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Digital economy and regional economic resilience: a dual-test of industrial structure mediation and institutional environment moderation

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Introduction: As a crucial driver of growth under the new development pattern, the digital economy requires in-depth examination regarding its role in enhancing regional economic resilience.
Methods: Using China's provincial panel data from 2011 to 2023, this study investigates the mechanisms through which the digital economy affects regional economic resilience by employing fixed-effects models, mediation tests, and interaction tests.
Result: The findings are as follows: First, the development of the digital economy significantly strengthens regional economic resilience, with particularly prominent performance in the dimensions of transformation and development capabilities. Second, this effect is transmitted through the dual mediating mechanisms of rationalization and upgrading of the industrial structure. Third, the positive effect of the digital economy displays a clear institutional dependence, and can materialize fully only when strong policy support and a high level of marketization coexist. Finally, the impact of the digital economy exhibits significant regional heterogeneity: the effect is most pronounced in the Central region, while it has not yet fully emerged in the western region.
Discussion: This research establishes a theoretical framework linking the digital economy, industrial structure, and economic resilience; reveals the mediating role of industrial structure optimization and the moderating role of institutional conditions; enriches the theoretical understanding of how the digital economy shapes economic resilience; and provides practical insights for fostering a new pattern of regional economic resilience.

KEYWORDS

digital economy, industrial structure, institutional environment, marketization level, regional economic resilience

1 Introduction

With the acceleration of globalization and the intensification of uncertainties, economic systems are facing increasingly frequent and complex external shocks. The successive occurrence of black swan events such as the COVID-19 pandemic and geopolitical conflicts has made enhancing regional economic resilience a focus of attention for academics

and policymakers. Meanwhile, the digital economy has become a key force driving the new wave of technological progress and industrial transformation. It is reshaping economic growth patterns and transforming the competitive landscape across regions. Statistics from the China Academy of Information and Communications Technology indicate that the global digital economy hit $50 trillion in 2024, making up over 40% of the world's GDP. In China, the digital economy amounted to 50.2 trillion yuan, representing 41.5% of the nation's GDP. Governments around the world have introduced supportive policies, such as China's issuance of the 14th Five-Year Plan for Digital Economy Development, the European Union's launch of the "Digital Europe Programme", and the United States' implementation of the "Digital Economy Agenda". The booming development of the digital economy is closely related to Goal nine of the United Nations Sustainable Development Goals (SDGs), particularly Target 9.4: "By 2030, all countries, in accordance with their capabilities, take action to upgrade infrastructure and retrofit industries to make them sustainable". This reflects the core role of the digital economy in promoting industrial transformation and upgrading and building sustainable development models.

Existing studies mainly focus on the impact of the digital economy on economic growth, industrial upgrading, and innovation-driven development; however, discussions on how it enhances regional economic resilience remain underexplored. Specifically, first, although theoretical studies suggest that the digital economy may enhance economic resilience by improving information processing efficiency and reducing the cost of resource reorganization, systematic empirical evidence remains limited. Second, the transmission mechanism through which the digital economy affects economic resilience has not been fully uncovered, and in particular, the mediating role of industrial structure optimization requires further examination. Third, research on the moderating effect of the institutional environment is relatively fragmented, failing to fully consider the complementarity between government support and the level of marketization. Fourth, research on regional heterogeneity remains insufficient, which limits the ability to provide targeted guidance for formulating differentiated policies.

This study attempts to make up for the above deficiencies, with its main innovations and contributions as follows: First, it builds a theoretical framework regarding how the digital economy affects regional economic resilience and carries out an empirical test using China's provincial panel data, thereby enriching the theoretical studies on economic resilience. Second, it introduces the dual mediating role of industrial structure optimization, revealing the transmission pathway through which the digital economy impacts economic resilience by means of the rationalization and advancement of the industrial structure. Third, based on the theory of institutional complementarity, it examines the joint moderating effect of government support and the level of marketization, deepening the understanding of the mechanism of action of the institutional environment. Fourth, through sub-regional research, it reveals the spatial heterogeneity of the impact of the digital economy, providing a basis for formulating differentiated policies.

The practical significance of this study lies in the following aspects: On the one hand, against the backdrop of countercurrents in economic globalization and rising external uncertainties, the research results help to understand the positive role of the digital economy in enhancing regional economic resilience and provide theoretical support for promoting digital transformation. On the other hand, the analysis of industrial structure optimization pathways and institutional mechanisms provides policy insights for improving digital economy development strategies and building a resilient regional development system.

2 Theoretical basis and research hypothesis

2.1 Theoretical basis

2.1.1 Regional economic resilience theory

Regional economic resilience initially stems from the concept of system resilience in ecology, which reflects the ability of economic systems to cope with external shocks. Martin and Sunley [1] define economic resilience as the ability of a region to maintain its original development trajectory or shift to a new equilibrium state in the face of shocks. Economic resilience includes not only short-term resilience and recovery capacity, but also long-term adaptation and transformation capacity [2, 3]. Studies have shown that technological innovation, industrial diversification and institutional environment are the key factors affecting regional economic resilience [4–6].

2.1.2 The theory of digital economy empowerment

The digital economy refers to a set of economic activities that take digital knowledge and information as key production factors, rely on the modern information network as an important carrier, and utilize information and communication technology to improve efficiency [7]. In a narrow sense, the digital economy includes digital industrialization fields such as information and communication industry and Internet platform economy; in a broad sense, it also includes the industrial digital transformation of traditional industries through digital technology [8]. The digital economy reshapes the organizational structure of economic activities and the mechanisms of resource allocation through continuous technological innovation. It contributes to reducing information asymmetry, improving resource allocation efficiency, and promoting the diffusion of innovation [9–11]. These features help to enhance the adaptability and innovation vitality of economic systems. Sun et al. [12] discovered that the growth of the digital economy has notably increased the flexibility of industrial chains and the resilience of economic systems. Therefore, the digital economy is likely to emerge as a key driver in strengthening regional economic resilience.

2.1.3 Theory of institutional complementarity

The theory of institutional complementarity suggests that different institutional arrangements generate mutually reinforcing effects. The coordination between government support and the level of marketization exerts a significant influence on the development of the digital economy [13]. A well-functioning institutional environment can not only reduce the institutional transaction costs associated with digital technology innovation and application but also provide institutional support for the rapid

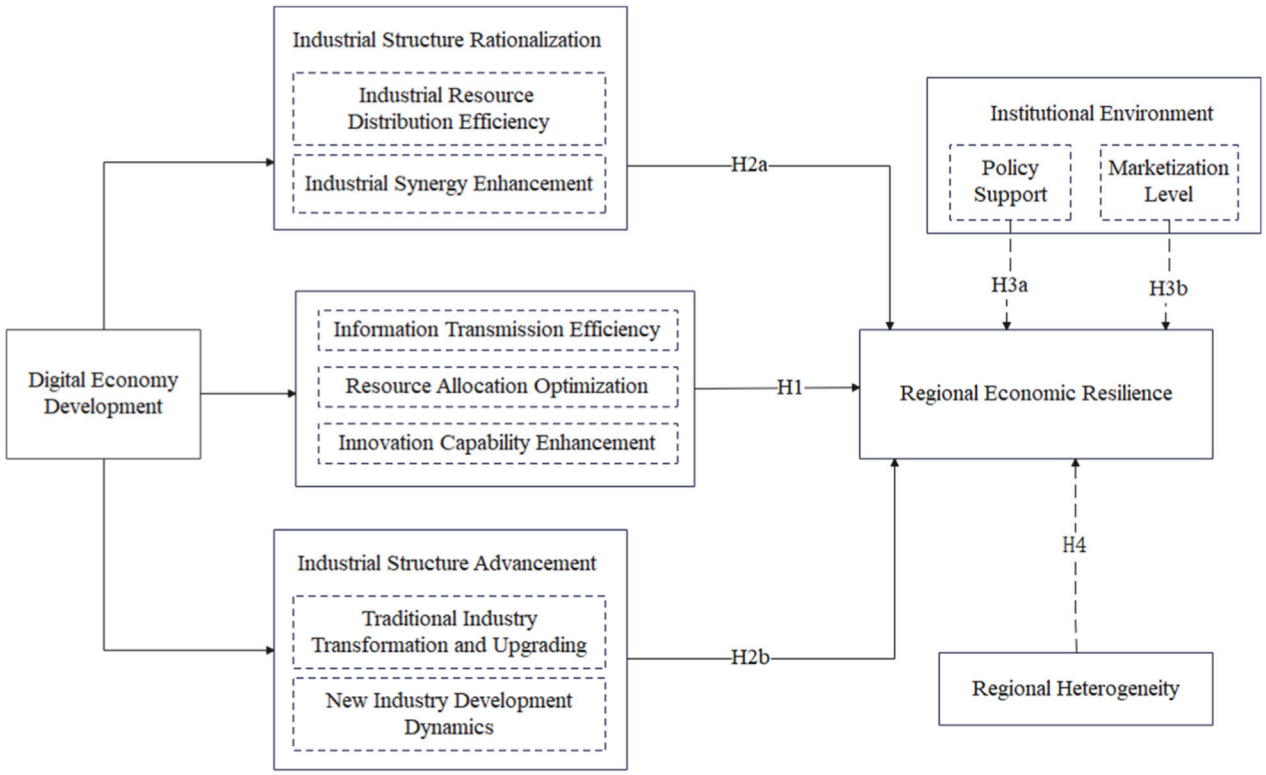

FIGURE 1
Theoretical framework of digital Economy's impact on regional economic resilience.

adjustment of the economic system [14]. This offers a theoretical foundation for analyzing the moderating role of the institutional environment in how the digital economy shapes regional economic resilience.

