuses on the technology research and development, and the education of the main participants, and transformation capability focuses on the development of regional e-commerce. Based on the characteristics of China's grain situation, we have built an evaluation system of GSC resilience. We employ the entropy method to measure the indicators' weights, which is shown in Table 1.

In order to clearly reflect the index of the provincial GSC resilience, the measurements from 2011 to 2021 are selected, and the 31 provinces are grouped into three levels by using the natural breaks of Arcgis10.8, as shown in Figure 2.

According to the above figure, it can be seen that the development of GSC resilience in space presents a clear "clustering" phenomenon, and this clustering is gradually shifted to the provinces with higher indexes of GSC resilience, which is now evolving into "Shandong-Henan" as the center. In 2011, the average of the GSC resilience index was 0.1623, and in 2021 it was 0.2695. There is still much room for further development of GSC resilience. At present, it is necessary to seek effective means to accelerate the development of GSC resilience, in particular, to break through the spatial limitations of regional natural resources and environment, and to build a synergistic mode of complementary advantages between provinces.

3.1.2 Core explanatory variable

Digital economy: The entropy method is applied to calculate the provincial DE index and evaluate it in terms of both internet development and digital financial inclusion (Zhao et al., 2020). Four internet development measurement indicators are used: internet availability rate, number of internet-related employees, internet-related outputs, and mobile phone penetration rate. For digital financial development, the China Digital Inclusive Finance Index is used. DE evaluation framework is shown in Table 2.

Similarly, we measure the DE index by the entropy method, and in order to demonstrate the spatial characteristics of DE over the study period, the provincial DE index in 2011 and 2021 are selected as representatives, and the 31 provinces are divided into three levels in the same way, which are shown in Figure 3.

The comparative analysis shows that DE has a diffusion effect, gradually penetrating into inland areas from the coastal areas. The higher and medium indexes of the provincial digital economy are mainly in the eastern and central regions, while the DE index of provinces in the northeastern region and western region are almost stagnant. Moreover, the DE has an affinity propagation, and it has been found that the neighboring provinces with higher DE indexes have faster growth rates in their DE indexes. Combined with Figure 2, we notice that both the development of the DE and the GSC resilience have a spatial polarization, and the spatial mismatch of resources between stronger areas in the development of the DE and those stronger areas in the GSC resilience, which highlights that the DE continues to increase the GSC resilience also requires external assistance.

3.1.3 Moderating variable

Government innovation-driven: Many existing studies only use grant-in-aid to measure GI, which makes it difficult to measure the overall GI. This study adopts the percentage of innovation-related words in the provincial government study report and the percentage

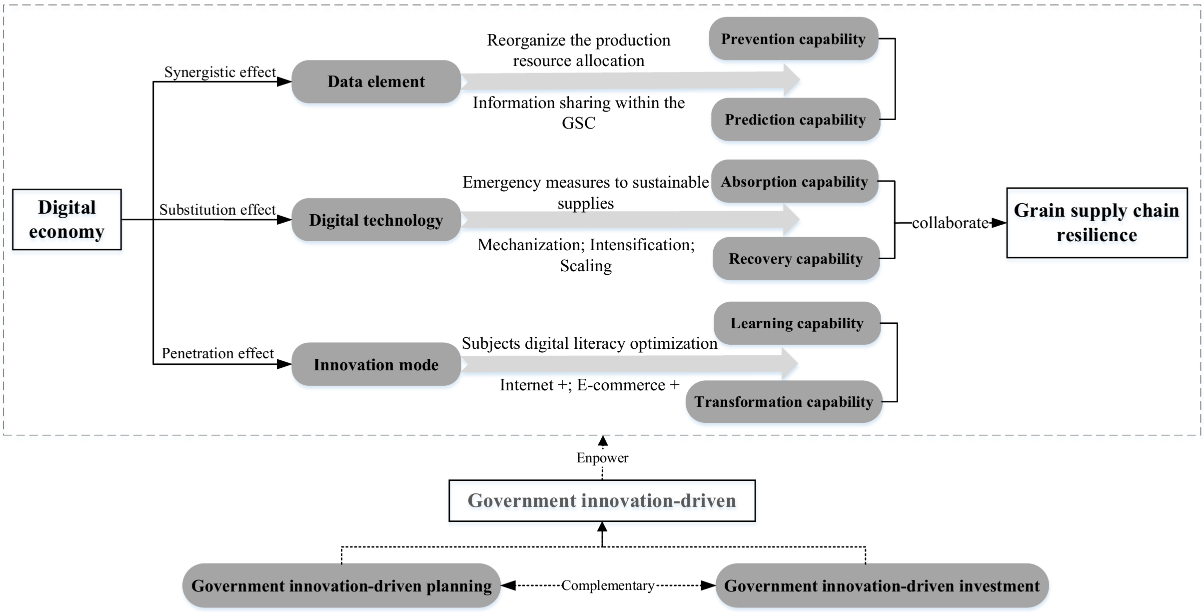

FIGURE 1
Conceptual framework.

of provincial expenditures on science and technology as the proxy variables for GI. We also introduce them in the full-text regression model to strengthen the rigor of the empirical study, respectively. For ease of exposition, the percentage of innovation-related words in the provincial government study report is defined as government innovation-driven planning (GIP), and the percentage of provincial expenditures on science and technology is defined as government innovation-driven investment (GII). Drawing on scholars' approaches (Chen et al., 2018), by text preprocessing techniques, such as stopword removal and partitioning, for the provincial government study report in China using Python, we calculated the number of innovation-related words, the total words in the provincial government study report, and the ratio of the number of innovation-related words to the total words in the provincial government study report. The innovation-related vocabulary comprises 13 words, including innovation (*chuangxin*), patent (*zhuanli*), R&D (*yanfa*), scientific research (*keyan*), science and technology (*keji*), science (*kexue*), new technology (*xinjishu*), key technology (*guanjianshishu*), industry-university-research (*chanxueyan*), trademark (*shangbiao*), intellectual property (*zhishichanquan*), creativity (*chuangyi*), and talents (*rencai*). We then calculate the one proxy for GI for province *i* in year *t* as:

$$GIP_{it} = \frac{\text{related words in province } i \text{ year } t'\text{sgovernment work report}}{\text{total words in province } i \text{ year } t'\text{s government work report}}$$

