ISSN:2790-5187 Vol 4, No.1, 2026

A Study on the Impact of the Digital Economy on Ecological and Environmental Resilience in the Yellow River Basin

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Abstract

As China transitions into the era of the digital economy, this transformation is fostering novel business models and catalyzing fresh development momentum — thereby presenting critical opportunities and a robust technological foundation for enhancing urban ecological resilience. Accordingly, we construct a comprehensive indicator system integrating dimensions of the digital economy and ecological–environmental resilience. Utilizing panel data from 94 cities in the Yellow River Basin spanning 2011–2022, we empirically examine the impact of the digital economy on ecological–environmental resilience and elucidate its underlying mechanisms. Our findings reveal:1) Digital economy development significantly enhances ecological – environmental resilience—a result that remains robust under rigorous sensitivity analyses and endogeneity checks; 2) The geographical elements, the geographical climatic conditions play a regulatory role. Specifically, inverse temperature and altitude have a positive regulatory effect on promoting the ecological resilience of the digital economy; 3) Geographic characteristics—particularly spatial location—induce heterogeneity in impacts. Specifically, the positive effect of the digital economy on ecological–environmental resilience is more pronounced in economically advanced regions, resource-dependent areas, and cities located in the middle reaches of the Yellow River Basin; 4) Socioeconomic factors serve as key mediating pathways through which geographic context shapes outcomes. The digital economy promotes economic growth, accelerates technological innovation, and unlocks human capital potential — collectively strengthening ecological – environmental resilience. Based on this finding, we recommend enhanced policy support for the digital economy. Region-specific environmental policies — tailored to the natural geographical characteristics of each area—should be implemented, and the digital economy's catalytic role in advancing socioeconomic development should be fully harnessed.

Keywords

Digital economy, ecological environment resilience, geographical elements, Yellow River Basin.

1. Introduction

Since the initiation of the reform and opening-up policies, China's economy has experienced rapid growth, achieving remarkable accomplishments that have garnered global attention. However, this growth has been accompanied by severe environmental degradation, posing a significant challenge to human survival and development. The 2024 Central Economic Work Conference highlighted environmental protection as a central focus of high-quality development, underscoring the importance of continuing efforts to protect blue skies, clear waters, and clean soil. It further called for accelerating the comprehensive green transformation of economic and social development, while persistently deepening institutional reforms for ecological civilization. The Yellow River Basin plays a crucial role, not only as a key economic region but also as a critical area for ecological preservation; the stability of its ecological environment is vital to China’s sustainable development. At present, the basin faces increasingly severe challenges related to water-sediment imbalance and water scarcity. On one hand, the continuous accumulation of sediment in the lower reaches has resulted in a “suspended river above ground,” amplifying the risks of droughts and floods, and placing significant strain on flood control efforts. On the other hand, water resources in the basin are extremely limited. With only 2% of the nation’s total runoff, the basin supports irrigation for 15% of the country’s arable land and provides water for 12% of its population. The water resource utilization rate has reached 80%, well above the internationally recognized threshold of 40% for severe water stress. On January 20, 2025, the Political Bureau of the CPC Central Committee reviewed the "Opinions on Comprehensively Promoting Ecological Conservation and High-Quality Development in the Yellow River Basin," emphasizing the need to maintain the strategic focus of “prioritizing protection and focusing on governance.” The opinion stressed the importance of leveraging comprehensive reforms to ensure the effective implementation of the “Yellow River Protection Law,” adhering to natural laws, and prioritizing the coordination of water resources with population, food, and energy needs. This approach aims to comprehensively promote a green transition in development models. Ecological and environmental protection in the Yellow River Basin not only directly affects the living standards of its residents and its long-term socio-economic development, but also has a profound impact on the overall ecological security of the nation. Simultaneously, the rapid development of the digital economy presents new opportunities for the green transformation of the ecological environment. According to the "China Digital Economy Development Research Report (2024)," the digital economy, which relies on modern information networks and the deep integration of digital technologies with the real economy, is demonstrating considerable momentum. By promoting resource sharing and optimizing resource allocation, the digital economy has the potential to drive ecological and environmental protection through innovation, thereby enhancing the resilience of urban ecosystems. This, in turn, can support the Yellow River Basin—and the entire country—in achieving the dual objectives of economic development and ecological conservation.Therefore, conducting a comprehensive study of the 94 cities in the Yellow River Basin to explore whether and how the digital economy can empower ecological and environmental resilience is of significant theoretical and practical importance.

Holling defined ecological resilience as the dynamic, adaptive capacity of an ecosystem to recover from, or even exceed, its original state following a shock or disturbance[1]. This concept emphasizes dynamic processes, encompassing the full cycle from pre-disturbance resistance, through adaptation during the disturbance, to post-disturbance recovery. The Pressure-State-Response (PSR) model describes the dynamic adaptive mechanisms through which ecosystems respond to disturbances, focusing on the interactions between“Pressure,”“State,”and“Response”[2]. In this framework,“Pressure”refers to the disturbance conditions faced by the ecosystem[3];“State”represents the quality of the system, as constituted by natural resources and ecological elements[4]; and“Response”reflects the system’s ability to adapt to disturbances and return to equilibrium[5]. As such, the PSR model offers a theoretical basis for analyzing the impact of the digital economy on ecological resilience throughout the entire "Pressure-State-Response" cycle.Existing research on the relationship between the digital economy and ecological resilience primarily focuses on the following dimensions: In terms of impact, the digital economy is often considered a “green engine”[6], capable of enhancing energy efficiency, driving technological advancements in pollution control, facilitating synergies between pollution reduction and carbon emission cuts[7], promoting green economic development[8], and advancing urban low-carbon transformation[9]. These effects collectively enhance urban ecological resilience and contribute to sustainable development[10]. At the same time, the positive impact of the digital economy on the urban ecological environment is subject to threshold effects based on factors such as city size[11], the level of financial development[12], and the degree of industrial agglomeration[13]. Its promotional role becomes significantly pronounced only once certain threshold values are surpassed. Moreover, research also suggests that the high energy consumption inherent in digital infrastructure, coupled with the increase in electronic waste resulting from the expansion of digital consumption, may place new pressures on the ecological environment[14]. In terms of mechanisms, as a key driver of economic growth, the digital economy positively influences ecological and environmental resilience primarily through the following channels: fostering the upgrading of industrial structures and innovation[15], accelerating the transition from traditional to new growth drivers; enhancing the efficiency of information exchange and strengthening regional connectivity[16]; and increasing the degree of economic agglomeration[17]. The digital economy not only drives local ecological and environmental protection efforts but also promotes the ecological and sustainable development of neighboring cities through spatial spillover effects[18].