2.2 Research hypotheses

Based on the theory of regional economic resilience, the theory of digital economy empowerment, and the theory of institutional complementarity, this study constructs a comprehensive analytical framework of "digital economy-industrial structure-economic resilience." The theory of digital economy empowerment reveals that digital technologies enhance industrial operational efficiency and coordination at the micro level by reducing information asymmetry, improving factor allocation efficiency, and promoting innovation diffusion, thereby providing a technical foundation for structural optimization. The rationalization of industrial structure is reflected in the efficient flow and balanced allocation of resources among industries, while the upgrading of structure is manifested in the increased proportion of high-value-added industries and strengthened innovation-driven development. The theory of regional economic resilience emphasizes the economic system's ability to resist, recover, and regenerate in the face of shocks, with its core rooted in structural flexibility and systemic adaptability. The theory of institutional complementarity further points out that the institutional environment has an amplifying and coordinating effect in this process: when market mechanisms and policy support collaborate, digital economy empowerment can be more effectively transformed into structural optimization and systemic resilience. In summary, the three theories collectively form a logical chain from technological empowerment to structural evolution and then to institutional support, laying a theoretical foundation for the proposal of subsequent hypotheses. The mechanism-hypothesis framework related to how the digital economy influences regional economic resilience is presented in Figure 1.

2.2.1 Digital economy and regional economic resilience

Digital economy affects regional economic resilience by improving information transmission efficiency, optimizing resource allocation and enhancing innovation capacity. To be specific: First, digital technologies improve the capacity for information acquisition and processing, reduce transaction costs, and strengthen the regional economy's ability to respond quickly to external shocks [15]. Second, digital platforms promote the efficient flow and optimal allocation of production factors, thereby improving the adaptive adjustment capacity of regional economies [16]. Third, digital innovation drives the development of new business forms and models, enhancing the transformative and developmental capabilities of regional economies [17]. Based on this, it is proposed that:

Hypothesis 1: The development of digital economy significantly improves regional economic resilience.

2.2.2 The mediating effect of industrial structure optimization

The digital economy influences regional economic resilience by shaping the rationalization and upgrading of the industrial structure. On the one hand, the widespread application of digital technologies improves the efficiency of resource allocation across industries, promotes industrial structure rationalization, strengthens inter-industry synergies, and enhances the stability of the economic system [18]. On the other hand, the digital economy facilitates the transformation and upgrading of traditional industries, accelerates the development of emerging sectors, raises the level of industrial advancement, and enhances the innovation capacity of the economic system [19]. Based on this, it is proposed that:

Hypothesis 2a: Industrial structure rationalization plays a significant mediating role in the process through which the digital economy affects regional economic resilience.

Hypothesis 2b: Industrial structure advancement plays a significant mediating role in the process through which the digital economy affects regional economic resilience.

2.2.3 Moderating effect of institutional environment

The theory of institutional complementarity emphasizes that different institutional elements jointly influence economic performance through synergistic interactions. The coordination between policy support and market-oriented mechanisms is a crucial condition for the digital economy to fully exert its effectiveness. Policy support reduces entry barriers and transaction costs for digital enterprises through infrastructure construction, financial incentives, and institutional arrangements, providing safeguards for innovation and diffusion [20]. Market-oriented mechanisms improve policy implementation efficiency and the speed of factor mobility through competitive pressure and optimal resource allocation [6]. When the two interact positively, a circular mechanism emerges in which policy guidance shapes the direction of innovation, market feedback promotes policy adjustment, and institutional optimization is reinforced. The synergy between strong policy support and a high level of marketization can maximize the contribution of the digital economy to economic resilience, whereas relying on a single institutional factor yields limited effects. Based on this, it is proposed that:

Hypothesis 3: Policy support and marketization exhibit a significant complementary relationship, and their synergistic interaction amplifies the positive impact of the digital economy on regional economic resilience.

2.2.4 Regional heterogeneity effect

The heterogeneous impacts of the digital economy across regions reflect the staged nature of digital transformation and align with the core principles of regional economic resilience theory, which emphasizes the capacity of economic systems to resist, recover, adapt, and regenerate under shocks. The diffusion of digital technologies, the degree of path dependence, and the absorptive capacity of local systems jointly shape the extent to which digitalization influences resilience. Existing research suggests that the digital economy initially enhances information transparency, reduces coordination costs, and improves factor allocation efficiency, thereby contributing to industrial structure rationalization. However, digital transformation also induces structural reconfiguration, including factor reallocation, industry substitution, and supply chain restructuring. According to resilience theory, regions undergoing deep structural adjustments may experience short-term instability when traditional industries contract and high value-added sectors have not yet fully matured. This transitional growing pain effect may temporarily weaken resilience despite long-term potential gains. The effect tends to be more pronounced in regions marked by rapid digitalization, intense industrial substitution pressure, or limited absorptive capacity. Based on this, it is proposed that:

Hypothesis 4: The impact of the digital economy on regional economic resilience exhibits significant regional heterogeneity and differs across regions.

3 Research design

3.1 Data sources and sample selection

The empirical analysis draws on provincial panel data spanning 2011–2023, covering 31 provinces in mainland China. The economic resilience indices are constructed using provincial and national statistical yearbooks. Digital economy metrics incorporate data from multiple authoritative sources: the Digital Economy Development Report, Peking University's Digital Financial Inclusion Index, the Information Yearbook, and the Industrial Information Security Development Research Center. Linear interpolation addresses occasional data gaps. Industrial structure indicators stem from the Industrial Statistical Yearbook and the National Bureau of Statistics database. Control variables are sourced from the National Statistical Yearbook and supplemented with data from the Wind database.

3.2 Entropy weight method

The entropy weight method is used to assign objective weights to the indicators. This method evaluates the amount of information contained in each indicator based on its variation across provinces and years and assigns greater weights to indicators with higher information content. The procedure consists of three steps. First, all indicators are standardized to remove differences in units and to ensure comparability. Second, the entropy value and redundancy of each indicator are calculated to capture its information contribution. Third, indicator weights are obtained by normalizing the redundancy values. This approach avoids subjectivity in weight assignment and ensures that the composite index reflects the relative importance of each indicator. A small number of missing observations are processed using linear interpolation.

TABLE 1 Comprehensive evaluation index system of economic resilience.

Primary indicators	Secondary indicators	Tertiary indicators	Indicator attributes
Regional economic resilience	Resistance-recovery capacity	Per capita GDP	Positive
		Per capita disposable income of rural residents	Positive
		Per capita disposable income of urban residents	Positive
		Registered urban unemployment rate	Negative
		Total import and export/GDP	Negative
	Adaptive-adjustment capacity	General fiscal budget revenue/expenditure	Positive
		Total retail sales of consumer goods/GDP	Positive
		Industrial added value/GDP	Positive
		The proportion of the tertiary industry in GDP	Positive
		Total fixed capital formation	Positive
	Transformation-development capacity	The average number of students in institutions of higher learning per 100,000 population	Positive
		Fiscal education expenditure/GDP	Positive
		Fiscal science and technology expenditure/GDP	Positive
		Domestic patent applications granted/permanent resident population	Positive

3.3 Variable design and measurement

3.3.1 Dependent variable

Regional economic resilience is used as the dependent variable and is measured through a composite index constructed using the entropy weight method. The measurement framework covers three theoretical dimensions: resistance–recovery capacity, adaptive–adjustment capacity, and transformation–development capacity. These dimensions follow the mainstream resilience literature and capture the ability of a regional economy to withstand shocks, adjust to structural changes, and maintain long-term growth momentum. Table 1 presents the full indicator system.

The resistance–recovery dimension reflects the capacity of a region to absorb external shocks and restore economic activity. Indicators such as per capita GDP, per capita disposable income, the registered urban unemployment rate, and the ratio of total import and export to GDP are closely related to the short-term stability and recovery potential of the local economy. The adaptive–adjustment dimension captures the ability of a region to adjust its economic structure and maintain operational efficiency after a disturbance. It includes indicators such as fiscal revenue and expenditure, total retail sales of consumer goods, industrial added value, the share of the tertiary industry, and fixed asset investment, all of which reflect the flexibility and resource reallocation capacity of the economy. The transformation–development dimension measures the long-term growth potential of a region and covers indicators related to human capital, innovation input, and knowledge creation, including higher education enrollment, fiscal investment in education, science and technology expenditure, and domestic patent applications per capita.

3.3.2 Independent variable

The level of digital economy development is the core explanatory variable in this study. Following mainstream research practices and the statistical standards of China's digital economy accounting system, we construct a provincial digital economy index from three dimensions: digital infrastructure, digital industry development, and industrial digitalization, as shown in Table 2. The digital infrastructure dimension captures regional conditions related to broadband access, mobile communication capacity, fiber optic cable deployment, and the allocation of network resources, which together form the basic foundation for digital economic activities. The digital industry development dimension reflects the scale and activity of digital industries such as information transmission, software,

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TABLE 2 Digital economy index system.

Primary indicators	Secondary indicators	Tertiary indicators	Indicator attributes
Digital economy	Digital infrastructure	Internet broadband access rate	Positive
		Internet broadband penetration rate	Positive
		Scale of mobile phone facilities	Positive
		Length of long-distance optical cable lines	Positive
		Number of web pages	Positive
		Number of domain names	Positive
	Digital industrialization	Per capita telecommunications business volume	Positive
		Mobile phone penetration rate	Positive
		Number of legal entities in information transmission, software and information technology services	Positive
		Proportion of employees in information software industry	Positive
		Number of domestic patent applications accepted	Positive
	Industrial digitization	Peking university digital financial inclusion index	Positive
		Proportion of enterprises with e-commerce transactions	Positive
		E-commerce sales volume	Positive
		Number of websites per 100 enterprises	Positive
		Value added of secondary and tertiary industries	Positive
		R&D expenditure of industrial enterprises above designated size	Positive
		Express delivery volume	Positive

and information technology services. The industrial digitalization dimension measures the extent to which digital technologies penetrate manufacturing and services, and includes process-based indicators such as e-commerce usage, enterprise participation in digital activities, digital financial inclusion, express delivery volume, and the number of websites.