Meanwhile, learning from Li and Yang (2018) way, GII is reflected in the ratio of science and technology expenditures in government expenditures to local government expenditures, and we compute the other proxy for GI for province *i* in year *t* as:

$$GII_{it} = \frac{\begin{array}{c}\text{science and technology expenditures in}\\ \text{province } i \text{ year } t'\text{s government expenditures}\end{array}}{\text{province } i \text{ year } t'\text{s total government expenditures}}$$

In addition, combining the above explanation, GI must be effective and appropriate. We take GIP and GII as threshold variables to reflect the optimal moderating effect of government innovation-driven.

3.1.4 Control variables

In this study, control variables are selected from the urbanization process, consumption level, resource allocation, industrial development, and openness to fully reflect the utility of the digital economy on the grain supply chain resilience, thereby improving the rigor of the empirical results. These include (1) Urbanization level (Urb), which is the ratio of total urban population to total provincial population; (2) Household consumption level (Hc), which is the ratio of residential food expenditure to total consumption expenditures; (3) Innovative human capital (Ihc), the innovative human capital is mainly divided into the innovative human capital of education type and innovative human capital of investment type, which is measured by multiplying the number of university graduates, the number of graduated graduate students and the number of professional and technical personnel with the average annual monetary wage of employees in other units, the investment type is measured by R&D expenditures (Huang et al., 2009); (4) Grain output level (Go), a larger value of grain industry represents a better production efficiency, which is expressed as the total value of the regional grain industry; and (5) Openness (Open), which is expressed as the foreign direct investment amount.

TABLE 1 Evaluation system of grain supply chain resilience.

First-level indicator	Second-level indicator	Indicator interpretation	Property	Weight
prevention	Replanting index	The ratio of the total area sown (or transplanted) with grain to the total cultivated land area	+	0.0193
	The growth rate of grain purchases	Year-on-year growth rate of grain purchases by state-owned enterprises	+	0.0139
	Grain import and export dependence	Grain trade volume/total grain sales	–	0.0010
	Intensity of roads in the area	The density of roads in the district and the area of the district ratio	+	0.0379
	Productivity of major agricultural products of grain processing enterprises	Average productivity of major agricultural products by grain processing enterprises	+	0.0746
prediction	Grain output in per unit area	Grain production per hectare	+	0.0145
	Disaster-affected area	The ratio of the grain-affected area to the cultivated area	–	0.0068
	Price monitoring networks	Macro-controlled grain price monitoring networks at all levels	+	0.0801
	Grain commodity rate	Grain marketization index	+	0.0897
absorption	Total emergency supplies	Emergency supplies at all levels to ensure grain market sustainable supply	+	0.0476
	Total logistic enterprises	Total emergency storage enterprises and distribution center enterprises	+	0.0779
	Total emergency processing enterprises	Total emergency processing grain enterprises at all levels	+	0.0657
recovery	Grain labor productivity ratio	The ratio of total grain production to rural workforce × a	+	0.0590
	Grain cultivation mechanization level	Total power of agricultural machinery per year × b	+	0.0752
	Processing capacity of the grain processing industry per year	Year-on-year growth rate of total annual processing volume of grain processing enterprises	+	0.0795
learning	Agricultural plant variety authorization	Number of new agricultural varieties developed and authorized each year	+	0.1037
	Education level of farmers	Average years of education of farmers	+	0.0054
	Cumulative rate of employees acquiring national licenses in the grain industry	The ratio of the cumulative number of people who have obtained national Licenses to the total employees in the grain industry	+	0.0397
transformation	Enterprise e-commerce coverage	The ratio of the number of enterprises with e-commerce trading activities to the total number of enterprises	+	0.0412
	E-commerce development index	E-commerce transactions as a share of GDP	+	0.0672

a, grain (unprocessed food grains) output value/agricultural output value; b, grain sown area/crop sown area.

3.2 Model construction

Based on Hypothesis 1, characterizing the driving effect of DE on GSC resilience, the benchmark regression model is constructed as follows:

$$GSCR_{it} = \beta_0 + \beta_1 DE_{it} + \alpha \sum X_{it} + \sigma_i + \mu_t + \varepsilon_{it}$$

Where $GSCR_{it}$ represents the GSC resilience index of province i in year t; DE_{it} represents the DE index of province i in year t; X_{it} represents the urbanization level, household consumption level, innovative human capital, grain output level, openness; σ_i is the province fixed; μ_t is the time fixed; ε_{it} is the random disturbance term; β_0 is the constant term; β_1, β_2, and α are the corresponding variable coefficients.

In view of Hypothesis 2, introducing an interactive item of DE and GI, and the moderating model is as follows:

$$GSCR_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 GI_{it} + \beta_3 \left(DE_{it} - \overline{DE_{it}}\right) \times \left(GI_{it} - \overline{GI_{it}}\right) + \alpha \sum X_{it} + \sigma_i + \mu_t + \varepsilon_{it}$$

Where GI_{it} represents the government innovation-driven of province i in year t; β_2 is the coefficient of government innovation-driven; β_3 is the coefficient of interaction term of DE_{it} and GI_{it}.