In summary, existing studies offer valuable insights into the impact of agricultural industrial structure optimization on eco-economic efficiency; however, several limitations remain: First, most scholars have examined the effects of the digital economy on the ecological environment from a singular perspective, such as pollutant emissions (e.g., carbon dioxide), urban low-carbon transitions, or industrial structure upgrades. This narrow focus fails to capture the complexity of the ecological environment. In contrast, this paper uses urban ecological resilience as a proxy for urban ecological conditions, as it serves as an indicator of ecosystem persistence[1] and offers a more comprehensive reflection of the urban ecological environment. Second, existing research primarily focuses on national or provincial levels, with limited studies addressing specific geographical units such as river basins. Given the vulnerability of river basin ecosystems, the impact of digital economic development on the ecological resilience of these regions may follow distinct patterns. Therefore, examining how digital economic development enhances the ecological resilience of cities within the Yellow River Basin, and exploring the underlying mechanisms, is of considerable significance. To address these gaps, the potential contributions of this paper are threefold: First, it broadens the research perspective by focusing on the impact of the digital economy on the multidimensional construct of ecological resilience. Utilizing panel data from 94 cities in the Yellow River Basin, the study empirically examines the role of the digital economy in enhancing urban ecological resilience, thereby providing new empirical evidence to deepen our understanding of the complex relationship between the digital economy and the ecological environment. Second, it enriches theoretical research by systematically identifying the transmission mechanisms through which digital economy development influences

ISSN:2790-5187 Vol 4, No.1, 2026
ecological and environmental resilience, offering novel theoretical insights and practical pathways for improving the overall ecological and environmental governance system and promoting green agricultural development. Third, through empirical analysis, it uncovers the impact of the digital economy on ecological and environmental resilience and its underlying mechanisms, providing empirical support for strategies aimed at effectively enhancing ecological and environmental resilience.

2. Theoretical Analysis and Research Hypotheses

2.1. The Digital Economy and Ecological Resilience

The sustained development of the digital economy is introducing new momentum into urban ecological resilience, with its direct impact assessable at both macro and micro levels. At the macro level, the digital economy supports governments in refining macroeconomic policies and promoting the development of digital infrastructure, including 5G networks, cloud computing, and IoT platforms. Digital-based smart environmental protection systems are capable of collecting and analyzing environmental data in real-time, thereby improving the efficiency of pollution control and ecological restoration efforts. This, in turn, enhances the protection of the ecological environment, reduces pollution, and strengthens the resilience of urban ecosystems to various disturbances.At the micro level, against the backdrop of the digital economy, enterprises are progressively adjusting their development goals and innovating their governance structures and management models[19]. As the concept of sustainable development takes root, the principle of green development is being increasingly adopted by businesses, with technological innovation facilitating energy conservation, reduced consumption, and optimized resource allocation. Simultaneously, the widespread adoption of the internet and digital platforms has become a powerful tool for promoting green and healthy lifestyles. By leveraging the vast resources and convenient access provided by digital platforms, the public has significantly lowered the cost of learning about low-carbon lifestyles and accessing environmental information. This shift is transforming individual behavior and consumption patterns, encouraging more environmentally responsible choices, and thereby reducing pressure on ecosystems. Furthermore, digital platforms have made it easier for the public to monitor non-environmentally friendly behaviors. Public participation in environmental oversight is thereby enhanced, strengthening accountability for corporate violations, such as illegal emissions, and fostering more efficient and transparent environmental governance. Based on the above analysis, the following research hypothesis is proposed:

H1: The development of the digital economy can promote the enhancement of ecological and environmental resilience.

2.2. The Digital Economy, Geographical Factors, and Ecological Resilience

In philosophy, "First Nature" refers to the pristine natural state, untouched by human influence, while "Second Nature" denotes the natural environment that has been reshaped by human productive activities and imbued with humanistic attributes. In the context of regional development, First Nature primarily encompasses natural geographic elements such as resource endowments, environmental and climatic conditions, and maritime accessibility, all of which form the fundamental conditions for human survival and development. In contrast, Second Nature involves socio-economic factors such as institutional differences, human capital, and industrial structure, reflecting the process through which human activities shape and adapt to the natural environment. Building on the theoretical frameworks of spatial economics and new economic geography, existing research has examined the combined influence of physical geographical factors[20] and socio-economic factors[21] on regional economic activities. Some studies emphasize that regional development is a product of the interaction and interdependence between these physical and socio-economic factors[22]. Urban ecological resilience refers to the capacity of an urban system to maintain the basic stability of its structure and functions, enabling adaptive recovery or even transformation when confronted with external environmental pressures, natural disasters, or human-induced disturbances. This capacity depends not only on the natural characteristics of the ecological environment but is also significantly influenced by human socio-economic activities. As a new economic model characterized by data as a core factor of production and digital technology as the primary driving force, the digital economy is fundamentally reshaping urban modes of production, resource allocation patterns, and governance mechanisms. This, in turn, exerts a comprehensive and systematic influence on urban ecological resilience.

（1）The Digital Economy, Physical Geography, and Ecological Resilience

Physical geographical factors encompass both geographic and climatic conditions as well as characteristics of geographical location. Geographic and climatic conditions primarily include factors such as topographical relief, temperature inversions, precipitation, and elevation, while geographical location characteristics are typically reflected in aspects such as the level of economic development and natural endowments.