Direct micro-level data on firm adoption of digital technologies are not available at the provincial level. Therefore, following official digital economy accounting practices, this study uses the value added of the secondary and tertiary industries as an outcome-based proxy to capture the output effects of digital technology use in traditional sectors. Existing research shows that this measure is strongly correlated with digital infrastructure coverage, the intensity of information technology investment, and the diffusion of digital tools among enterprises. It thus provides a reasonable reflection of the overall progress of industrial digitalization. The final digital economy index is obtained by aggregating all weighted indicators. This index provides a systematic assessment of regional development in digital infrastructure, digital industry activity, and the penetration of digital technologies into economic sectors. A higher index value indicates stronger digital foundations, more dynamic digital industries, broader use of digital technologies, and a higher overall level of digital economy development.

3.3.3 Mediator variable

This paper takes industrial structure as the mediator variable. The level of industrial structure is measured from two dimensions: rationalization and advancement. The rationalization of industrial structure is measured by the Theil index, which reflects the equilibrium degree of the industrial structure. A smaller index value

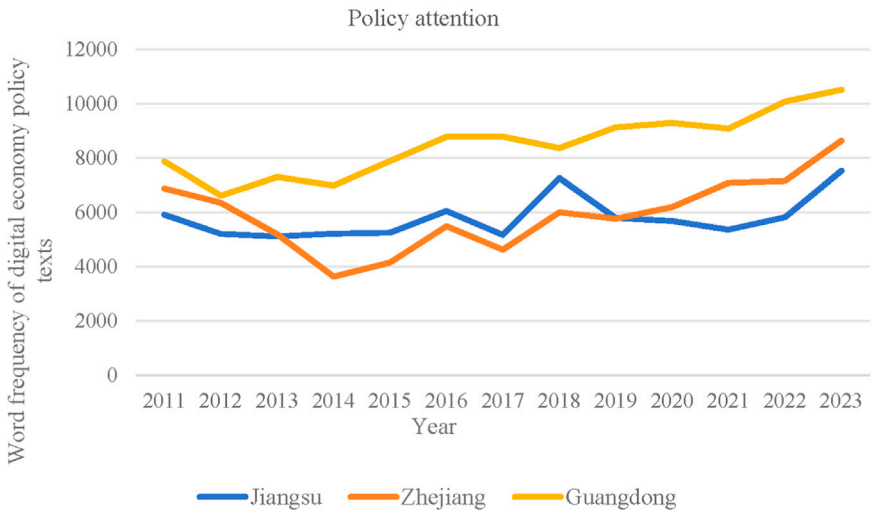

FIGURE 2
Policy attention trend analysis.

indicates that the industrial structure tends to be more reasonable. Compared with alternative indicators such as structural deviation degree, the Theil index, based on the principle of information entropy, boasts advantages of decomposability and additivity. It can simultaneously characterize the differences in resource allocation both between and within industries, making it more suitable for dynamic comparisons across regions and periods. In addition, the Theil index has been widely applied in domestic and international studies for measuring the rationalization of industrial structure [21, 22], which helps ensure the comparability and robustness of the research results. The advancement of the industrial structure is measured by the ratio of the added value of the tertiary industry to that of the secondary industry. A larger ratio indicates a higher degree of advancement of the industrial structure.

3.3.4 Moderator variable

Policy support intensity and marketization level constitute the key moderating variables. The measurement of policy support draws on textual analysis of provincial government work reports (2011–2023) across 31 regions. Python-based word segmentation identifies frequencies of digital economy-related terminology, including "digital economy," "digitalization," "intelligentization," and "Internet+." The natural logarithm of these frequencies quantifies governmental support intensity, reflecting local administrative emphasis on digital economic development. The Fan Gang Marketization Index captures market development levels through its comprehensive assessment of government-market relations, private sector growth, product market evolution, factor market sophistication, intermediary organization development, and legal infrastructure.

To enhance the transparency of policy support measurement, this study further incorporates a descriptive trend analysis based on provincial text frequencies. The results show clear spatial differentiation: coastal provinces exhibit substantially higher levels of policy attention than inland regions, with Guangdong, Zhejiang, and Jiangsu consistently ranking among the top three throughout the sample period. This pattern reflects their long-standing advantages in digital economy planning, institutional supply, and policy responsiveness. As illustrated in Figure 2, policy attention remained relatively stable between 2011 and 2016, but increased sharply after 2017, coinciding with the nationwide rollout of major initiatives such as "Digital China" and "Internet Plus Government Services." The marked rise in digital economy-related terminology indicates a strengthened policy commitment to digital transformation and reveals the staged nature of regional policy orientation. Overall, these descriptive insights confirm that the text-frequency-based indicator effectively captures both the cross-regional heterogeneity and temporal dynamics of policy attention, thereby supporting its validity for empirical analysis.

3.3.5 Control variables

To control for the impact of other factors on regional economic resilience, this paper selects the following control variables: (1) Economic development level: Measured by the natural logarithm of regional gross domestic product (GDP), which reflects the regional economic strength and development foundation. (2) Urbanization level: Expressed as the proportion of urban population to the total regional population, which reflects the regional urbanization process and population agglomeration effect. (3) Level of opening-up: Measured by the natural logarithm of the actual utilized foreign capital, which reflects the degree of regional opening-up and internationalization. (4) Financial development level: Expressed by the natural logarithm of the added value of the financial industry, which reflects the regional financial service capacity and resource allocation efficiency. (5) Human capital level: Measured by the average years of education per capita, which is calculated by weighting the proportion of the population at each education level by the corresponding number of years of education. This indicator more comprehensively reflects the regional human capital accumulation level. The descriptions and sources of the variables are shown in Table 3.

TABLE 3 Variable description and source.

Variable	Name	Symbol	Source
Dependent variable	Economic resilience	res	[17, 23]
Independent variable	Digital economic	dig	[24–26]
Mediator variable	Industrial structure rationalization	rat	[22, 21, 27]
	Industrial structure advanced	adv	[28, 29]
Moderator variable	Digital economy policy	Policy	[30–32]
	Market level	market	[33–35]
Control variable	Economic development	lngdp	[36, 37]
	Urbanization level	urb	[38, 39]
	International direct investment	lnfdi	[40, 41]
	Financial development	lnfin	[42, 43]
	Human capital level	edu	[44, 45]

3.4 Model settings

To examine the impact mechanism of the digital economy on regional economic resilience, this paper constructs the following econometric model:

3.4.1 Benchmark regression model

To test Hypothesis H1, a benchmark regression model is constructed as follows:

$$res_{it} = \beta_0 + \beta_1 dig_{it} + \beta_2 controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

In Equation 1, i and t represent region and year respectively; res denotes regional economic resilience; dig stands for the development level of the digital economy; controls is the set of control variables; μ_i is the regional fixed effect; λ_t is the time fixed effect; and ε_{it} is the random disturbance term.

3.4.2 Mediator effect model

To test Hypothesis H2, referring to the method of Wen and Ye [46], a mediator effect model is constructed as follows:

The total effect equation:

$$res_{it} = \delta_0 + \delta_1 dig_{it} + \delta_2 rat_{it} + \delta_3 adv_{it} + \delta_4 controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Mediator effect equation:

$$rat_{it} = \gamma_0 + \gamma_1 dig_{it} + \gamma_2 controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

$$adv_{it} = \alpha_0 + \alpha_1 dig_{it} + \alpha_2 controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

In Equations 2–4, i and t represent region and year respectively; rat denotes the rationalization of industrial structure; adv stands for the advancement of industrial structure; controls is the set of control variables; μ_i is the regional fixed effect; λ_t is the time fixed effect; and ε_{it} is the random disturbance term.

3.4.3 Moderator effect model

To test Hypothesis H3 and examine the moderating effects of the intensity of digital economy policy support and the level of marketization, this paper constructs the following moderator effect models:

$$res_{it} = \phi_0 + \phi_1 dig_{it} + \phi_2 policy_{it} + \phi_3 (dig_{it} \times policy_{it}) + \phi_4 controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

$$res_{it} = \varphi_0 + \varphi_1 dig_{it} + \varphi_2 market_{it} + \varphi_3 (dig_{it} \times market_{it}) + \varphi_4 controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

In Equations 5, 6, policy and market represent the intensity of digital economy policy support and the level of marketization, respectively. $dig_{it} \times policy_{it}$ and $dig_{it} \times market_{it}$ are interaction terms, whose coefficients ϕ_3 and φ_3 reflect the moderating effects of the moderating variables. Controls is the set of control variables; μ_i is the regional fixed effect; λ_t is the time fixed effect; and ε_{it} is the random disturbance term. If ϕ_3 and φ_3 are significantly positive, it indicates that the moderating variables have a positive moderating effect on the relationship between digital economy development and economic resilience; conversely, it indicates a negative moderating effect.

4 Analysis of empirical results

4.1 Descriptive statistical analysis

4.1.1 Basic statistical characteristics

Descriptive statistics in Table 4 reveal substantial regional variation in digital economy development (dig), with values ranging from 0.00719 to 0.747 around a mean of 0.134 (SD = 0.116). Regional economic resilience (res) exhibits moderate stability across provinces, averaging 0.260 (SD = 0.104). The industrial structure metrics show contrasting patterns: rationalization (rat) demonstrates relative uniformity with a mean of 0.0844 (SD = 0.0391), while advancement (adv) displays marked regional heterogeneity, averaging 1.384 (SD = 0.751). Control variables reflect diverse regional patterns. The urbanization rate (urb) averages 0.597, characteristic of accelerated urban development across regions. Per capita GDP (lngdp: mean = 9.811, SD = 1.011) highlights persistent regional economic disparities. Similar spatial variations emerge in education levels (edu), utilized foreign capital (lnfdi), and financial development (lnfin). The distribution parameters suggest appropriate sample variation, effectively capturing inter-provincial development dynamics during the study period.