To further test whether the GI has a nonlinear moderating effect, which gains in strength of GI influences how DE enhances GSC resilience, according to Hansen's method (Hansen, 2000), we construct a panel threshold model as follows:

$$GSCR_{it} = \beta_0 + \beta_1 DE_{it} \times I\left(GI_{it} > \theta\right) + \beta_2 DE_{it} \times I\left(GI_{it} > \theta\right) + \alpha \sum X_{it} + \sigma_i + \mu_t + \varepsilon_{it}$$

DE_{it} is the core explanatory variable affected by the threshold variable; GI_{it} is the threshold variable; θ is threshold values; $I()$ is the indicative function, when satisfying the condition takes the value of 1, and the opposite is 0.

3.3 Data description

Due to data acquisition limitations, the sample size of this research contains only 31 provinces (including autonomous

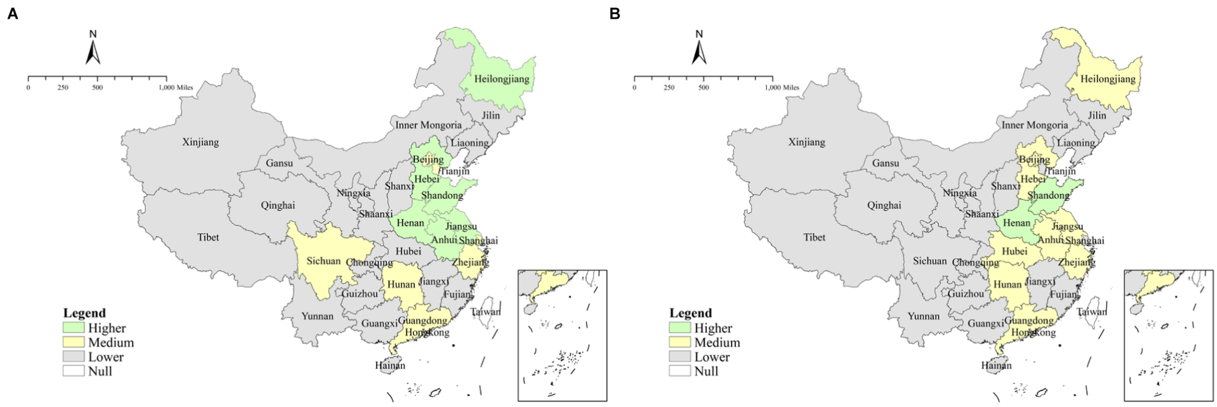

FIGURE 2
China's grain supply chain resilience index in 2011 and 2021.

TABLE 2 Evaluation system of the digital economy.

First-level indicator	Second-level indicator	Indicator interpretation	Property	Weight
Digital economy	Internet availability rate	Internet users per 100 people	+	0.2201
	Number of internet-related employees	Ratio of employees in the information transmission and software, information services industry	+	0.1901
	Internet-related outputs	Total telecommunication services *per capita*	+	0.4040
	Mobile phone penetration rate	Number of mobile phone subscribers per 100 people	+	0.0909
	The development of digital financial inclusion	Provincial Digital Inclusive Finance Index	+	0.0949

regions and municipalities) in China from 2011 to 2021, excluding data from Hong Kong, Macao, and Taiwan. In particular, the provincial government study report was obtained from the official website of each province from 2011 to 2021. Data for other indicators are derived from the China Grain Yearbook (renamed Yearbook on Food and Strategic Reserves in China in 2019), China Rural Statistical Yearbook, China Statistical Yearbook on Science and Technology, China Population & Employment Statistical Yearbook, China Statistical Yearbook, Institute of Digital Finance Peking University, and Bric Big Data. To enhance the accuracy of data, we select the interpolation method to supplement the vacant data and take the logarithm of the variables for dimensional normalization. Descriptive statistics are presented in Table 3.

4 Empirical results

4.1 Data test and model selection

To avoid spurious regression, stability tests, multicollinearity tests, and correlation tests are performed before the benchmark regression. These are shown in Appendix Table A1. Due to the panel data, we select the Levin-Lin-Chu test because the p-values of the original sequences for all variables are significant at the 1% level, which passes the panel unit root test and can be considered stable. The maximum VIF is 6.65 and the mean value is 2.96. The VIF value of variables is much less than 10, and the multicollinearity between variables is negligible. Pearson correlation coefficient shows that the core variables are all significant at the 1% level, which is a preliminary indication of the correctness of variables selection for the study.

4.2 Static model analysis

Based on the Hausman test, the fixed effects model for benchmark regression is more proper. The results are shown in Table 4, where columns (1) to (2) are the regression results of the mixed OLS model, columns (3) to (4) are the regression results of the two-way fixed effects model, and columns (5) to (6) are the regression results of random effects model. All the estimated coefficients of the DE are positive, and the DE passes the significance test, which indicates that the DE has a strong strength in GSC resilience. Hypothesis 1 is verified. Moreover, by comparing the models' results, we observe that the two-way fixed effects model displayed better enhancement effects.

It is worth mentioning that after the introduction of the control variables, the estimated coefficients of DE are reduced from 0.290 to 0.092, 0.236 to 0.233, and 0.209 to 0.060, which indicates that the control variables are valid. Among these, urbanization level and household consumption level do not pass the significance test, reflecting GSC resilience compared to the pace of economic development is a little slow in the current stage. The grain supply side is insufficient for the

