

Original Article



How Does Digital Economy Empowering Synergistic Governance of Pollution and Carbon Reduction? An Empirical Study in the Yellow River Basin of China

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Abstract:

This study examines the role of the digital economy in fostering the synergistic governance of pollution reduction and carbon mitigation within China's Yellow River Economic Belt. Using dynamic panel data from nine provinces (2012–2022), we employ a two-way fixed effects model and mediation analysis to explore the mechanisms driving these environmental co-benefits. The results indicate that digital economy development significantly enhances the efficiency of coordinated pollution and carbon reduction. This effect operates through three key pathways: green technological innovation, industrial structure upgrading toward cleaner energy systems, and strengthened public environmental oversight enabled by digital platforms. Further heterogeneity analysis reveals regional disparities, with more pronounced synergistic effects observed in economically advanced regions and areas with lower population density, attributed to superior digital infrastructure and greater flexibility in structural adjustments. Robustness checks confirm the stability of these findings. By integrating multi-dimensional mechanisms and spatial heterogeneity, this research advances the theoretical understanding of the digital economy's dual environmental benefits and provides actionable insights for leveraging digital solutions to achieve low-carbon transitions in ecologically vulnerable regions.

Keywords: digital economy; pollution-carbon synergy; Yellow River Economic Belt; mediation model; heterogeneity analysis

Introduction

With the continuous exacerbation of environmental pollution problems globally and the proposal of the "dual carbon" goals, against the backdrop of the accelerated evolution of the global climate system and the prominence of complex environmental issues, the coordinated governance of pollution control and carbon emissions has become a focal issue in the global governance system. As the world's largest developing country, China is accelerating the construction of an ecological civilization institutional system under the guidance of the dual carbon goals. Through innovative policy tools such as establishing a carbon emission trading market and implementing clean production

standards, China is continuously guiding the green upgrading of the industrial structure. Xi Jinping Thought on Ecological Civilization clearly points out that coordinating pollution prevention and control with greenhouse gas emission reduction is the core path to achieve a comprehensive green transformation of economic and social development, providing fundamental guidance for the modernization of environmental governance in the new era. Since the main sources of greenhouse gases and air pollutants are both the widespread use of fossil fuels, and their emissions are highly correlated, studying the coordinated governance of these two aspects not only has theoretical value but also holds significant practical significance^[1].

At the same time, considering that China's energy structure is dominated by high-carbon energy and its industrial system is generally characterized by high energy consumption, achieving sustainable development of the ecological environment requires the coordinated promotion of pollution prevention and control and carbon emission control^[2], even though this model significantly differs from the traditional "pollution first, treatment later" approach of developed countries. The vigorous development of the digital economy has become an important feature of the global economy, and China is currently in a crucial stage of rapid digital economy development. The digital economy, with its characteristics of high efficiency, greenness, and sustainability, provides new opportunities for addressing environmental challenges^[3]. However, although the digital economy has potential advantages in promoting the synergy between pollution reduction and carbon emission reduction, there is still a lack of precise and clear research findings on the relationship between the two. Therefore, an in-depth study of the relationship between the digital economy and the synergy of pollution reduction and carbon emission reduction not only helps to clarify the specific internal mechanisms of the digital economy in promoting environmental improvement but also provides scientific support for the formulation of relevant policies.

From the perspective of the research theme, pollution reduction and carbon emission reduction mainly focus on exploring the synergistic effects between the reduction of greenhouse gases and atmospheric pollutants. Scholars aim to comprehensively analyze the direct and indirect relationships between greenhouse gases and atmospheric pollutants, and evaluate the synergistic effects of different emission reduction measures in reducing atmospheric pollutants while also cutting down greenhouse gas emissions^[4-6]. In terms of the research scope, studies related to pollution reduction and carbon emission reduction cover industries with high energy consumption, such as the power, industrial, and transportation sectors. Analyses of their synergistic effects are conducted through model construction. Meanwhile, at the overall economic level, scholars study the role of the pollution reduction effects brought about by carbon reduction measures in offsetting the costs of carbon reduction policies, as well as the impact