4.1.2 Temporal and spatial distribution characteristics

Figure 3 shows the temporal evolution of China's digital economy development level and regional economic resilience from 2011 to 2023. Overall, both indicators show an upward trend, but

TABLE 4 Descriptive statistics.

Variables	N	Mean	Sd	Min	Max
dig	403	0.134	0.116	0.00719	0.747
res	403	0.260	0.104	0.124	0.685
rat	403	0.0844	0.0391	0.0159	0.202
adv	403	1.384	0.751	0.527	5.690
urb	403	0.597	0.129	0.227	0.896
lngdp	403	9.811	1.011	6.416	11.82
edu	403	7.891	0.313	6.987	8.672
lnfdi	403	11.43	1.625	6.588	15.62
lnfin	403	7.126	1.080	3.431	9.453
Number of id	31	31	31	31	31

there are significant differences in their growth rates and fluctuation characteristics. The regional economic resilience index has gradually increased from 0.18 in 2011 to 0.34 in 2023, showing a relatively stable linear growth trend, which reflects that China's regional economy has continuously enhanced its ability to cope with external shocks. The development level of the digital economy has risen rapidly from 0.05 in 2011 to 0.21 in 2023, with a significantly accelerated growth rate, especially between 2017 and 2020. This is closely related to the in-depth implementation of the national digital economy strategy and the demand for digital transformation triggered by the COVID-19 pandemic. It is worth noting that the development of the digital economy experienced a brief pullback after 2020 but then returned to an upward trajectory, indicating that the development of the digital economy has entered a new, more rational stage. The synergistic upward trend of the two trend lines initially confirms that the development of the digital economy may have a positive impact on enhancing regional economic resilience.

4.2 Benchmark regression results

4.2.1 Overall effect test

Table 5 demonstrates robust positive relationships between digital economy development (dig) and regional economic resilience across all specifications. The coefficients remain positive and significant at the 1% level, ranging from 0.7103 to 0.4208, despite the sequential inclusion of controls, which is consistent with Hypothesis 1. Among the control variables, economic development (lngdp) and financial depth (lnfin) show significantly positive associations, highlighting the importance of economic and financial foundations for resilience performance. Urbanization (urb) is negatively associated with resilience, potentially reflecting structural vulnerabilities arising from rapid urban expansion. Opening-up levels (lnfdi) do not show a statistically significant association with resilience. Model diagnostics reveal high explanatory power, with Within R-squared values rising from 0.8223 to 0.8989. The F-statistics remain statistically significant at the 1% level across all specifications.

4.2.2 Analysis of the dimension effect

Examining heterogeneous effects on economic resilience dimensions, we decompose resilience into resistance–recovery, adaptation–adjustment, and transformation–development capacities. Table 6 presents differential associations between the digital economy and these dimensions. The digital economy exhibits the strongest associations with transformation–development capacity ($\beta = 0.4790$, $p < 0.01$), followed by resistance–recovery capacity ($\beta = 0.4168$, $p < 0.05$), with relatively modest associations for adaptation–adjustment capacity ($\beta = 0.3151$, $p < 0.01$). These patterns are consistent with potential underlying mechanisms. The digital economy is associated with structural upgrading and innovation through digital transformation, corresponding to higher levels of transformation capacity. Digital technologies are related to improvements in information processing and risk warning systems, which may support shock resistance. The weaker association with adaptation capacity may relate to its reliance on broader institutional and organizational reforms beyond technological advancement.

Although the baseline and dimensional estimations present consistent patterns, potential endogeneity concerns may still arise. First, the level of digital economy development may be influenced by unobserved regional characteristics, such as governance quality, innovation traditions, or long-term investment preferences, which could bias coefficient estimates. Second, reverse causality cannot be fully excluded, since more resilient regions may have greater incentives or resources to invest in digital technologies. Third, measurement error in both digital economy indicators and resilience indices may introduce additional noise into the estimation process. To address these issues, the subsequent section applies a series of robustness checks and introduces an instrumental variable strategy based on the "Broadband China" policy, together with placebo and pre-trend tests, in order to enhance the credibility of the empirical findings.

4.2.3 Robustness test

To verify the reliability of the research conclusions, this paper conducts robustness tests using methods such as outlier processing, excluding samples from the epidemic period, replacing core explanatory variables, and lag period processing. Table 7 reports the test results: Column (1) shows that after excluding extreme values, the impact coefficient of the digital economy on economic resilience is 0.4355 ($p < 0.01$); Column (2) shows that after excluding the samples from the 2020–2022 epidemic period, the impact coefficient is 0.4848 ($p < 0.01$); Columns (3)–(4) use indicators of digital industrialization and industrial digitalization to replace the overall indicator of the digital economy, respectively. The results show that both have a significant positive impact on economic resilience ($\beta = 0.2351$ and 0.4172, $p < 0.01$); Column (5) shows that after adopting the one-period lag processing, the impact of the digital economy remains significantly positive ($\beta = 0.4284$, $p < 0.01$). In addition, to test the phased robustness after the policy node, this study conducts a subsample regression analysis with 2015 as the structural breakpoint. As shown in columns (6)–(7), the coefficient of the digital economy was 0.326 ($p < 0.1$) before 2015 and rose to 0.406 ($p < 0.01$) after 2015, with both significance and impact

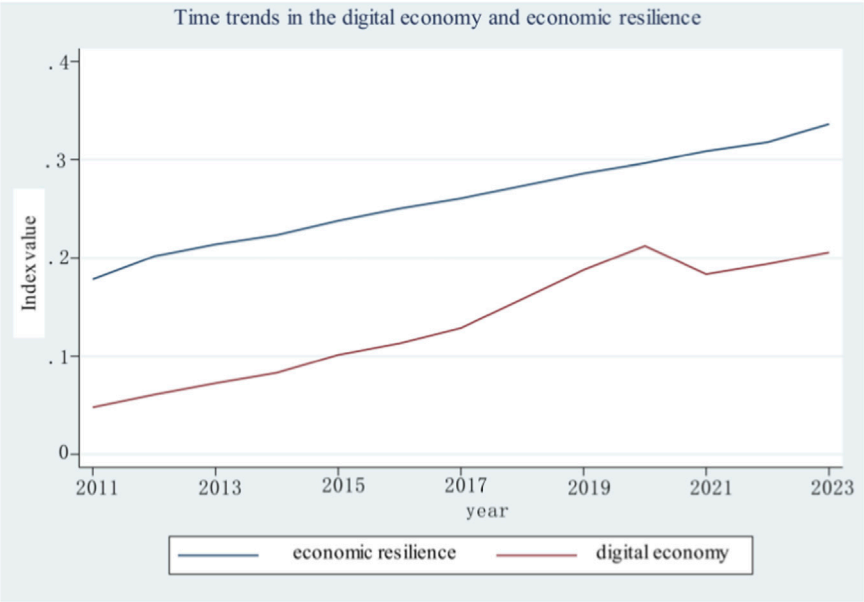

FIGURE 3
Time trend chart of digital economy and economic resilience.

TABLE 5 Results of benchmark regression.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
dig	0.7103***	0.4625***	0.4395***	0.4396***	0.4219***	0.4208***
	(11.31)	(10.16)	(10.16)	(10.23)	(9.73)	(9.13)
lngdp		0.0704***	0.1156***	0.1123***	0.0856***	0.0750***
		(6.52)	(4.66)	(4.45)	(3.64)	(2.97)
urb			−0.2819**	−0.2906**	−0.3631***	−0.4675***
			(−2.08)	(−2.13)	(−2.86)	(−3.23)
lnfdi				0.0022	0.0034	0.0014
				(0.50)	(0.84)	(0.29)
lnfin					0.0272*	0.0358**
					(1.90)	(2.22)
edu						0.0419
						(1.61)
_cons	0.1649***	−0.4923***	−0.7648***	−0.7516***	−0.6523***	−0.8541***
	(19.53)	(−4.84)	(−4.44)	(−4.40)	(−4.27)	(−4.45)
N	403	403	403	403	403	403
Within R-sq	0.8223	0.8839	0.8907	0.8910	0.8953	0.8989
F-statistics	128.0115	241.7999	206.8115	153.5095	150.3529	113.4213

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01.

TABLE 6 Impact of digital economy on economic resilience by dimension.

Variables	(1)	(2)	(3)
	Resistance and recovery capacity	Adaptation and adjustment capacity	Transformation and development capacity
dig	0.4168**	0.3151***	0.4790***
	(2.46)	(2.94)	(7.87)
lngdp	0.3481***	0.0096	−0.0391
	(6.34)	(0.20)	(−1.09)
urb	−1.2092***	0.0898	−0.3588*
	(−3.08)	(0.44)	(−1.81)
lnfdi	−0.0034	−0.0100	0.0099
	(-0.63)	(−1.59)	(1.15)
lnfin	0.0455	−0.0042	0.0516**
	(1.65)	(−0.17)	(2.13)
edu	0.0556	0.0096	0.0515
	(1.61)	(0.28)	(1.35)
_cons	−3.1736***	0.2014	−0.1494
	(-8.01)	(0.84)	(−0.54)
N	403	403	403
Within R-sq	0.9372	0.4332	0.6851
F-statistics	175.6651	5.5593	39.6318

t statistics in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01.

intensity significantly enhanced. This indicates that the promoting effect of the digital economy on economic resilience has been strengthened following the launch of the national "Internet Plus" Action Plan and the systematic advancement of the digital economy strategy. In addition, to examine whether the empirical results are sensitive to the measurement of regional economic resilience, this study constructs an equal-weighted resilience index as an alternative dependent variable and re-estimates the baseline model. As reported in Column (8), the coefficient of the digital economy remains positive and statistically significant, and its magnitude is similar to that in the baseline regression. All test results maintain a significant positive impact relationship, and the coefficient sizes and significance levels are also basically stable, which indicates that the core research conclusions of this paper have strong robustness.