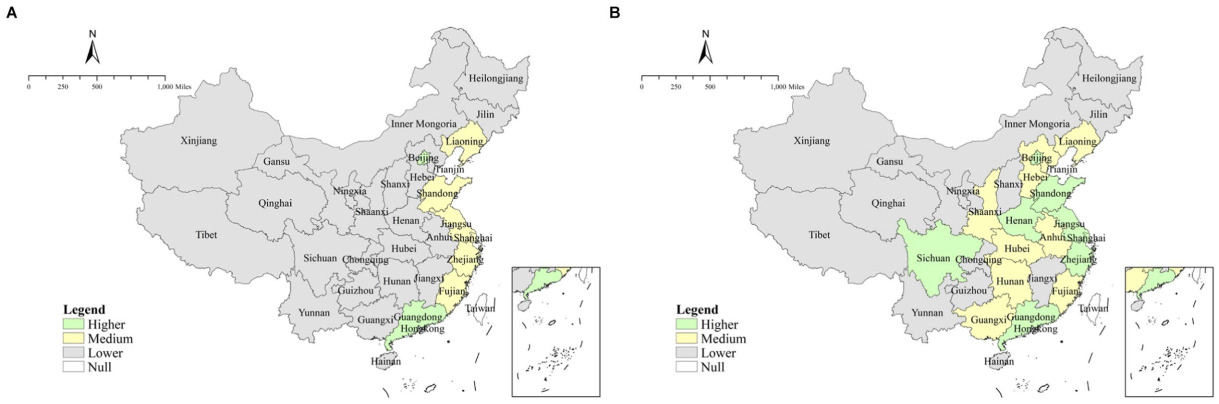

FIGURE 3
China's digital economy index in 2011 and 2021.

TABLE 3 Descriptive statistics of variables.

Variables		Sample size	Mean	Standard deviation	Minimum	Maximum
GSCR		341	0.229	0.097	0.055	0.566
DE		341	0.242	0.152	0.034	0.821
GI	GIP	341	0.013	0.004	0.006	0.026
	GII	341	0.021	0.015	0.003	0.068
Urb		341	0.588	0.131	0.228	0.943
Hc		341	0.307	0.054	0.181	0.502
Ihc		341	6.028	1.307	1.872	8.602
Go		341	5.730	1.285	1.887	7.875
Open		341	1.531	2.991	0.005	31.236

increasingly diverse grain needs, and the reason GSC develops slowly is revealed. Innovative human capital to the GSC resilience perform the inhibition effect, because of the uneven distribution of innovative human resources in the country's grain industry among the provinces during the study period, and the grain industry to absorb the number of innovative human capital is seriously insufficient, GSC cannot activate the transformation of the grain industry with the help of talent, resulting in its development is stuck in a bottleneck. The food output level negatively affects GSC resilience, revealing that there is still an imbalance in the distribution of benefits between the grain production and marketing areas. This is seriously hindering the coordinated development of GSC resilience between the regions. There is an urgent need to increase the return on production of the grain production advantage areas and ensure sustained grain supply-side efficiency. The openness level has an incentive effect on GSC resilience, indicating that China has achieved the basic self-sufficiency of grain, and has the capacity to maintain stability in fluctuations of domestic and international grain supply and demand markets.

4.3 Moderating effect

Introducing GI as a moderating variable and selecting a two-way fixed effects model for analysis. Columns (1) and (2) utilize GIP as a proxy variable for GI. Column (1) is the regression result of GSC resilience, DE, and GI while column (2) is the regression result of adding the interaction term of DE and GI drive on this basis. Columns (3) and (4) use GII as a proxy variable for GI, and select the same way to regress. Results are shown in Table 5.

From columns (1) and (3) of the above table, it is found that the coefficients of DE and GI are positive, which makes it clear that DE and GI both have incentive effects on GSC resilience. The regression results indicate that the transformation and upgrade of regional GSC must rely on the depth of digitalization driven and the government's stronger support for the planning and investment. In particular, in comparison to Tables 4, 5, we find that after introducing GIP, the DE's coefficient increased from 0.233 to 0.248, which reveals the importance of an innovative development environment to DE to strengthen the empowering effect on GSC resilience. However, after the introduction of GII, the DE's coefficient decreased to 0.175, and the GII coefficient was 1.814. This indicates that China's current grain industry development is more dependent on government financial support for agriculture. Combined with the estimation results presented in columns (2) and (4), the coefficients of DE and GI are positive, and have passed the significance test. In addition, the interaction term between DE and GI is significant. The results strongly indicate that GI has a distinct moderating effect on promoting DE to enhance GSC resilience. The empirical results indicate that the interaction between

DE and GI has an obvious multiplier impact on GSC resilience, and in the uncertainty-prone macro-environment, and that provincial governments urgently need to deepen the regional innovation development planning and increase innovation subsidies for DE to encourage GSC resilience, and jointly give an impetus to the high-quality development of GSC.

4.4 Heterogeneity analysis

The heterogeneity analysis is oriented toward functional zones of grain production in China and divides them into the major grain-producing (MGP) areas, the major grain-consuming (MGC) areas, and the grain production-and-consuming-balancing (GPCB) areas. This can demonstrate regional differences in the enhancement effect of DE on GSC resilience and the moderating effect of GI on DE empowers GSC resilience. The analysis results are summarized in Table 6. Columns (2), (5), and (8) use GIP as a proxy variable for GI, and columns (3), (6), and (9) use GII as a proxy variable for GI.

(1) Heterogeneity analysis in the enhancement effect of DE. Columns (1), (4), and (7) conclude that: the incentive effect of DE on GSC resilience presents that MGC areas > MGP areas > GPCB areas. In particular, the regression result shows that the estimated coefficients of DE in GPCB areas are insignificant, fully demonstrating that the basic environment of DE in intra-regional provinces is weak, and the process of digitization of the grain industry is delayed. Immediately optimizing the high-quality GSC resilience in the GPCB areas will rapidly improve China's overall level. The MGP areas should step up the depth and breadth of construction in DE, and add long-term momentum to GSC resilience through digitalization. Taking into account that the DE has a diffusion effect, relying on the advantages of the DE in the MGC areas, it has become an effective path to carry out strategic cooperation with the MGP areas and GPCB areas in order to realize win-win cooperation.