First, geographic and climatic conditions influence the impact of the digital economy on ecological resilience by shaping regional environmental governance. Specifically, increased topographical ruggedness generally exacerbates transportation barriers, hinders information transmission, and complicates ecological monitoring and governance[22]. This significantly raises the difficulty and maintenance costs associated with digital infrastructure development, impedes signal transmission and real-time data exchange, and diminishes the immediacy and coverage of digital governance. Consequently, in areas with substantial topographical variation, the overall effectiveness of the digital economy in enhancing ecological resilience may be constrained, resulting in a negative moderating effect of topographical variation on the digital economy's ability to promote ecological resilience. Temperature inversion phenomena inhibit the dispersion of atmospheric pollutants, often leading to pollution accumulation and placing sustained pressure on urban ecosystems[23]. The development of the digital economy, through the establishment of IoT monitoring networks, intelligent air quality early warning systems, and real-time pollution source tracking platforms, significantly enhances the speed of identifying and responding to pollution events under temperature inversion conditions. This makes regions prone to frequent temperature inversions increasingly reliant on digital tools to achieve refined environmental management, thereby reinforcing the digital economy’s positive role in fostering ecological resilience. Precipitation levels and their spatiotemporal variability directly affect regional water resource allocation, flood and drought risks, and agricultural ecological security[24]. Extreme precipitation or highly variable rainfall can damage digital equipment, disrupt networks, and delay data analysis, which in turn limits the stable operation and effectiveness of digital governance systems. In particular, in areas with complex hydrological conditions, the reliability of digital methods declines, suggesting that precipitation levels may negatively modulate the digital economy's role in promoting ecological resilience. High-altitude regions are characterized by fragile ecosystems and complex climatic conditions, where traditional governance models are costly and have limited effectiveness[25]. The digital economy, through technologies such as satellite remote sensing, drone inspections, and ecological big data platforms, enables continuous, comprehensive monitoring and intelligent management of the ecological environment in these regions, significantly improving the precision and adaptability of ecological conservation and restoration efforts. Therefore, the higher the altitude, the more pronounced the role of the digital economy in enhancing ecosystem stability and resilience, positively moderating its beneficial impact on urban ecological resilience. Based on the above analysis, the following research hypotheses are proposed:

H2: Influenced by geographic and climatic conditions, terrain undulation and precipitation will negatively moderate the digital economy’s promotional effect on ecological resilience, while temperature inversions and altitude will positively moderate the digital economy’s promotional effect on ecological resilience.

Second, geographical characteristics can influence ecological and environmental governance, leading to varying impacts of the digital economy on ecological and environmental resilience. Economic heterogeneity, for instance, significantly affects the effectiveness of the integration of digital technology with ecological governance, shaped by regional development foundations[26]. Cities with higher levels of economic development tend to possess more robust digital infrastructure, a more dynamic innovation environment, and greater fiscal support. These factors provide strong foundations for the deep integration of digital technologies into ecological monitoring, environmental management, and resilience-building, thereby substantially enhancing data-driven environmental decision-making and intelligent governance. Conversely, regions with weaker economic foundations face constraints due to insufficient investment in digitalization and lagging technology adoption, which results in relatively limited ecological empowerment from the digital economy. Resource heterogeneity further moderates the role of the digital economy in ecological restoration and system stability through industrial structure and transformation pressures[27]. Resource-dependent cities often face significant historical ecological deficits and pronounced system fragility. In such cases, the digital economy offers essential tools for intelligent pollution control, resource recycling monitoring, and ecological restoration assessment, aiding these cities in overcoming the "resource curse" and environmental constraints, thus leading to more substantial marginal improvements. In contrast, non-resource-based cities rely more heavily on the digital economy to enhance systemic risk prevention and ecological service functions, suggesting divergent pathways for ecological empowerment between these two types of cities. Regional heterogeneity also manifests as gradient characteristics, shaped by differences in natural conditions, developmental stages, and ecological positioning across the upper, middle, and lower reaches of the Yellow River Basin[26]. In the upper reaches, digital technologies primarily strengthen ecological monitoring and disaster early warning capabilities, focusing on building source-based protective resilience. In the middle reaches, digital technologies primarily serve joint pollution prevention and control, as well as resource cycle regulation, with an emphasis on enhancing process-regulatory resilience. In the lower reaches, although

ISSN:2790-5187 Vol 4, No.1, 2026

digital technologies support climate adaptation and optimization of ecological networks, the region's established foundation in ecological and environmental governance, coupled with its relatively mature digital economy, means that the marginal contribution of technology to resilience enhancement tends to plateau. In this region, the formation of system-adaptive resilience relies more on institutional and structural synergies. Therefore, the ecological empowerment effect of the digital economy is not homogeneous but evolves dynamically, influenced by differences in regional development stages, environmental pressures, and governance needs. Based on the above analysis, the following research hypothesis is proposed：

H3: Differences in economic conditions, resource endowments, and the geographical characteristics of river basin segments lead to differentiated impacts of the digital economy on ecological and environmental resilience.

（2）The Digital Economy, Socio-Geographic Factors, and Ecological Resilience

The digital economy can influence ecological and environmental resilience through mechanisms of economic growth, technological innovation, and talent dividends. Economic Growth Mechanisms. The development of the digital economy stimulates industrial digitization and intelligent transformation, enhancing resource utilization efficiency and environmental governance. This facilitates the transition to a green, low-carbon economy. The adoption of digital technologies enables the optimization of energy structures and the reduction of pollution emissions, thereby strengthening urban resilience in the face of environmental shocks and improving ecological stability. Additionally, the digital economy fosters green investment and consumption, stimulates the development of green finance and the circular economy, and directs resources such as capital and technology toward eco-friendly industries. These factors collectively promote high-quality economic development that aligns with ecological sustainability, further bolstering the stability and resilience of urban ecosystems.Technological Innovation Mechanisms. The concept of digital economy empowerment suggests that the widespread adoption of digital technologies can reduce the costs associated with the research, development, and implementation of green technologies. This, in turn, drives innovation in fields such as environmental monitoring, smart environmental protection, and clean production. These technologies not only enhance the efficiency of environmental governance but also improve cities' ability to address ecological risks such as climate change and pollution incidents, contributing to greater ecological resilience. Moreover, the digital economy has facilitated the emergence of data-driven ecological and environmental management models, encouraging the collaborative involvement of governments, enterprises, and the public in ecological governance. This has fostered an ecosystem of innovation in technology, institutions, and behavior, thereby strengthening the adaptability and resilience of urban ecosystems.Talent Dividend Mechanisms.The development of the digital economy has led to an increased demand for highly skilled, multidisciplinary talent, driving the optimization of human capital toward green and digital fields. The professional expertise of high-caliber talent in areas such as digital technology application, environmental management, and ecological planning plays a crucial role in enhancing urban ecological governance and system resilience. At the same time, the digital economy exerts a strong talent aggregation effect, attracting experts in fields like green technology research and development, smart environmental protection, and ecological governance. This results in knowledge spillovers and innovation synergies, providing cities

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with technological advantages and organizational flexibility when responding to environmental challenges, thus improving ecological resilience. Based on the analysis above, the following research hypothesis is proposed:

H4:The digital economy influences ecological and environmental resilience through socioeconomic factors, specifically by driving economic growth, fostering technological innovation, and leveraging the talent dividend.