4.2.4 Endogeneity tests

To address potential reverse causality between the digital economy and regional economic resilience, this study employs an exogenous instrumental variable for identification. The "Broadband China" pilot city policy, implemented in centrally planned batches beginning in 2014, provides a suitable source of exogenous variation because the selection of pilot cities was determined by national authorities rather than local economic conditions. The policy substantially promoted broadband infrastructure investment, fiber-optic network deployment, and the diffusion of information services, creating an external shift in the level of digital development across regions. Following existing studies [47, 48], provinces that contain at least one pilot city are coded as treated from 2014 onward, which captures the policy-driven expansion of digital infrastructure. The policy affects regional economic outcomes primarily through improvements in digital connectivity, and its influence on economic resilience operates only through its impact on digital economy development. This satisfies both the relevance and exclusion requirements for a valid instrumental variable.

Table 8 presents the two-stage least squares results. In the first stage, the coefficient on the instrumental variable is positive and highly significant ($\beta = 0.0536$, $p < 0.01$), the Kleibergen–Paap LM statistic ($p = 0.006$) rejects the hypothesis of underidentification, and the Sanderson–Windmeijer F statistic (27.37, which is greater than the commonly used threshold of 10) indicates that weak instruments

TABLE 7 Summary of robustness test results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outlier processing	Exclusion of epidemic years	Digital industrialization	Industrial digitalization	One-period lag	Before 2015	After 2015	Alternative resilience index
dig	0.4555***	0.4848***				0.326**	0.406***	0.3179***
	(16.10)	(15.36)				(0.148)	(0.107)	(3.84)
dig_ind			0.2351***					
			(8.47)					
ind_dig				0.4172***				
				(10.47)				
L_dig					0.4284***			
					(12.73)			
lngdp	0.0624**	0.0540**	0.1135***	0.0612**	0.0501*	−0.031	0.032	0.0762**
	(2.72)	(2.36)	(3.92)	(2.70)	(2.02)	(0.038)	(0.035)	(2.62)
urb	−0.4084***	−0.3492**	−0.6268***	−0.2779**	−0.3526*	0.014	−0.457	0.0583
	(-2.90)	(-2.63)	(-4.40)	(-2.24)	(-2.02)	(0.299)	(0.376)	(0.32)
lnfdi	−0.0007	−0.0001	−0.0012	0.0040	−0.0002	0.008	0.003	0.0085*
	(-0.13)	(-0.01)	(-0.27)	(0.82)	(-0.03)	(0.007)	(0.006)	(1.70)
lnfin	0.0352**	0.0309*	0.0470**	0.0345**	0.0414**	0.005	0.073**	0.0346
	(2.23)	(1.93)	(2.75)	(2.32)	(2.30)	(0.014)	(0.034)	(1.61)
edu	0.0520**	0.0595**	0.0565*	0.0143	0.0390	−0.023	0.041	0.0077
	(2.10)	(2.44)	(1.96)	(0.61)	(1.64)	(0.051)	(0.033)	(0.25)
_cons	−0.8227***	−0.8132***	−1.2759***	−0.6302***	−0.6735***	0.507	−0.723*	−0.8687***
	(-4.53)	(-4.21)	(-6.76)	(-3.53)	(-3.21)	(0.395)	(0.401)	(-3.12)
N	403	310	403	403	372	124	279	403

(Continued on the following page)

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TABLE 7 (*Continued*) Summary of robustness test results.

Variables	(1) Outlier processing	(2) Exclusion of epidemic years	(3) Digital industrialization	(4) Industrial digitalization	(5) One-period lag	(6) Before 2015	(7) After 2015	(8) Alternative resilience index
Within R-sq	0.9010	0.8962	0.8660	0.9126	0.8746	0.8203	0.8410	0.8430
F-statistics	226.5601	181.4892	69.1814	171.1175	191.7080	72	67.52	69.2632

t statistics in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

are not a concern. In the second stage, the estimated effect of the digital economy on regional economic resilience remains significantly positive ($\beta = 0.9110$, $p < 0.01$), and the magnitude is consistent with the benchmark fixed-effects results. These findings confirm that the main conclusions of the study remain robust after addressing potential endogeneity.

To strengthen the credibility of the instrumental variable strategy, this study performs an event-study test using the rollout timing of the Broadband China pilot. Figure 4 reports the dynamic coefficients relative to the policy year (base year $t = -1$). The results indicate that, for $t \leq -2$, all pre-treatment coefficients are small and statistically indistinguishable from zero, confirming the absence of differential pre-trends between treated and untreated provinces and supporting the exogeneity of policy assignment. After the pilot begins, the coefficients turn positive and gradually increase, consistent with the progressive expansion of broadband infrastructure and its effect on the digital economy. Together with the weak-instrument diagnostics, the event-study evidence reinforces the plausibility of the exogeneity assumption and validates the instrumental variable approach adopted in this study.

4.3 Test of mediating effect

Table 9 reports the mediation results for industrial structure rationalization and upgrading, and the findings are consistent with the expectations of Hypotheses H2a and H2b. The digital economy is significantly and positively associated with economic resilience ($\beta = 0.727$, $p < 0.01$). Along the mediating path, the digital economy shows a significant association with industrial structure rationalization ($\beta = -0.180$, $p < 0.01$), which may relate to its role in reducing information asymmetry across industries and improving factor mobility, thereby contributing to a more balanced industrial configuration. In addition, the digital economy is positively associated with the rising share of the tertiary sector relative to the secondary sector ($\beta = 2.345$, $p < 0.01$). This pattern suggests that the diffusion of digital technologies coincides with faster growth of modern services and the emergence of platform- and sharing-based business models, indicating an upgrading trend toward a more service-oriented industrial structure.

Table 10 reports the mediation results of industrial structure in the relationship between the digital economy and economic resilience. The total association (0.727) includes contributions through industrial structure rationalization (0.126, 17.355%) and industrial upgrading (0.100, 13.753%), with a direct association of 0.501. These significant indirect paths are consistent with Hypotheses H2a and H2b, suggesting that structural rationalization and upgrading are relevant channels through which the digital economy relates to resilience. The significant direct association indicates that the digital economy may be linked to improvements in technological progress, information efficiency, and risk management capabilities. The rationalization pathway may reflect the role of digital platforms in facilitating resource allocation, reducing structural frictions, and improving coordination across industries. The upgrading pathway aligns with the interpretation that digital transformation corresponds to

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TABLE 8 Instrumental variable estimation results (2SLS).

Variables	First stage: Dependent variable = Digital economy (dig)	Second stage: Dependent variable = Economic resilience (res)
Broadband China (z_bc)	0.0536***	—
	(0.0111)	
dig	—	0.9110***
		(0.2234)
urb	−1.1161**	0.2016
	(0.5459)	(0.3642)
lngdp	0.1199*	0.0141
	(0.0644)	(0.0350)
edu	0.0313	0.0008
	(0.0792)	(0.0360)
lnfdi	−0.0105	0.0087
	(0.0089)	(0.0069)
lnfin	0.0264	0.0356*
	(0.0399)	(0.0211)
Year FE	Yes	Yes
Province FE	Yes	Yes
Observations	403	403
Clusters	31	31
F-statistic	23.33*	
Kleibergen–paap LM	3.52	
	(p = 0.006)	
Cragg–donald wald F	9.71	
Sanderson–windmeijer F	27.37*	
R-squared	0.65	0.957

Robust standard errors clustered at province level in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

adjustments in traditional sectors and the expansion of emerging activities.

The results of the dual mediation analysis indicate that the indirect association of the digital economy through industrial structure rationalization (17.35%) is larger than that through industrial structure upgrading (13.75%). This difference suggests a pattern consistent with the staged nature of structural transformation under digitalization. According to digital empowerment and structural evolution theories, digital development is often associated with initial improvements in information sharing and factor mobility, which may reduce coordination costs across industries and improve resource allocation efficiency. These changes correspond to the rationalization stage, characterized by greater balance and coordination in the industrial system. Structural upgrading tends to occur only after such efficiency and coordination adjustments have taken place, when digitalization becomes associated with the expansion of higher value-added activities and innovation-driven sectors. In this sense, the relationship between the digital economy and economic resilience aligns with a sequence in which efficiency-oriented

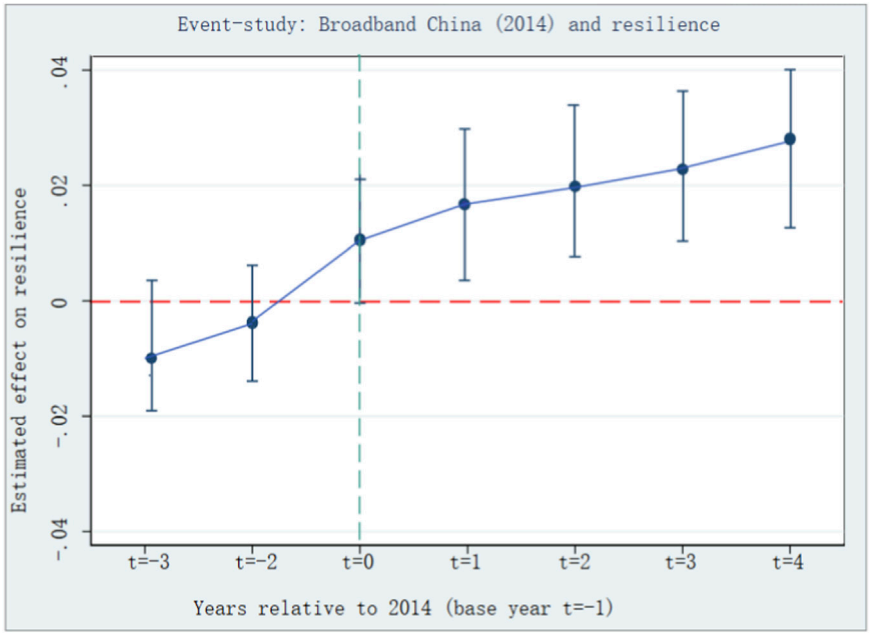

FIGURE 4
Event-study of the Broadband China policy.