(2) Heterogeneity analysis in the moderating effect of GI. Columns (2) and (3) indicate that the GI in the MGP areas has an increased moderating effect on DE strengthening GSC resilience, which reflects that the sustainability and high quality of the grain industry within the MGP areas closely rely on government support. Thus, the MGP areas should dynamically balance GIP and GII to synergistically help optimize the GSC resilience. While in MGC areas, the GI has not played a moderating effect, because the rapid development of DE has gradually demonstrated a "crowding effect" in the agglomeration of production factors such as capital, information, and technology. The continuous investment of GI has produced a "crowding out effect" on the innovation activities of grain enterprises, coupled with the relative inadequacy of natural resources in the grain industry, so DE and GI have been unable to form a synergistic force to strengthen GSC resilience. In the GPCB areas, the regression result for column (8) indicates that GIP exhibits a significantly stronger moderating effect, while the regression results for column (9) indicate that the GII does not have a moderating effect. We propose that in the relatively backward region of DE development, it is very necessary to enlarge the macro-government regulation and assistance. The first step is for the government to increase focus on innovation and improve the regional digital foundation, followed by the government to increase financial investment in technical R&D projects. During the study period, the government science and technology expenditures were relatively insufficient in GPCB areas, and the inability of DE to reconfigure GSC has resulted in the development of GSC resilience.

Especially, the commonality in the three regions is that the contribution of DE to GSC resilience is significantly strengthened by introducing GIP as the moderating variable. Comparison of columns (1) and (2), (4) and (5), and (7) and (8) in Table 6, shows that the regression coefficient for DE in the MGP areas increases from 0.074 to 0.090 and the regression coefficient for DE in the MGC areas increases from 0.404 to 0.472. The regression coefficient for DE in the GPCB areas changes from non-significant to 0.112. The moderating results of our studies highlight that the provincial government's planning and support for innovation development have a direct impact and force on the effectiveness of DE empowerment.

4.5 Threshold effect

The threshold effect is intended to further identify a potential nonlinear moderating effect of GI. Both GIP and GII are introduced into the threshold model as threshold variables respectively, and Bootstrap is used to recognize the quantity of GI's threshold. The results of threshold tests and the results of threshold models are shown in Tables 7, 8.

(1) GIP has a significant double-threshold effect. When GIP is less than 0.010, the DE's estimated coefficient is −0.009 and insignificant; when GIP is between 0.010 and 0.018, the DE is 0.067 and is significant at the 1% level; and when GIP is greater than 0.018, the DE is 0.130 and passes the significance test. These regression results reflect that the "enhancement mode" moderating effect can be generated only when GIP crosses the first threshold value and that the moderating effect is further strengthened when GIP crosses the second threshold value. The increased moderating effect of GIP shows a process of digestion and absorption, and the moderating effect of GIP to DE promotes GSC resilience only becomes apparent after reaching the first threshold value, which will be further enhanced with the accumulation of GIP.

(2) GII has a significant single-threshold effect. When GII is less than 0.026, the DE's estimated coefficient is −0.004 and insignificant; however, GII is higher than 0.026, and DE is 0.106 and passes the significance test. According to test results, we found that only when GII crosses the single-threshold value has an enhanced moderating effect, effectively helping DE to strengthen GSC resilience. We conclude that as the ratio of science and technology expenditures in government expenditures increases, the stronger the GII driving effect becomes, and the moderating effect is also evident.

Thus, based on the above analysis, Hypothesis 2 is verified.

4.6 Robustness tests

(1) Considering that the GSC resilience index is between 0 and 1, which qualifies as a limit-dependent variable model, we use the Tobit model to re-estimate according to formula 4 and consider the control variables, with fixed province and year. The results are presented in columns (1) to (2) of Table 9. (2) Beijing, Tianjin, Shanghai, and Chongqing are excluded to avoid regression errors due to regional policy, economic, and other advantages. The results are shown in columns (3) to

TABLE 4 The benchmark regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
DE	0.290***	0.092***	0.236***	0.233***	0.209***	0.060***
	(0.030)	(0.026)	(0.054)	(0.058)	(0.013)	(0.017)
Urb		−0.067		0.107		0.025
		(0.045)		(0.106)		(0.071)
Hc		−0.101*		0.0103		−0.005
		(0.059)		(0.075)		(0.041)
Ihc		0.047***		−0.027*		0.057***
		(0.005)		(0.014)		(0.009)
Go		0.017***		−0.028***		0.003
		(0.004)		(0.010)		(0.007)
Open		0.002*		0.002**		0.002**
		(0.001)		(0.001)		(0.001)
Constant	0.158***	−0.105***	0.142***	0.382***	0.178***	−0.165***
	(0.008)	(0.037)	(0.006)	(0.088)	(0.0146)	(0.048)
Province			Yes	Yes		
Year			Yes	Yes		
Hausman test				16.04**		
Sample size	341	341	341	341	341	341
R^2	0.208	0.660	0.706	0.722		

Standard errors in parentheses, * presents $p < 0.1$, ** presents $p < 0.05$, *** presents $p < 0.01$.
The following tables are the same as this.

(4) of Table 9. Furthermore, columns (1) and (3) use GIP as a proxy variable for GI, while columns (2) and (4) use GII as a proxy variable for GI. All of the results confirm that DE, GI, and the interaction term between DE and GI are positive. The conclusion that “GI has a positive moderating effect on the DE to improve the GSC resilience” is more reliable.

4.7 Endogeneity tests

Columns (5) and (7) use GIP as a proxy variable for GI, while columns (6) and (8) use GII as a proxy variable for GI in Table 9. Given that the potential reverse causality between the DE, GI, and GSC resilience may lead to regression errors, we selected two methods for endogeneity tests. (1) In columns (5) and (6), we use the first-order lag terms of DE (L. DE) and GI (L. GI) as instrumental variables and analyze them based on the 2SLS model. The result of Kleibergen-Paap rk LM refuses the original hypothesis indicating that the instrumental variables are under-identified. The result of Cragg-Donald Wald F similarly rejects the original hypothesis, showing that the instrumental variables are weakly instrumental. Thus, instrumental variables are effective. (2) As columns (7) and (8), introduce first-order lag terms of GSC resilience (L. GSCR) in the benchmark model to construct a dynamic panel model, we choose the SYS-GMM model. The estimation results indicate that the *p*-value of Hansen's test is 1.000, which cannot reject the original hypothesis that the instrumental variables do not suffer from the over-identification problem. Additionally, the p-value of AR (1) is less than 0.1, while the p-value of AR (2) is greater than 0.1. There is only the first-order serial correlation but not the second-order serial correlation, which conveys that the SYS-GMM model better overcomes the problem of endogeneity of the explanatory variable, and the regression results are valid. All endogeneity tests substantiate our findings.