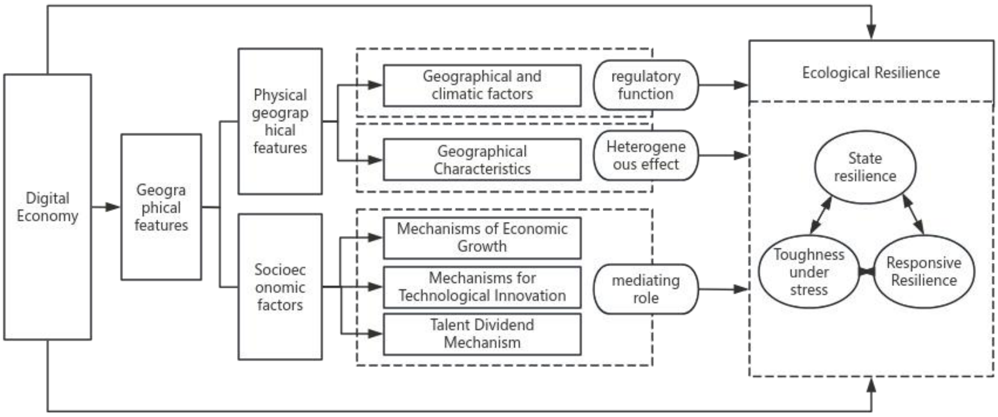

Figure 1: Mechanisms and Transmission Channels of the Digital Economy's Impact on Ecological and Environmental Resilience

3. Research Methods and Data Sources

3.1. Model Development

（1）Baseline regression model. To examine the impact of digital economic development on ecological and environmental resilience, the following econometric model was constructed:

$$UER_{it} = \alpha_0 + \alpha_1 DIG_{it} + +\alpha_2 G_{it} + \mu_{\mathrm{i}} + \gamma_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (1)$$

In Equation （1）: i represents a city, t represents a year, UER_{it} represents ecological and environmental resilience, and DIG_{it} represents the level of digital economic development as the core explanatory variable; G denotes control variables such as population size, economic development level, level of openness to the outside world, urbanization rate, degree of government intervention, and scale of fiscal investment. μ_i is province-fixed, γ_t is year-fixed, ε_{it} is the random error term, and α_1, α_2, α_3 denote the coefficients to be estimated.

（2）Mechanism testing model. To avoid the shortcomings of traditional three-step mediation models, the mechanism testing section will only include a regression of the core explanatory variable X on the mechanism variable M_{it}. As for the effect of M_{it} on the dependent variable UER_{it}, we will rely on supporting evidence from the literature and theoretical analysis. The model is specified as follows:

$$M_{\mathrm{it}} = \alpha_0 + \alpha_1 DIG_{it} + \alpha_2 G_{it} + \mu_{\mathrm{i}} + \gamma_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (2)$$

In Equation（2）: Mit is the mechanism variable, α1, α2, and α3 are the coefficients to be

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estimated, and the meanings of the other terms are the same as those described above.

3.2. Variable Selection

（1）Dependent Variable. This study employs the Urban Ecological Resilience Index (UER) as the dependent variable. This index is designed to assess a city's overall performance in pollution emission control, the maintenance of ecological and environmental conditions, and the enhancement of governance capabilities in response to environmental pressures or sudden shocks. Based on the work of Guo, H[28], and integrating the environmental quality performance evaluation approach proposed by Zhang J[29], as well as incorporating urban socioeconomic characteristics[30], the UER is decomposed into three key sub-dimensions: the State Resilience Index, the Stress Resilience Index, and the Response Resilience Index. These three components collectively form a chain-structured indicator system for urban ecological resilience. Furthermore, these secondary indicators are further quantified through 14 tertiary indicators (see Table 1). Given that each indicator contributes to the overall resilience index in different ways, this study follows the methodologies of Zhou et al[31]. and Wang Jun et al[32]. to normalize the values of each indicator. The entropy method is then applied to determine the appropriate weights, resulting in the calculation of the ecological and environmental resilience index for each city, represented as UER.

Table 1：Ecological environment resilience measurement index system

Level 1 indicator	Level 2 indicator	Level 3 indicator
Ecological and Environmental Resilience Index	State Resilience Index	Per capita water resources
		Green coverage rate in built-up areas
		Per capita park green space
		Per capita built-up area
	Stress Toughness Index	Per capita industrial wastewater discharge
		Per capita industrial sulfur dioxide emissions
		Per capita industrial dust emissions
		Per capita carbon emissions
		Annual average concentration of PM 2.5
	Resilience Index	Industrial sulfur dioxide removal efficiency
		Industrial dust removal efficiency
		Rate of harmless treatment of municipal solid waste
		Centralized treatment rate at wastewater treatment plants
		Comprehensive Utilization Rate of Industrial Solid Waste

（2）Explanatory Variables.In terms of measuring the digital economy, this study draws upon the digital economy framework developed by the China Academy of Information and Communications Technology (CAICT). Given the availability of city-level data, the study comprehensively evaluates the level of digital economic development through two main dimensions: internet development and digital financial inclusion. To assess the level of urban internet development, this study follows the methodology outlined by Huang et al[33]. and incorporates four indicators: internet penetration rate, the size of the relevant workforce, related output, and mobile phone penetration rate. Specifically, these indicators include: the number of broadband internet subscribers per 100 people; the proportion of employees in the computer services and software industry relative to the total urban workforce; the total

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volume of telecommunications services per capita; and the number of mobile phone subscribers per 100 people. The raw data for these indicators are sourced from the China Urban Statistical Yearbook. Regarding the development of digital finance, this paper adopts the China Digital Inclusive Finance Index[34], jointly compiled by the Digital Finance Research Center at Peking University and Ant Group. By standardizing the data for the aforementioned five indicators and applying principal component analysis to reduce dimensionality, a comprehensive digital economy development index, labeled as DIG, is ultimately synthesized.

（3） Mechanism variables. To verify the mechanism through which the digital economy influences ecological and environmental resilience, this study builds upon existing research[35][22] and selects economic factors (INC), innovation factors (LNN), and talent factors (TAL) as mechanism variables. Among these, economic factors are represented by per capita disposable income of urban and rural residents; innovation factors are represented by the number of applications for green invention and utility patents; the talent factor is represented by the ratio of the number of local undergraduate and vocational students to the registered population. Additionally, the mechanism variables are log-transformed.