TABLE 9 Mediating effect model test.

Variables	res	rat	adv	res
Constant	0.163**(34.998)	0.109**(42.838)	1.068**(19.935)	0.193**(20.440)
dig	0.727**(27.720)	−0.180**(−12.583)	2.345**(7.757)	0.501**(21.350)
rat				−0.701**(−10.193)
adv				0.043**(13.102)
Observations	403	403	403	403
R-squared	0.657	0.283	0.13	0.814
F-statistics	768.372***	158.328***	60.166***	583.167***

***p < 0.01, **p < 0.05, *p < 0.1; t-value is in parentheses.

TABLE 10 Summary of effect size results of mediator.

Model effects	Conclusion	Gross effect	Mediator effect	Direct effect	Effect size
dig=>rat=>res	Partial mediation effect	0.727	0.126	0.501	17.355%
dig=>adv=>res	Partial mediation effect	0.727	0.1	0.501	13.753%

adjustments precede structural upgrading. The relatively larger rationalization effect suggests that the digital economy may be more closely associated with improvements in factor allocation and inter-industry linkages that contribute to system stability, whereas upgrading may reflect longer-term innovation and service-oriented transformation related to resilience enhancement.

4.4 Analysis of moderating effects

To examine whether the level of marketization and policy support moderate the relationship between digital economy development and economic resilience, this paper conducts a moderating effect analysis. The results are reported in Table 11.

TABLE 11 Moderating effect test.

Variables	(1)	(2)	(3)	(4)
	Model 1	Model 2	Model 3	Model 4
dig	0.216***	0.320***	0.402***	0.461***
	(0.058)	(0.049)	(0.095)	(0.055)
market	0.008**		0.006	
	(0.003)		(0.004)	
dig_market	0.051***		0.028*	
	(0.013)		(0.015)	
policy		−0.002		−0.002
		(0.003)		(0.003)
dig_policy		0.084***		0.054***
		(0.023)		(0.018)
urb	−0.246**	−0.300**	−0.179	−0.153
	(0.117)	(0.134)	(0.179)	(0.193)
lngdp	0.057**	0.050**	0.062**	0.046**
	(0.021)	(0.019)	(0.026)	(0.019)
edu	0.016	0.040	0.020	0.027
	(0.026)	(0.024)	(0.029)	(0.030)
lnfdi	0.004	0.002	0.006	0.005
	(0.005)	(0.005)	(0.005)	(0.005)
lnfin	0.038**	0.054***	0.044**	0.050**
	(0.015)	(0.014)	(0.019)	(0.020)
Constant	−0.596***	−0.781***	−0.761**	−0.712**
	(0.198)	(0.166)	(0.291)	(0.277)
Observations	403	402	403	402
R-squared	0.916	0.911	0.924	0.925
Number of id	31	31	31	31
Year FE	No	No	Yes	Yes
Province FE	Yes	Yes	Yes	Yes

Robust standard errors in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

From the results of Model 1 and Model 3, the moderating effect of marketization level (market) is significantly positive ($\beta = 0.051$, $p < 0.01$; $\beta = 0.028$, $p < 0.1$), suggesting that regions with a higher degree of marketization tend to experience a stronger association between digital economy development and economic resilience. The results of Model 2 and Model 4 show that the moderating effect of digital economy policy support (dig_policy) is also significantly positive ($\beta = 0.084$, $p < 0.01$; $\beta = 0.054$, $p < 0.01$), indicating that stronger policy support is linked to a more pronounced positive relationship between the digital economy and resilience. This result remains robust after controlling for year-fixed effects and province-fixed effects, and the explanatory power of the model is relatively high ($R^2 > 0.91$), indicating that the level of marketization and policy support are important institutional conditions for the development of the digital economy to improve economic resilience. Thus, hypotheses H3 is verified.

To further examine the dynamic characteristics of the interaction terms, this study analyzes how the marginal effect of the digital economy varies with the intensity of policy support under different levels of marketization. Figure 5 presents the changing pattern of these marginal effects. As policy support strengthens, the marginal effect of the digital economy on economic resilience shows a clear upward trend. However, the magnitude of this increase differs across marketization contexts. In regions with high marketization, the marginal effect rises more noticeably as policy support improves, suggesting that policy support and market mechanisms tend to reinforce each other. In regions with low marketization, the marginal effect increases only slightly and remains at a relatively low level. These patterns indicate that policy incentives alone may be insufficient to fully enhance the contribution of the digital economy in regions where institutional flexibility is limited. Improvements in market-oriented mechanisms appear to be an important condition for policy support to operate effectively. Overall, the results are consistent with the idea that the positive influence of the digital economy on regional economic resilience is more likely to be strengthened when policy support and the market environment operate in a complementary manner.

4.5 Heterogeneity analysis

Based on the regional heterogeneity results reported in Table 12, the effects of digital economy development on economic resilience differ across regions, which is consistent with the expectations of Hypothesis 4. The digital economy is positively associated with economic resilience in both the eastern and central regions, with coefficients of 0.354 and 0.532 respectively (both $p < 0.01$), and the association is strongest in the central region. In the western region, the coefficient is positive (0.105) but does not reach statistical significance. These regional differences may relate to several factors. The eastern region, benefiting from an early-mover position, has developed relatively complete digital infrastructure and innovation ecosystems. However, as digital development in this region has reached a more mature stage, the marginal effects appear to have moderated. The central region, which developed its digital economy at a later stage, has shown the strongest association between digitalization and resilience. This may reflect the combined effects of industrial transfer, policy incentives, and a comparatively solid industrial base and human capital endowment. In contrast, the western region faces constraints such as weaker

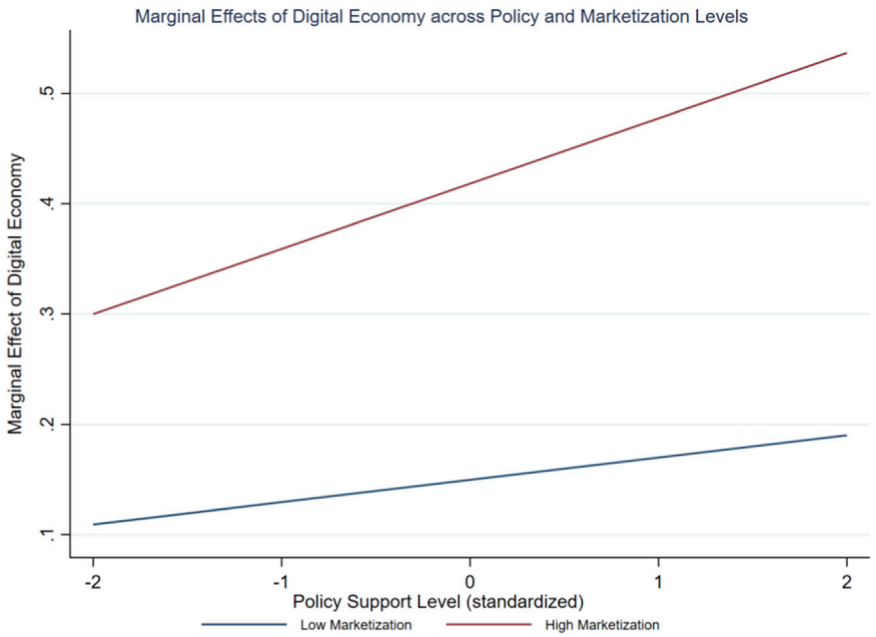

FIGURE 5
Marginal effect of digital economy under different policy-market levels.

digital infrastructure, limited innovation resources, and the outflow of digital talent, which may contribute to the weaker and statistically insignificant association observed. These findings provide useful insights for designing differentiated regional strategies to promote digital economy development and enhance economic resilience.

To further examine internal differences within the western region, this study subdivides the west into four economic zones following the regional classification of the National Development and Reform Commission: the Chengdu–Chongqing Economic Circle, the Guanzhong–Tianshui Economic Zone, the Yunnan–Guizhou–Guangxi Economic Zone, and the Qinghai–Xinjiang–Tibet Economic Zone. According to the results reported in Table 13, the association between digital economy development and economic resilience varies substantially across these zones. In the Chengdu–Chongqing Economic Circle, the coefficient is negative and statistically significant at the 1 percent level (−1.236), suggesting that the relationship between digitalization and resilience may be at an early adjustment stage and may not yet be aligned with the region's structural conditions. In the Guanzhong–Tianshui, Yunnan–Guizhou–Guangxi, and Qinghai–Xinjiang–Tibet regions, the coefficients are either statistically insignificant or unstable in sign, indicating a marked spatial divergence in how digital economy development relates to regional resilience. These differences are consistent with the idea that the effects of digitalization depend on the compatibility between digital development and local industrial structures, factor agglomeration, and institutional environments. Although the Chengdu–Chongqing area functions as a core growth pole of the western region, its digital transformation may still be undergoing structural adjustments, which could contribute to short-term pressures rather than immediate improvements in resilience. In the other zones, limited digital infrastructure, weaker innovation bases, and less developed market mechanisms may constrain the extent to which digital development translates into measurable resilience outcomes. These findings highlight the contextual dependence and phased characteristics of digital economy effects in western China.

The heterogeneity analysis reveals that the Chengdu-Chongqing Economic Circle presents a significantly negative coefficient. This pattern is consistent with regional resilience theory, which emphasizes that resilience outcomes are shaped by the interaction between structural conditions and the stage of regional transformation [49, 50]. Among western subregions, Chengdu-Chongqing is the most digitally developed area, and its rapid digital transformation coincides with an intensive period of industrial restructuring. Existing studies note that when regions with relatively complex industrial structures undergo accelerated technological upgrading, short-term resilience may decline due to transitional pressures [51]. Digitalization in Chengdu-Chongqing has improved technology adoption and factor mobility, yet it may also be associated with faster contraction of traditional sectors, increased volatility during resource reallocation, and temporary disruptions in supply-chain coordination. Since emerging digital industries and high-tech services have not yet developed sufficient capacity to offset these adjustment costs, the region may experience what resilience literature describes as a "short-term adjustment stage," during which resilience temporarily weakens before longer-term benefits emerge. In contrast, other western subregions display insignificant or unstable coefficients, which may relate to more foundational constraints. These regions still face limitations in digital infrastructure, industrial base development, and absorptive capacity, conditions that have been widely shown to hinder resilience formation [52]. As a result, the association between digital development and resilience is less evident. These findings reinforce the contextual and path-dependent nature of resilience

TABLE 12 Analysis results of regional heterogeneity.