TABLE 5 Moderating model regression results.

Variables	(1)	(2)	(3)	(4)
DE	0.248***	0.220***	0.175***	0.108*
	(0.057)	(0.056)	(0.056)	(0.062)
GI	1.330**	0.981*	1.814***	1.488***
	(0.562)	(0.548)	(0.323)	(0.346)
DE × GI		12.05***		1.872**
		(2.559)		(0.750)
Control variables	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Sample size	341	341	341	341
R^2	0.727	0.746	0.749	0.754

5 Conclusion and recommendation

5.1 Conclusion

In this research, the hypotheses and regression results in this research are self-consistent with constructing an empirical analysis of

TABLE 6 Heterogeneity analysis results.

Variables	MGP areas			MGC areas			GPCB areas		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
DE	0.074**	0.090***	0.059*	0.404***	0.472***	0.292*	0.098	0.112*	0.056
	(0.032)	(0.033)	(0.033)	(0.100)	(0.133)	(0.147)	(0.064)	(0.059)	(0.062)
GI		0.025	1.377*		3.112**	0.584		0.898*	−0.078
		(1.004)	(0.733)		(1.256)	(0.491)		(0.492)	(0.503)
DE × GI		9.899*	3.837**		5.825	1.016		6.112**	2.002
		(5.623)	(1.681)		(5.585)	(1.555)		(2.833)	(1.830)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	143	143	143	77	77	77	121	121	121
R^2	0.790	0.796	0.810	0.890	0.808	0.895	0.833	0.832	0.817

TABLE 7 Threshold tests.

Threshold variables	Type	Threshold	F-stat	P-value	Confidence interval	BS times
GIP	Single-threshold	0.010	22.21	0.004	[0.009,0.010]	500
	Double-threshold	0.018	12.58	0.072	[0.017,0.018]	500
GII	Single-threshold	0.026	39.17	0.006	[0.024,0.026]	500

DE, GI, and GSC resilience from a macro perspective. (1) The DE has contributed significantly to the GSC's resilience. The DE makes up for the shortcomings of GSC with its synergistic, substitution, and penetration, which help to fundamentally reduce the risk of chain breaks in the system. Driving the integrated development of the grain supply chain's core functions through digitalization has become an effective means to improve the GSC's resilience at the current stage. (2) GI has an "enhancement mode" moderating effect, which can not only effectively promote the enhancement effect of DE on GSC resilience but also present a synergistic DE that presents a multiplier effect on the optimization of GSC resilience. Besides, when compared to GII, GIP has a stronger moderating effect, indicating that local governments should pay much attention to such as innovation planning policy, technical R&D, and adequate financial investment. These factors are crucial for the stronger empowerment of DE incentives for GSC resilience. Moreover, GI exhibits threshold effects, wherein, GIP exhibits a significant double-threshold effect, and GII exhibits a significant single-threshold effect. The best threshold of government function is defined, which provides a better reference for policymaking. (3) The heterogeneity analysis of this study is based on functional zones for grain production in China. The enhancement effect of DE on GSC resilience indicates that MGC areas > MGP areas > GPCB areas. The moderating effect of GI presents that MGP areas > GPCB areas > MGC areas. At this stage, there is an urgent need to overcome the obstacle of regional polarization of GSC resilience and to improve the coordination of functional zones for grain production and GSC resilience in China.

5.2 Recommendation

Referring to the above findings from this study, we put forward the following recommendations for practice: (1) Extend DE to empower the depth of GSC and make up for shortcomings with system resilience. At present, the DE embedded in GSC in the majority of the provinces is still mainly replaced by informatization and mechanization technology. Under the international and domestic double cycle, in particular, digitalization drives the prediction, absorption, and recovery capabilities of GSC, and fundamentally consolidates the GSC resilience to ensure food safety, health, and high quality. (2) The government's flexible, innovation-driven strategy accurately helps regions promote coordination. Through government assistance, we can fundamentally solve the spatial mismatch between DE and GSC resilience, and optimize the basic allocation of DE to enhance GSC resilience. The government should attach great importance to the planning of regional innovation and development and should promote the digitalization process of the grain industry in MGP areas. The government realizes complementary advantages between regions through the service and assistance mode of the MGC areas driving the MGP areas and GPCB areas. It is imperative to dynamically adjust the government investment in science and technology to help the differentiated construction demands of the regional DE and realize the effective moderating effect of the DE to enhance GSC resilience in a planned, purposeful, and methodological manner. (3) Strengthen the absorption of innovative talents to help add impetus to the grain industry. Let innovative talents lead the upgrading of the grain industry in an all-round, multi-angle, and wide-ranging, they also lead smallholders and grain enterprises to implement new policies, new modes, new channels, and new technologies, which enhance the learning and transformation capabilities of GSC.

Additionally, the empirical study on the grain supply chain resilience in China is also conducive to enhancing it in developing

TABLE 8 Threshold model regression results.

Variables	Threshold interval	Coefficient	T-statistic	P-value	Confidence interval
DE×I	GIP≤0.010	−0.011	−0.52	0.608	[−0.054,0.032]
	0.010<GIP≤0.018	0.067	3.68	0.001	[0.030,0.104]
	GIP>0.018	0.130	3.79	0.001	[0.060,0.200]
DE×I	GII≤0.026	−0.004	−0.17	0.866	[−0.048,0.041]
	GII>0.026	0.106	3.64	0.001	[0.046,0.165]

TABLE 9 Robustness tests and endogeneity tests results.