（4）Control variables. To avoid bias caused by omitting important variables, control for the effects of other significant factors on urban ecological resilience, and ensure the accuracy of the empirical results, we refer to relevant literature[36][37], we selected six control variables: population size (POP, logarithm of registered population), economic development level (GDP, logarithm of per capita regional GDP), level of openness (OPE, actual foreign direct investment/regional GDP), urbanization rate (URB, non-agricultural population/registered population), degree of government intervention (GOV, local general budget expenditures/regional GDP), and intensity of fiscal investment (FIN, fixed-asset investment/general government expenditures). Descriptive statistics for each variable are presented in Table 2. Control variables. To avoid biases caused by omitting important variables, to control for the effects of other significant factors on urban ecological resilience, and to ensure the accuracy of the empirical results, we selected six control variables based on relevant literature[36][37], we selected six control variables: population size (POP, logarithm of registered population), level of economic development (GDP, logarithm of per capita regional GDP), level of openness to the outside world (OPE, actual foreign direct investment / regional GDP), urbanization rate (URB, non-agricultural population/registered population), degree of government intervention (GOV, local general budget expenditures/regional GDP), and intensity of fiscal investment (FIN, fixed-asset investment/general government expenditures). Descriptive statistics for each variable are presented in Table 2.

Table 2： Descriptive statistics of variables

Dimension	Variable name	Variable symbol	Assignments and Notes	mean	Standard deviation
dependent variable	Ecological Resilience	UER	Calculated using the entropy method	0.314	0.007
Explanatory variable	Digital Economy	DIG	Calculated using the entropy method	0.084	0.062
Mechanism variables	Economic factors	INC	Per capita disposable income of urban and rural residents	10.27	0.297

	Elements of Innovation	LNN	Number of Applications for Green Invention and Utility Model Patents	4.809	1.488
	Human Capital	TAL	Number of Applications for Green Invention and Utility Model Patents	-4.523	1.030
control variable	Population size	POP	Take the logarithm of the registered population	5.890	0.665
	Level of economic development	GDP	Take the logarithm of per capita regional GDP	10.672	0.629
	Level of openness to the outside world	OPE	Ratio of actual foreign direct investment to regional gross domestic product	0.001	0.002
	Urbanizatio n rate	URB	Ratio of the non-agricultural population to the registered population	0.346	0.168
	Level of government intervention	GOV	Ratio of local government general budget expenditures to regional gross domestic product	0.208	0.115
	Level of fiscal investment	FIN	Ratio of fixed-asset investment to general government expenditures	6.294	3.917

4. Analysis of Empirical Results

4.1. Regression Results and Analysis of the Baseline Model

The regression results for the baseline model are presented in Table 3, which includes both the regression without control variables and the regression with control variables. As shown in Table 3, regardless of the inclusion of control variables, the regression coefficient for the digital economy's impact on ecological and environmental resilience is significantly positive. This finding indicates that the digital economy plays a pivotal role in enhancing ecological and environmental resilience. Specifically, it suggests that the digital economy, through the adoption of smart governance models and supported by advanced digital infrastructure and environmental monitoring networks, facilitates the real-time collection, intelligent analysis, and early warning of environmental data. This, in turn, significantly improves the efficiency of pollution prevention and control measures, as well as ecological restoration efforts, directly strengthening the stability and resilience of ecosystems.

Regarding the control variables, the impact of population size on ecological and environmental resilience is significantly positive, suggesting that population growth may stimulate the intensive utilization of environmental governance resources and the diffusion of technology through agglomeration effects, thus enhancing the adaptive capacity of ecosystems. The level of economic development also shows a significantly positive impact on ecological and environmental resilience, indicating that higher economic levels provide a material foundation for investment in environmental protection and green technological innovation, which contributes to bolstering regional ecological resilience. The effect of the level of openness on ecological and environmental resilience was not found to be statistically significant, which may be attributed to the dual nature of openness: it can both facilitate the transfer of pollution and promote technology spillovers, with its net effect being complex and influenced by the strength of local environmental regulation. The urbanization rate exhibits a significantly positive impact on ecological and environmental resilience, suggesting that the urbanization process drives infrastructure upgrades and enhances the efficiency of environmental management, thereby fostering a more sustainable human-ecological balance. Similarly, the degree of government intervention shows a significantly positive impact on ecological and environmental resilience, reflecting that government action, through the formulation and enforcement of environmental policies, can effectively curb detrimental practices and guide ecological conservation efforts. Finally, the intensity of fiscal investment in ecological and environmental matters is significantly positively associated with ecological and environmental resilience, indicating that the allocation of fiscal resources toward ecological restoration and the development of environmental protection infrastructure directly strengthens the physical capacity to respond to environmental risks.

Table 3： Regression results of the benchmark model

Variable	Regression coefficient			
	Control variables were not included		Include control variables	
DIG	0.010**	(0.004)	0.010**	(0.004)
POP			0.012***	(0.004)
GDP			0.004***	(0.001)
OPE			-0.149	(0.169)
URB			0.018***	(0.003)
GOV			0.012**	(0.005)
FIN			0.000***	(0.000)
Constant	0.312***	(0.001)	0.189***	(0.027)
Individual fixed	Yes		Yes	
Time fixed	Yes		Yes	
Sample	1128		1128	
R^2	0.110		0.155	

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively (the absence of * indicates that the test of significance was not passed); the values in parentheses are standard errors; R^2 is the coefficient of determination; the same applies below.

4.2. Robustness Tests

Robustness tests were conducted on the baseline regression model through three approaches: truncation (removing sample data outside the 1st and 99th percentiles for the explanatory and dependent variables, as well as data outside the 5th and 95th percentiles), lag effects (incorporating a one-period lag of the digital economy as an explanatory variable into the model), and clustered standard errors (replacing robust standard errors with clustered standard errors). The results of all three robustness tests (see Table 4) are consistent with the baseline regression findings, indicating that the regression coefficient for the first-order term of digital economic development remains significantly positive. This suggests that digital economic development enhances ecological and environmental resilience, thereby confirming the robustness of the baseline regression model.