Variables	(1)	(2)	(3)
	East region	Central region	West region
dig	0.354***	0.532***	0.105
	(0.049)	(0.144)	(0.101)
urb	−0.432	−0.912**	0.506**
	(0.264)	(0.292)	(0.226)
lngdp	0.206**	0.062	−0.002
	(0.066)	(0.055)	(0.018)
edu	−0.011	0.102**	0.024
	(0.059)	(0.034)	(0.032)
lnfdi	0.000	−0.006	−0.007
	(0.003)	(0.005)	(0.007)
lnfin	−0.028	0.082**	0.006
	(0.039)	(0.033)	(0.010)
_cons	−1.265*	−1.263***	−0.197
	(0.600)	(0.206)	(0.209)
N	143	104	156
Adjust R squared	0.938	0.938	0.863
F-statistics	434.300	1127.883	87.336

Standard errors in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01.

formation. They also suggest that the resilience effects of the digital economy depend not only on the level of digitalization but also on the compatibility between digital transformation and regional industrial structures, institutional capacity, and local absorptive conditions.

5 Research conclusion and prospects

5.1 Research conclusion

Through the analysis of provincial panel data from 2011 to 2023, this study finds that the digital economy has become an important driving force for enhancing regional economic resilience. Firstly, the development of the digital economy has significantly strengthened the overall resilience of the regional economy, particularly in the transformation capacity and development potential of the economic system, reflecting the key role of the digitalization process in promoting economic structure optimization and growth quality improvement. Secondly, this promoting effect is mainly transmitted through two paths: the rationalization and upgrading of industrial structure. This indicates that the digital economy not only optimizes the efficiency of factor allocation but also drives the continuous upgrading of industrial levels, thereby forming an internal mechanism for enhancing economic resilience. Thirdly, the study finds that the positive effect of the digital economy has obvious institutional dependence. The synergistic effect of policy support and marketization level is a key condition for it to exert maximum effectiveness, and institutional complementarity plays a core role in strengthening the transformation of digital dividends. Finally, there are significant regional differences in the impact of the digital economy on economic resilience. The promoting effect is most prominent in the central region, showing its dual advantages in policy orientation and industrial transformation stage. In contrast, the western region is constrained by insufficient infrastructure and innovation ecosystems, so the digital-driven effect has not yet been fully realized.

5.2 Theoretical contributions

This study provides several incremental contributions to the literature on regional economic resilience, particularly in mechanism identification and contextual analysis. First, it examines the relationship between the digital economy and economic resilience through the two channels of industrial structure rationalization and structural upgrading, and shows that efficiency-oriented adjustments and upgrading-oriented transitions contribute with different magnitudes. This helps clarify the underlying logic behind regional differences in resilience performance. Second, the study emphasizes the contextual nature of digital transformation by considering variations in marketization, policy support and regional development conditions. The evidence from western China further illustrates that digital transformation may generate limited or even negative short-term outcomes during periods of structural adjustment, adding to the theoretical discussion on stage-based and path-dependent resilience patterns. Finally, drawing on multi-dimensional resilience frameworks and institutional complementarity, the study uses interaction terms, subgroup regressions and regional heterogeneity tests to examine the combined influence of institutional settings, industrial structures and digitalization processes. These findings enrich theoretical understanding of the mechanisms through which the digital economy affects resilience and extend the spatial and temporal relevance of research in this field.

5.3 Policy recommendations

Based on the empirical research results, this study puts forward the following policy recommendations:Firstly, consolidate digital infrastructure and innovation ecosystems, with particular emphasis on enhancing the resilience support capacity of the western region. A hierarchical advancement target system should be established, incorporating indicators such as broadband penetration rate, 5G coverage rate, and data center capacity into assessments. Implement a “digital talent retention program” to attract and stabilize local technical talents through special staffing quotas and industry-university-research collaboration mechanisms. Secondly, improve

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TABLE 13 Results of heterogeneity analysis of western economic belt grouping.

Variables	(1)	(2)	(3)	(4)
	Chengdu-Chongqing	Guanzhong-Tianshui	Yunnan-Guizhou-Guangxi	Qinghai-Xinjiang-Tibet
dig	−1.236**	1.049	−0.091	0.388
	(0.067)	(0.552)	(0.491)	(0.617)
urb	1.065**	1.757	0.446	0.722
	(0.062)	(0.820)	(0.302)	(0.629)
lngdp	−0.121**	0.028	0.014	0.010
	(0.004)	(0.132)	(0.053)	(0.013)
edu	0.464**	−0.025	0.127**	−0.090
	(0.021)	(0.142)	(0.025)	(0.051)
lnfdi	0.018**	−0.018	−0.010**	0.026
	(0.001)	(0.007)	(0.002)	(0.010)
lnfin	0.068**	−0.098*	−0.008	−0.006
	(0.003)	(0.027)	(0.090)	(0.006)
_cons	−3.379**	−0.013	−0.939	0.289
	(0.171)	(2.393)	(0.756)	(0.213)
N	26	39	39	39
Within R-squared	0.999	0.969	0.977	0.910

Standard errors in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01.

the synergistic constraint system of policy support and market mechanisms to give play to the institutional complementarity effect. Construct a competitive subsidy mechanism, introduce market competition principles for the allocation of digital support funds, and promote the market-oriented reform of data factors. Establish regional data trading and supervision platforms, and improve resource allocation efficiency through clear property rights and price formation mechanisms. Thirdly, promote the digital remodeling of industrial structure and strengthen the dual mediating paths of rationalization and upgrading. For traditional industries, advance digital twin and intelligent supply chain transformation to optimize factor allocation. For emerging industries, improve the digital financial support system, guide capital agglomeration in high-tech and green fields, and promote structural upgrading by establishing an industrial digitalization performance evaluation system. Fourthly, implement regionally differentiated strategies and build a multi-level digital economy pattern. Eastern regions should deepen institutional innovation and international connectivity advantages; central regions should seize the synergistic opportunities of industrial digitalization and greening; western regions should focus on infrastructure improvement and innovation ecosystem cultivation.

Given the substantial internal disparities within western China, more granular and region-specific policy interventions are required. For the Chengdu–Chongqing Economic Circle, policy design should focus on mitigating the short-term "growing-pain" effect associated with rapid digital transformation. On the one hand, a targeted "digital transition support program" for traditional manufacturing should be introduced, including subsidies for technological upgrading, deployment of digital tools, and construction of regional supply-chain coordination platforms, which can reduce the risks of capacity contraction and factor misallocation during early-stage transformation. On the other hand, leveraging Chengdu and Chongqing's strong innovation bases, efforts should accelerate the development of high-tech services, platform-based industries, and digital creative sectors to shorten the incubation period of new growth drivers and stabilize the structural adjustment process. For less-developed western zones such as Qinghai–Xinjiang–Tibet, digital policies should prioritize foundational infrastructure. National regional development funds, Western Development Special Programs, and centrally administered State-Owned Enterprise digital infrastructure investments can be used to expand communication networks, establish inclusive data centers, and promote public digital service platforms. Meanwhile, the adoption of "lightweight digital solutions" (e.g., cloud-based

ERP, remote industrial services, digital government access points) can improve digital accessibility while avoiding cost-induced lock-in effects.

5.4 Limitations and future prospects

Although this study systematically explores the relationship between the digital economy and regional economic resilience, there are still the following limitations that require in-depth research: First of all, constrained by data accessibility, the indicators employed in this paper to gauge the digital economy might fail to fully reflect the overall landscape of digital economy development. Subsequent research could explore the construction of a more comprehensive and detailed evaluation index system. Secondly, this study mainly focuses on the transmission mechanism of industrial structure optimization, while the path through which the digital economy affects economic resilience may be more complex. Subsequent studies can further explore other potential mechanisms such as innovation-driven development and factor reconstruction. Thirdly, as the digital economy surges forward, its impact on economic resilience may demonstrate signs of dynamic transformation. It is suggested that future studies should adopt panel data with a longer time series and combine dynamic panel models to conduct in-depth analysis on the long-term effects of the digital economy.

Data availability statement

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

Author contributions

PQ: Writing – original draft. HN: Methodology, Writing – review and editing. NY: Software, Writing – review and editing. QW: Writing – review and editing, Conceptualization.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that generative AI was not used in the creation of this manuscript.

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References

1. Martin R, Sunley P. Regional economic resilience: evolution and evaluation. In: *Handbook on regional economic resilience*. Cheltenham: Edward Elgar Publishing (2020). p. 10–35.