Variables	Robustness tests				Endogeneity tests			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
DE	0.220***	0.108*	0.213***	0.131**				
	(0.052)	(0.057)	(0.056)	(0.056)				
GI	0.981*	1.488***	0.013*	1.184***				
	(0.507)	(0.320)	(0.008)	(0.378)				
DE×GI	12.050***	1.872***	14.560***	2.671***				
	(2.368)	(0.694)	(2.846)	(0.765)				
L. DE					0.156***	0.125***		
					(0.051)	(0.042)		
L. GI					5.010*	1.349***		
					(2.638)	(0.461)		
DE							−0.053*	−0.071**
							(0.029)	(0.031)
GI							−2.081	0.016
							(2.764)	(0.032)
L. GSCR							0.542*	0.630**
							(0.281)	(0.261)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Under-identification test					15.318***	59.067***		
Weak-identification test					10.742	63.606		
					{7.03}	{7.03}		
Sample size	341	341	297	297	310	310	310	310
R^2			0.766	0.770	0.652	0.658		
AR (1)							0.042	0.017
AR (2)							0.155	0.113
Hansen							1.000	1.000

countries. During the current situation, there is no doubt that the digital economy has become a key force to improve the grain supply chain resilience, which is crucial to ensure domestic grain supply. Meanwhile, the governments must increase their support to strengthen the infrastructure of the agri-food system. To sum up, the joint efforts of the digital economy, government innovation-driven, and innovative human capital strengthen the robustness of the grain supply chain under uncertain shocks, and finally promote the sustainable development of the food security and agri-food system.

6 Limitation

Since some yearbooks have not been updated, the timeliness of the study needs to be strengthened. The study constructs panel data from

2011 to 2021, which only show the index of grain supply chain resilience fluctuations during the COVID-19 pandemic in 2020 and 2021. Additionally, with the rapid development of the DE, a more comprehensive and scientific evaluation will help to more clearly identify the dynamics of the digital economy, such as digital platforms and deep learning. These limitations will be addressed through further research to enhance their practical value. Besides, in the selection of moderating variables, the characteristics of the digital economy and the grain industry dictate that government guidance is the first step in promoting their development quickly and effectively. This study will be biased since micro-planning investment and market mechanisms are not considered. In the follow-up study, we will explore how to better promote digital technologies to enhance grain supply chain resilience from the micro-interventions and the market strategies to ensure grain supply chain resilience in developing countries under uncertainty shocks. This will strengthen the foundations of sustainable food security.

Data availability statement

The original contributions presented in the study are included in the study/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

JC: Conceptualization, Formal analysis, Methodology, Writing – original draft. HJ: Funding acquisition, Supervision, Writing – review & editing. JL: Software, Writing – review & editing. ML: Data curation, Methodology, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research is supported by the Ministry of Education of Humanities and Social Science Project of China (Grant/Award Number: 23YJC790025) and the Jilin Provincial Social Science Fund Project of China (Grant/Award Number: 2023C36).

Acknowledgments

We are grateful to all of those who provided useful suggestions for this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abban, R., and Abebe, G. K. (2022). Exploring digitalization and sustainable practices in African agribusinesses and food supply chains: a literature review. *Int. J. Food Syst. Dynam.* 13, 470–474. doi: 10.18461/ijfsd.v13i4.D7

Bukht, R., and Heeks, R. (2017). Defining, conceptualising and measuring the digital economy. *Development Informatics Working Paper*, 1–26. doi: 10.2139/ssrn.3431732

Chang, J., and Jiang, H. (2023). Spatio-temporal differentiations and influence factors in China's grain supply chain resilience. *Sustain. For.* 15:8074. doi: 10.3390/su15108074

Chen, Z., Kahn, M. E., Liu, Y., and Wang, Z. (2018). The consequences of spatially differentiated water pollution regulation in China. *J. Environ. Econ. Manag.* 88, 468–485. doi: 10.1016/j.jeem.2018.01.010

Davis, K. F., Downs, S., and Gephart, J. A. (2021). Towards food supply chain resilience to environmental shocks. *Nat. Food* 2, 54–65. doi: 10.1038/s43016-020-00196-3

FAO (2021). The state of food and agriculture 2021. FAO, Rome: Making Agri-Food Systems More Resilient to Shocks and Stresses.

Ferguson, R., Mishra, S., Qureshi, S., Injac, L., Talukder, B., and Orbinski, J. (2024). Digital technologies and food security during crisis: COVID-19 experiences from smallholder farmers in Odisha, India. *Front. Sustain. Food Syst.* 7:1150197. doi: 10.3389/fsufs.2023.1150197

Gu, R., Li, C., Yang, Y., and Zhang, J. (2023). The impact of industrial digital transformation on green development efficiency considering the threshold effect of regional collaborative innovation: evidence from the Beijing-Tianjin-Hebei urban agglomeration in China. *J. Clean. Prod.* 420:138345. doi: 10.1016/j.jclepro.2023.138345

Hansen, B. E. (2000). Testing for structural change in conditional models. *J. Econ.* 97, 93–115. doi: 10.1016/S0304-4076(99)00068-8

Huang, J. B., Xie, L., and Zhong, M. R. (2009). An empirical study on the relationship between innovative human capital and economic growth in China. *Sci. Technol. Prog. Policy* 26, 1–4.