Table 4: The results of the robustness test

Variable	Regression coefficient			
	bottom 1%	bottom 5%	Lag effect	Cluster standard error
DIG	0.009**	0.010***	0.008*	0.009*
	(0.004)	(0.004)	(0.004)	(0.005)
POP	0.009**	0.005**	0.012***	0.012
	(0.003)	(0.002)	(0.004)	(0.008)
GDP	0.004***	0.003***	0.005***	0.004
	(0.001)	(0.001)	(0.001)	(0.004)
OPE	-0.081	-0.030	-0.218	-0.148
	(0.151)	(0.117)	(0.172)	(0.291)
URB	0.009***	0.001	0.018***	0.018
	(0.003)	(0.002)	(0.004)	(0.015)
GOV	0.008*	0.005	0.014***	0.012
	(0.004)	(0.004)	(0.005)	(0.011)
FIN	0.000***	0.000	0.000***	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.216***	0.249***	0.185***	0.190**
	(0.025)	(0.018)	(0.028)	(0.081)
Individual Fixed	Yes	Yes	Yes	Yes
Time Fixed	Yes	Yes	Yes	Yes
Sample	1128	1128	1128	1128
R^2	0.166	0.232	0.153	0.154

4.3. Endogeneity Tests

In empirical analyses using econometric models, endogeneity issues often arise due to bidirectional causality between the dependent and independent variables, omitted variables, or measurement errors, which can lead to biased estimates. To address this concern, this study adopts the approach of Wang J[38], as well as Gao J[39], by selecting the lagged value of digital economic development as an instrumental variable and using two-stage least squares (2SLS) to conduct an endogeneity test on the baseline model. The results presented in Table 5 indicate that the direction and significance of the impact of digital economic development on ecological and environmental resilience are consistent with those of the baseline regression, suggesting that the empirical conclusions are robust.Additionally, recognizing that heteroskedasticity in the data on digital economic development and ecological and environmental resilience may not have been fully addressed, the study re-conducts the regression analysis using the Generalized Method of Moments (GMM), which is more robust to heteroskedasticity. As shown in Table 4, the GMM estimation results align with the baseline regression conclusions, further validating the robustness of the research findings.

Table 5: The results of the endogeneity test

Variable	Regression coefficient		
	2SLS		GMM
DIG		0.009**	0.020**
		(0.004)	(0.010)
L.DIG	0.096***		
	(0.003)		
control variable	Yes	Yes	Yes
Individual Fixed	Yes	Yes	Yes
Time Fixed	Yes	Yes	Yes
Sample	1128	1128	1026
R^2	0.166	0.232	0.138

4.4. Mechanism Validation

（1） Physical geographical features

Building on the theoretical analysis presented earlier, this paper investigates the moderating role of geographical and climatic factors in the relationship between the digital economy and ecological resilience. The empirical results are shown in Table 6.

First, terrain undulation does not exert a significant negative moderating effect on the digital economy's promotion of ecological resilience. This may be due to several reasons: on the one hand, the information and communication networks that underpin the digital economy are characterized by strong spatial penetration and resilience in coverage, meaning that infrastructure construction and maintenance are less directly constrained by terrain undulation. On the other hand, digital technologies such as remote sensing, the Internet of Things (IoT), and big data platforms are capable of overcoming terrain barriers, enabling dynamic monitoring and precise regulation of ecological environments across extensive areas. This capability mitigates the potential constraints posed by terrain undulation on governance efficiency.

Second, precipitation significantly negatively moderates the effect of the digital economy on ecological resilience. This may be attributed to several factors: regions with high precipitation levels often face increased operational and maintenance costs for digital infrastructure, as well as greater risks of natural damage. Extreme precipitation events can trigger floods, disrupting the physical stability of digital systems and data transmission. Additionally, heavy precipitation may exacerbate the spread of agricultural non-point source pollution. If digital governance fails to simultaneously strengthen environmental regulation and ecological restoration, the technological efficiency gains from digitalization may be offset by localized environmental pressures.

Third, temperature inversions have a significant positive moderating effect. Temperature inversions often result in the accumulation of atmospheric pollutants, which draws greater public and governmental attention to environmental quality. By establishing environmental big data monitoring networks, real-time pollution source tracking, and intelligent early warning platforms, the digital economy can substantially enhance the precision of responses and the systemic capabilities for preventing and controlling air pollution, thereby strengthening the resilience of ecological environments in regions prone to frequent temperature inversions.

Fourth, altitude has a positive moderating effect on the digital economy's ability to enhance ecological resilience. Ecosystems in high-altitude regions are generally more fragile and sensitive to human disturbance and environmental fluctuations. The digital economy can leverage technologies such as satellite remote sensing, drone inspections, and ecological data cloud platforms to achieve non-invasive, continuous ecological monitoring and assessment of remote high-altitude areas, thereby reducing ecological disturbances caused by on-site interventions. Through digital management, it can optimize resource allocation, promote the adoption of clean energy alternatives, and facilitate the implementation of ecological compensation mechanisms, ultimately enhancing the systemic stability and long-term adaptability of the ecological environment in these regions.

Table 6：The results of the mechanism test for geographical and climatic factors

Variable	Regression coefficient			
	①	②	③	④
DIG	0.012**	0.003**	0.020***	0.001**
	(0.006)	(0.006)	(0.006)	(0.005)
Terrain undulation	-0.003			
	(0.003)			
Precipitation		-5.793**		
		(2.386)		
Inversion			0.000**	
			(0.000)	
Elevation				0.000***
				(0.000)
Constant	0.189***	0.191***	0.193***	0.201***
	(0.027)	(0.027)	(0.027)	(0.027)
Control	Yes	Yes	Yes	Yes
Individual Fixed	Yes	Yes	Yes	Yes
Time Fixed	Yes	Yes	Yes	Yes
Sample	1128	1128	1128	1128
R^2	0.155	0.154	0.159	0.173

（2）Geographic characteristics

Furthermore, building on the theoretical analysis, this study posits that variations in economic development levels, resource endowments, and geographical conditions across different regions contribute to heterogeneity in the impact of digital economic development on ecological and environmental resilience. Therefore, following the approach of He Chun et al[26].this study conducts a grouped regression analysis on the research sample, with the results presented in Table 7.