2. Rose A, Krausmann E. An economic framework for the development of a resilience index for business recovery. *Int Journal Disaster Risk Reduction* (2013) 5:73–83. doi:10.1016/j.ijdrr.2013.08.003

3. Bristow G, Healy A. Innovation and regional economic resilience: an exploratory analysis. *The Annals Regional Science* (2018) 60(2):265–84. doi:10.1007/s00168-017-0841-6

4. He D, Miao P, Qureshi NA. Can industrial diversification help strengthen regional economic resilience? *Front Environ Sci* (2022) 10:987396. doi:10.3389/fenvs.2022.987396

5. Zheng X, Zhang X, Fan D. Digital transformation, industrial structure change, and economic growth motivation: an empirical analysis based on manufacturing industry in Yangtze River Delta. *Plos One* (2023) 18(5):e0284803. doi:10.1371/journal.pone.0284803

6. Zhang X, Tian C. Measurement and influencing factors of regional economic resilience in China. *Sustainability* (2024) 16(8):3338. doi:10.3390/su16083338

7. Williams LD. Concepts of digital economy and industry 4.0 in intelligent and information systems. *Int J Intell Networks* (2021) 2:122–9. doi:10.1016/j.ijin.2021.09.002

8. Zhang T, Li N. Measuring digital economy: from the perspective of digital industrialization and industry digitalization. *Proced Computer Sci* (2023) 221:1006–12. doi:10.1016/j.procs.2023.08.081

9. Ma D, Zhu Q. Innovation in emerging economies: research on the digital economy driving high-quality green development. *J Business Res* (2022) 145:801–13. doi:10.1016/j.jbusres.2022.03.041

10. Li J, Chen L, Chen Y, He J. Digital economy, technological innovation, and green economic efficiency—Empirical evidence from 277 cities in China. *Managerial Decis Econ* (2022) 43(3):616–29. doi:10.1002/mde.3406

11. Zhang B, Zhang J, Miao C. Urbanization level in Chinese counties: imbalance pattern and driving force. *Remote Sensing* (2022) 14(9):2268. doi:10.3390/rs14092268

12. Sun K, Wang H, Ye S. How does digital transformation enhance industrial chain resilience? Evidence from China. *Finance Res Lett* (2025) 75:106896. doi:10.1016/j.frl.2025.106896

13. Zhao Y, Chen X. The relationship between the withdrawal of the digital economy's innovators, government interventions, the marketization level and market size based

on big data. *J Enterprise Inf Manag* (2022) 35(4/5):1202–32. doi:10.1108/jeim-01-2021-0050

14. Song S, Wen J, Li Y, Li L. How does digital economy affect green technological innovation in China? New evidence from the "Broadband China" policy. *Econ Anal Pol* (2024) 81:1093–112. doi:10.1016/j.eap.2024.01.008

15. Khalil A, Abdelli MEA, Mogaji E. Do digital technologies influence the relationship between the COVID-19 crisis and SMEs' resilience in developing countries? *J Open Innovation: Technol Market, Complexity* (2022) 8(2):100. doi:10.3390/joitmc8020100

16. Qian W, Liu H, Pan F. Digital economy, industry heterogeneity, and service industry resource allocation. *Sustainability* (2022) 14(13):8020. doi:10.3390/su14138020

17. Ding J, Wang Z, Liu Y, Yu F. Measurement of economic resilience and analysis of influencing factors in China's contiguous poverty-stricken areas. *Prog Geogr* (2020) 39(6):924–37. doi:10.18306/dlkxjz.2020.06.004

18. Zheng Z, Zhu Y, Pei Y, Wang L. Spatial–temporal heterogeneity and influencing factors of the coupling between industrial agglomeration and regional economic resilience in China. *Environ Dev Sustainability* (2023) 25(11):12735–59. doi:10.1007/s10668-022-02588-w

19. Liu Y, Yang Y, Li H, Zhong K. Digital economy development, industrial structure upgrading and green total factor productivity: empirical evidence from China's cities. *Int J Environ Res Public Health* (2022) 19(4):2414. doi:10.3390/ijerph19042414

20. Liang L, Li Y. How does government support promote digital economy development in China? The mediating role of regional innovation ecosystem resilience. *Technol Forecast Soc Change* (2023) 188:122328. doi:10.1016/j.techfore.2023.122328

21. Gu R, Li C, Li D, Yang Y, Gu S. The impact of rationalization and upgrading of industrial structure on carbon emissions in the Beijing-Tianjin-Hebei urban agglomeration. *Int J Environ Res Public Health* (2022) 19(13):7997. doi:10.3390/ijerph19137997

22. Hu L, Yuan W, Jiang J, Ma T, Zhu S. Asymmetric effects of industrial structure rationalization on carbon emissions: evidence from thirty Chinese provinces. *J Clean Prod* (2023) 428:139347. doi:10.1016/j.jclepro.2023.139347

23. Liu X, Zhang X, Li S. Measuring China's macroeconomic resilience: a perspective of systemic risk. *Social Sci China* (2021) 1:12–32+204.

24. Shao Y, Hua J, Li B. The enabling effect and mechanism of digital economy on urban-rural integrated development. *Res Agric Modernization* (2024) 45(3):477–87. doi:10.13872/j.1000-0275.2024.0047

25. Wu J, Guo Y. Digital economy boosting new urbanization development: an analysis based on the spatial durbin model and threshold model. *Resource Dev and Market* (2024) 40(9):1350–61.

26. Pan K, Zhang X. Analysis of the mechanism of digital economy enabling common prosperity. *Jianghan Forum* (2024) 6:27–32.

27. Yuan S, Sun X, Chen W, Li Y. Study on the measurement of industrial structure "sophistication, rationalization and ecologicalization" based on the dynamic analysis of grey relations—a case study of Beijing-Tianjin-Hebei. *J Syst Sci Inf* (2020) 8(2):130–47. doi:10.21078/jssi-2020-130-18

28. Cheong TS, Wu Y. The impacts of structural transformation and industrial upgrading on regional inequality in China. *China Econ Rev* (2014) 31:339–50. doi:10.1016/j.chieco.2014.09.007

29. Xi B, Zhai P. Economic growth, industrial structure upgrading and environmental pollution: evidence from China. *Kybernetes* (2023) 52(2):518–53. doi:10.1108/k-02-2022-0279

30. Tao C, Ding Y. How digital economy policies affect manufacturing enterprise innovation: a perspective of suitability supply. *Contemp Finance and Econ* (2022) 3:16–27. doi:10.13676/j.cnki.cn36-1030/f.2022.03.001

31. Jin P, Yin D, Jin Z. City heterogeneity, institutional supply, and innovation quality. *The J World Economy* (2019) 42(11):99–123. doi:10.19985/j.cnki.cassjwe.2019.11.006

32. Han Y, Huang L, Wang X. Do industrial policies promote local industrial upgrading? Theoretical explanation and empirical evidence based on developmental local governments. *Econ Res J* (2017) 52(8):33–48.

33. Gang F, Xiaolu W, Guangrong M. The contribution of marketization to China's economic growth. *China Economist* (2012) 7(2):4.

34. Fan G, Ma G, Wang X. Institutional reform and economic growth of China: 40-year progress toward marketization. *Acta Oeconomica* (2019) 69(s1):7–20. doi:10.1556/032.2019.69.s1.2

35. Mei Y, Ma T, Su R. How marketized is China's natural gas industry? A bibliometric analysis. *J Clean Prod* (2021) 306:127289. doi:10.1016/j.jclepro.2021.127289

36. Hou X, Liu J, Zhang D. Regional sustainable development: the relationship between natural capital utilization and economic development. *Sustainable Dev* (2019) 27(1):183–95. doi:10.1002/sd.1915

37. Li B, Gao S, Liang Y, Kang Y, Prestby T, Gao Y, et al..Estimation of regional economic development indicator from transportation network analytics. *Scientific Reports* (2020) 10(1):2647. doi:10.1038/s41598-020-59505-2

38. Chen Y. Defining urban and rural regions by multifractal spectrums of urbanization. *Fractals* (2016) 24(01):1650004. doi:10.1142/s0218348x16500043

39. Zhang J, Lyu Y, Li Y, Geng Y. Digital economy: an innovation driving factor for low-carbon development. *Environ Impact Assess Rev* (2022) 96:106821. doi:10.1016/j.eiar.2022.106821

40. Chen S, Tan H. Region effects in the internationalization–performance relationship in Chinese firms. *J World Business* (2012) 47(1):73–80. doi:10.1016/j.jwb.2010.10.022

41. Sun H, Zhang L, Wang S. Research on the internationalization level of innovation in national high-tech zones and its influencing factors. *Sci and Tech Prog Pol* (2020) 37(4):42–51.

42. Kendall J. Local financial development and growth. *J Banking and Finance* (2012) 36(5):1548–62. doi:10.1016/j.jbankfin.2012.01.001

43. Yang L, Ni M. Is financial development beneficial to improve the efficiency of green development? Evidence from the "Belt and Road" countries. *Energ Econ* (2022) 105:105734. doi:10.1016/j.eneco.2021.105734

44. Weber S. Human capital depreciation and education level. *Int J Manpower* (2014) 35(5):613–42. doi:10.1108/ijm-05-2014-0122

45. Pelinescu E. The impact of human capital on economic growth. *Proced Econ Finance* (2015) 22:184–90. doi:10.1016/s2212-5671(15)00258-0

46. Wen Z, Ye B. Analyses of mediating effects: the development of methods and models. *Adv Psychological Sci* (2014) 22(5):731. doi:10.3724/sp.j.1042.2014.00731

47. Wang Q, Hu A, Tian Z. Digital transformation and electricity consumption: evidence from the broadband China pilot policy. *Energ Econ* (2022) 115:106346. doi:10.1016/j.eneco.2022.106346

48. Rao B. Does digital infrastructure construction serve as a new engine for green sustainable innovation? A quasi-natural experiment based on "the Broadband China" pilot policy. *Polish J Environ Stud* (2025) 34(4):4363–76. doi:10.15244/pjoes/195700

49. Martin R, Sunley P. On the notion of regional economic resilience: conceptualization and explanation. *J Econ Geogr* (2015) 15(1):1–42. doi:10.1093/jeg/lbu015

50. Boschma R. Towards an evolutionary perspective on regional resilience. *Reg Stud* (2015) 49(5):733–51. doi:10.1080/00343404.2014.959481

51. Simmie J, Martin R. The economic resilience of regions: towards an evolutionary approach. *Cambridge J Regions, Economy Soc* (2010) 3(1):27–43. doi:10.1093/cjres/rsp029

52. Pendall R, Foster KA, Cowell M. Resilience and regions: building understanding of the metaphor. *Cambridge J Regions, Economy Soc* (2010) 3(1):71–84. doi:10.1093/cjres/rsp028