Li, Y., Li, L., and Liu, J. (2022). Effective government, efficient market and high-quality development: empirical research based on moderating effect and threshold effect. *J. Shanxi Univ. Fin. Econ.* 44, 16–30. doi: 10.13781/j.cnki.1007-9556.2022.02.002

Li, Z., and Yang, S. (2018). Fiscal decentralization, government innovation preferences and regional innovation efficiency. *J. Manag. World*, 34, 29–42+110+193–194. doi: 10.19744/j.cnki.11-1235/f.2018.0031

Liu, B., and Pan, T. (2022). Local government innovation-driven and the economic gap between the north and the south of China: research based on the perspective of Enterprise productivity. *J. Financ. Econ.* 48, 18–32. doi: 10.16538/j.cnki.jfe.20211114.202

Lu, F., and Wang, S. (2021). A well-functioning government from the perspective of history and practice: based on the socialist political economics with Chinese characteristics. *J. Manag. World* 37, 77–90. doi: 10.19744/j.cnki.11-1235/f.2021.0138

Ma, X., Feng, X., Fu, D., Tong, J., and Ji, M. (2024). How does the digital economy impact sustainable development? —an empirical study from China. *J. Clean. Prod.* 434:140079. doi: 10.1016/j.jclepro.2023.140079

Ma, J., Li, G., and Han, D. (2023). Digital economy empowers food supply chain resilience: role path and policy orientation. *Soci. Sci. Xinjiang* 1:46–54. doi: 10.20003/j.cnki.xjshkx.2023.01.006

Mboup, G., and Oyelaran-Oyeyinka, B. (2019). "Relevance of smart economy in smart cities in Africa" in Smart economy in smart African cities (Singapore: Springer), 1–49.

Miao, Z. (2021). Digital economy value chain: concept, model structure, and mechanism. *Appl. Econ.* 53, 4342–4357. doi: 10.1080/00036846.2021.1899121

Sharifi, E., Amin, S. H., and Fang, L. (2024). Designing a sustainable, resilient, and responsive wheat supply chain under mixed uncertainty: a multi-objective approach. *J. Clean. Prod.* 434:140076. doi: 10.1016/j.jclepro.2023.140076

Shi, Z., Han, D., and Li, T. (2024). Government innovation preferences, human capital accumulation, and green technology innovation. *Stat. Decis.* 40, 162–168. doi: 10.13546/j.cnki.tjyjc.2024.04.029

Singh, N., Kumar, A., and Dey, K. (2023). Unlocking the potential of knowledge economy for rural resilience: the role of digital platforms. *J. Rural. Stud.* 104:103164. doi: 10.1016/j.jrurstud.2023.103164

Song, F., Reardon, T., Tian, X., and Lin, C. (2019). The energy implication of China's food system transformation. *Appl. Energy* 240, 617–629. doi: 10.1016/j.apenergy.2019.02.069

Tukamuhabwa, B. R., Stevenson, M., Busby, J., and Zorzini, M. (2015). Supply chain resilience: definition, review and theoretical foundations for further study. *Int. J. Prod. Res.* 53, 5592–5623. doi: 10.1080/00207543.2015.1037934

Urruty, N., Tailliez-Lefebvre, D., and Huyghe, C. (2016). Stability, robustness, vulnerability and resilience of agricultural systems. *A review. Agron. Sustain. Dev.* 36:15. doi: 10.1007/s13593-015-0347-5

Wei, H., Yuan, P., and Wang, S. (2022). China rural revitalization survey (2021). Beijing: China Social Sciences Press.

Wen, J., and He, J. (2024). Agricultural development driven by the digital economy: improved EfficientNet vegetable quality grading. *Front. Sustain. Food Syst.* 8:1310042. doi: 10.3389/fsufs.2024.1310042

Yang, Y., Chen, W., and Gu, R. (2023). How does digital infrastructure affect industrial eco-efficiency? Considering the threshold effect of regional collaborative innovation. *J. Clean. Prod.* 427:139248. doi: 10.1016/j.jclepro.2023.139248

Yang, Y., and Xu, X. (2015). Post-disaster grain supply chain resilience with government aid. *Transport. Res. Part E* 76, 139–159. doi: 10.1016/j.tre.2015.02.007

Zhang, Z., Sun, C., and Wang, J. (2023). How can the digital economy promote the integration of rural industries—taking China as an example. *Agriculture* 13:2023. doi: 10.3390/agriculture13102023

Zhao, G., Vazquez-Noguerol, M., Liu, S., and Prado-Prado, J. C. (2024). Agri-food supply chain resilience strategies for preparing, responding, recovering, and adapting in relation to unexpected crisis: a cross-country comparative analysis from the COVID-19 pandemic. *J. Bus. Logist.* 45:e12361. doi: 10.1111/jbl.12361

Zhao, T., Zhang, Z., and Liang, S. (2020). Digital economy, entrepreneurship, and high-quality economic development: empirical evidence from urban China. *J. Manag. World 36, 65–76. doi: 10.19744/j.cnki.11-1235/f.2020.0154*

 10.3389/fsufs.2024.1439593

Appendix

TABLE A1 Stability test, multicollinearity test, and correlation analysis.

Variables	LLC	VIF	GSCR	DE	GIP	GII	Urb	Hc	Ihc	Go	Open
GSCR	−8.522***		1								
DE	−6.033***	1.18	0.456***	1							
GIP	−7.016***	4.06	0.487***	0.479***	1						
GII	−17.886***	1.95	0.427***	0.187***	0.604***	1					
Urb	−7.070***	3.32	0.365***	0.516***	0.721***	0.520***	1				
Hc	−19.179***	1.27	−0.274***	−0.279***	−0.192***	−0.106*	−0.367***	1			
Ihc	−9.183***	6.65	0.774***	0.520***	0.688***	0.584***	0.622***	−0.311***	1		
Go	−6.256***	3.11	0.444***	−0.084	−0.239***	−0.045	−0.288***	−0.045	0.338***	1	
Open	−4.755***	1.51	0.342***	0.444***	0.517***	0.261***	0.419***	−0.035	0.418***	−0.088	1