First, differences in economic development levels may influence the effectiveness of the digital economy in enhancing ecological resilience. Using median per capita GDP as the grouping criterion, cities were classified into two groups: those with high levels of economic development and those with low levels. Regression analyses were performed separately for each group. The results reveal that the regression coefficients for digital economic development in both high- and low-economic-development cities passed the significance test, with all coefficients being positive. This indicates that, regardless of economic development level, the digital economy plays a significant role in enhancing ecological resilience. However, a comparison of the magnitudes of the regression coefficients between the two groups suggests that the digital economy has a more pronounced effect on enhancing urban ecological resilience in cities with lower levels of economic development. This may be due to the fact that cities with lower economic development tend to have less advanced digital infrastructure and digital technology applications, leaving greater room for improvement. As a result, the marginal utility of the digital economy in empowering urban ecological resilience is relatively higher, leading to a more substantial impact.

Second, variations in resource endowments also influence the effectiveness of the digital economy in promoting urban ecological resilience. Based on the classification of resource-based and non-resource-based cities outlined in the "National Sustainable Development Plan for Resource-Based Cities (2013–2020)" issued by the National Development and Reform Commission, cities within the Yangtze River Economic Belt were divided into two groups—resource-based and non-resource-based cities—and analyzed separately through regression. The results show that the coefficients for digital economic development in both resource-based and non-resource-based cities are positive at the 0.01 significance level, indicating that the level of digital economic development significantly enhances urban ecological resilience in both types of cities. A comparison of the magnitudes of the regression coefficients between the two groups reveals that the coefficient for resource-based cities is higher than that for non-resource-based cities. This can be attributed to the fact that the development of the digital economy effectively addresses the ecological challenges and developmental contradictions faced by resource-based cities. Compared to non-resource-based cities, resource-based cities typically have simpler industrial structures and economies that are highly dependent on specific local natural resources, such as coal, oil, natural gas, and metal ores. Consequently, resource-based industries, including energy-intensive sectors, account for a larger share of their economies. The digital economy promotes the transformation and upgrading of these industries, encouraging them to innovate production models, reduce pollutant emissions, and enhance resource efficiency, thereby helping to protect the local ecological environment.

Third, as the Yangtze River Economic Belt spans the upper, middle, and lower reaches, differences in the level of digital economic development across these regions may lead to varying impacts on urban ecological resilience. This study classifies cities within the Yangtze River Economic Belt by geographical location, dividing them into upper, middle, and lower Yangtze River cities for a heterogeneity analysis. The results show that cities in the upper and middle reaches of the Yangtze River passed the significance test and yielded positive results, while the impact of the digital economy on ecological resilience in cities in the lower reaches did not pass the significance test. A potential explanation for this is that cities in the lower reach of the Yangtze River are predominantly in the later stages of industrialization or post-industrialization, with an industrial structure dominated by the service sector and high-tech industries. The proportion of traditional, high-pollution industries is relatively low,

ISSN:2790-5187 Vol 4, No.1, 2026

and the ecological environment is comparatively stable, leaving limited potential for marginal improvements in pollution control and ecological restoration through digital technologies. Moreover, the overall level of digital economic development in the lower reaches is relatively high, indicating that these cities may have reached a plateau, where further enhancements in ecological resilience through digital economy initiatives are no longer significant.

Table 7：The results of the mechanism test for geographical location characteristics

variable	Regression coefficient						
	Economic Development		City Type		Region where the city is located		
	Low	High	Resource	Non-resource	Upstream	Midstream	Downstream
DIG	0.007***	0.006*	0.033***	0.008***	0.007*	0.009**	0.001
	(0.002)	(0.003)	(0.010)	(0.003)	(0.004)	(0.004)	(0.002)
POP	0.780***	0.220*	(0.010)	0.013***	0.371**	0.503***	0.054
	(0.099)	(0.112)	(0.008)	(0.004)	(0.152)	(0.163)	(0.094)
GDP	0.213***	0.100	0.002	0.008***	0.145*	0.560***	0.170***
	(0.066)	(0.083)	(0.002)	(0.002)	(0.082)	(0.131)	(0.053)
OPE	0.001	-0.002***	-0.007	-0.252	-0.003**	-0.001	-0.002
	(0.001)	(0.001)	(0.302)	(0.183)	(0.001)	(0.001)	(0.001)
URB	0.093***	-0.001	0.047***	0.002	-0.005	0.102***	-0.009**
	(0.008)	(0.010)	(0.006)	(0.004)	(0.017)	(0.008)	(0.004)
GOV	0.012**	0.032***	0.013**	0.012	-0.004	0.039***	0.021***
	(0.006)	(0.008)	(0.006)	(0.008)	(0.006)	(0.013)	(0.006)
FIN	0.002	0.006**	0.000**	0.000**	-0.009***	0.010***	-0.001
	(0.002)	(0.003)	(0.000)	(0.000)	(0.003)	(0.003)	(0.002)
Constant	-2.867***	-1.735***	0.211***	0.143***	-2.148***	-3.212***	-1.627***
	(0.225)	(0.259)	(0.055)	(0.034)	(0.301)	(0.453)	(0.225)
Individual Fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sample	590	538	576	552	252	180	384
R^2	0.414	0.086	0.292	0.016	0.182	0.743	0.365

（3）Socioeconomic factors

Based on the theoretical analysis presented above, this paper empirically examines the mediating role of socioeconomic factors in the relationship between the digital economy and ecological and environmental resilience. As shown in Table 8, the results suggest that the digital economy enhances the resistance, adaptation, and recovery capabilities of regional ecological and environmental systems through three key pathways: economic growth, technological innovation, and the talent dividend.

First, by promoting green and low-carbon economic growth, the digital economy provides structural support for enhancing ecological and environmental resilience. On the one hand, it empowers the transformation and upgrading of traditional industries through industrial digitization and intelligentization, significantly improving the efficiency of resource allocation and energy-intensive utilization. This results in reduced pollution emissions and ecological degradation at the source of production. On the other hand, the development of the digital economy has invigorated green financial markets, guiding resources such as capital and technology to concentrate in green sectors such as the circular economy and ecological restoration. This creates a stable economic foundation and market incentives for the continuous implementation of environmental governance and ecological construction, thereby systematically enhancing the structural adaptability and resilience of the region in responding to environmental shocks. Related studies also indicate that increasing the level of economic development and unlocking economic vitality are conducive to enhancing ecological resilience[40].

Second, by driving green technological innovation and diffusion, the digital economy directly enhances the precision and systemic capacity of ecological and environmental governance. On the one hand, digital platforms significantly reduce the information costs associated with green technology R&D and collaboration, facilitating breakthroughs and applications in key technologies such as environmental monitoring and early warning systems, clean production, and smart environmental protection. On the other hand, digital technologies, such as big data, the Internet of Things (IoT), and artificial intelligence—serving as general-purpose technologies—empower all aspects of ecological and environmental management. These technologies enable precise pollution tracking, real-time risk prevention and control, and intelligent resource allocation. This has led to the establishment of an integrated ecological governance system that combines technology, institutions, and behavior, significantly enhancing cities' capacity to respond to complex ecological risks and their systemic resilience. Relevant studies also suggest that the diffusion of green innovation technologies effectively promotes the enhancement of ecological and environmental resilience[28].

Third, the digital economy provides long-term knowledge and organizational safeguards for ecological and environmental resilience by optimizing the structure of human capital and promoting talent aggregation. On the one hand, the development of the digital economy drives the restructuring of the labor force towards di gitalization and greening, cultivating and attracting high-caliber talent with specialized skills in environmental data analysis, intelligent monitoring and assessment, and ecological planning and management. This directly improves the scientific and professional standards of ecological governance. On the other hand, the talent pool effect generated by the digital economy fosters knowledge sharing and collaborative innovation among governments, enterprises, research institutions, and the public, forming a resilient governance network characterized by multi-stakeholder co-governance and responsive agility. In turn, this enhances the long-term stability and sustainable recovery capacity of ecosystems at both the organizational and innovation resilience levels. Related studies also suggest that the aggregation of human capital contributes to enhancing ecological and environmental resilience[41].

Table 8： The results of the mechanism test for social and economic factors

Variable	Regression coefficient		
	Economic Growth	Technological Innovation	Demographic dividend

DIG	0.013*	(0.007)	0.098*	(0.056)	0.073*	(0.039)
Constant	10.578***	(0.315)	5.875**	(2.341)	9.527***	(1.710)
Control variable	Yes		Yes		Yes	
Individual Fixed	Yes		Yes		Yes	
Time Fixed	Yes		Yes		Yes	
Sample	1128		1128		1128	
R^2	0.966		0.802		0.442	

5. Research Findings and Policy Recommendations

5.1. Research Conclusions

（1） Overall, the rapid development of the digital economy significantly enhances urban ecological and environmental resilience. This conclusion holds true even after conducting robustness and endogeneity tests, which further reinforce the reliability of the research findings. Specifically, it suggests that the digital economy facilitates precise environmental governance through data-driven mechanisms, enhances the efficiency of pollution monitoring and emergency responses via information interconnectivity and intelligent analysis, and optimizes resource allocation through platform economies and sharing models. As a result, it helps reduce systemic ecological risks and systematically strengthens urban ecological and environmental resilience.

（2） Geographical and climatic conditions, through governance mechanisms, cause temperature inversions and elevation to exert a positive moderating effect on the relationship between digital economic development and ecological resilience, while terrain undulation and precipitation exert a negative moderating effect. However, terrain undulation did not pass the significance test. Additionally, geographical location characteristics, through environmental governance mechanisms, result in a more pronounced effect of digital economic development on ecological and environmental resilience in cities with lower economic development, resource-based economies, and those situated in the middle and upper reaches of the Yellow River.

（3） The development of the digital economy enhances ecological and environmental resilience through three intermediary mechanisms: promoting economic growth, fostering technological innovation, and unleashing the talent dividend. This highlights the role of the digital economy in driving the green transformation of industrial structures and improving resource utilization efficiency, thereby establishing a solid economic foundation for ecological governance and infrastructure development. Furthermore, it stimulates green technological innovation and diffusion, facilitating the practical application of clean production, pollution prevention, and ecological restoration technologies. Simultaneously, the concentration of digital industries attracts high-quality talent, enhances professional capabilities in environmental management and governance, and creates a systemic pathway for improvement through the synergistic integration of economy, technology, and talent.

5.2. Policy Recommendations

(1) Systematically advance the integration of the digital economy with ecological and environmental governance to enhance urban environmental resilience and governance effectiveness. Efforts should be made to expedite the development of an environmental governance system that prioritizes data as a central element. This includes promoting the digital transformation of key processes such as environmental monitoring, pollution tracing, and risk early warning, thereby enhancing the precision and responsiveness of governance mechanisms. Simultaneously, the development of platform-based models for resource sharing and recycling should be encouraged, facilitating the intelligent scheduling and optimized allocation of energy, water resources, and waste management systems. These actions will contribute to a systematic reduction in urban ecological risks. Additionally, the establishment of a dedicated support program for digital environmental protection could guide local governments and enterprises in collaborating on smart environmental protection initiatives, thereby strengthening the digital economy's foundational role in building ecological resilience.

(2) Implement regionally tailored, coordinated digital economy empowerment strategies to enhance the geographical and climatic adaptability of ecological governance. When formulating relevant policies, it is essential to consider the spatial heterogeneity of natural geographical and climatic conditions. In regions characterized by significant temperature inversions and high altitudes, digital technologies should be utilized to strengthen the joint prevention and control of air pollution and improve monitoring and protection in ecologically sensitive areas. In areas with complex topography and frequent precipitation, priority should be given to developing intelligent early warning systems for floods and geological disasters to mitigate the adverse effects of natural conditions on governance outcomes. Moreover, investment in digital infrastructure and targeted policy support should be increased in regions with lower levels of economic development, resource-dependent economies, and cities in the middle and upper reaches of the Yellow River. Digital tools should be employed to enhance the environmental governance capacities of these areas, thus preventing disparities in governance outcomes arising from a one-size-fits-all approach.

(3) Strengthen the synergistic roles of the digital economy in the three key mechanisms—economic, technological, and talent—creating a sustainable pathway for enhancing ecological and environmental resilience. Efforts should focus on promoting the deep integration of the digital economy with green industries, supporting green technological innovation, and facilitating the commercialization of research outcomes. This could be achieved by establishing dedicated programs for the R&D of digital green technologies, encouraging enterprises to leverage big data and artificial intelligence for clean production and ecological restoration. At the same time, mechanisms for cultivating and attracting high-level talent in the digital sector should be enhanced to build a multidisciplinary workforce with expertise in both digital technology and environmental governance, thereby increasing the intelligence and effectiveness of environmental governance. Additionally, fiscal incentives and tax breaks should be introduced to reduce the costs associated with the digital and green transitions for enterprises, stimulating the initiative of market players. A comprehensive system for enhancing ecological and environmental resilience should be developed, integrating economic support, technological innovation, and talent development.

Acknowledgements

Hunan Province Graduate Student Research and Innovation Projects（CX20251139）.

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