of lenient emission reduction measures on the overall economic synergistic benefits^[7-8]. Regarding research methods, scholars use quantitative assessment, model construction, and policy analysis, etc., to confirm the existence of the synergistic effect and conduct comprehensive evaluations^[9-12]. As a new economic form with data resources at its core, the digital economy has become a key driving force for China's transformation between old and new growth drivers. The relevant research in this paper mainly revolves around its measurement methods and its impact on the environment. In terms of measurement methods, existing studies use methods such as big data analysis or model construction to evaluate the development level of the digital economy^[13-15]. However, given that the digital economy encompasses a wide range of fields and diverse forms, the existing measurement methods may not be able to fully capture the entire picture of the digital economy, which may affect the scientific nature of the research conclusions. In terms of environmental effects, the research mainly focuses on resource optimization and allocation, energy conservation and emission reduction, and sustainable development, etc. There is a divergence in the academic community regarding the impact of the digital economy on the environment: Some scholars believe that digital technology may increase carbon emissions because it requires more energy consumption^[4-5]; while more scholars hold the view that digital technology can create new carbon emission reduction approaches and improve traditional pollutant emission reduction measures^[16-19].

The literature review reveals that although preliminary progress has been made in the research on the coordinated governance between the digital economy and the environment, multiple challenges still remain: (1) There are significant divergences in the classification standards of digital economy industries (such as the classification systems of the Organisation for Economic Co-operation and Development and the China Academy of Information and Communications Technology), the definition of core industries (such as whether to include digital technology application sectors), and the methods of index construction (such as the input-output method and big data measurement). These divergences lead to a lack of consistency in the

measurement results of the digital economy. (2) Most of the existing studies focus on the single impact of the digital economy on pollution reduction or carbon emission reduction, and there are few systematic explorations of its impact on the synergistic effect of pollution reduction and carbon emission reduction. (3) The digital economy has a "double-edged sword" characteristic. Precisely exploring its potential mechanisms on the synergistic effect of pollution reduction and carbon emission reduction is a topic worthy of in-depth research.

The Yellow River Economic Belt, characterized by the potential for achieving a win-win situation between economic development and environmental protection, plays an extremely important role in promoting the coordination of pollution reduction and carbon emission reduction. Therefore, by utilizing the panel data of the Yellow River Basin (including nine provinces) from 2012 to 2022, this paper conducts an empirical analysis and further performs a heterogeneity analysis in combination with the resource endowments of different regions. The aim is to provide theoretical support for the high-quality development and high-level protection of the Yellow River Economic Belt.

2. Research Hypotheses

2.1 Direct Impact of Digital Economy on Pollution-Carbon Synergy

The exponential growth of digital technologies has become a core enabling factor driving the transformation of the economic structure. Through deep integration with traditional industries, it not only promotes high-quality economic development but also demonstrates positive effects in the field of environmental protection, especially in reducing pollution and carbon emissions^[20]. From the perspective of administrative management, the development of the digital economy has significantly improved governance efficiency. By ensuring the precision of control and monitoring and the timeliness of data, the digital economy effectively breaks down information silos and enables seamless information exchange between central and local governments. This, in turn, effectively curbs potential collusive behaviors between local governments and enterprises, further enhancing the efficiency and fairness of environmental

governance. Analyzing the mechanism of action at the micro-enterprise level, the application of digital technologies, by being embedded in the entire process of research and development design, production and manufacturing, marketing, and service, promotes the improvement of the total factor productivity of enterprises. This not only optimizes the allocation of enterprise resources but also stimulates technological innovation and industrial upgrading. Moreover, the convenience and extensive penetration of the digital economy break down the boundaries of traditional markets, accelerate the circulation of information, and drive the research, development, and application of new energy technologies, providing strong support for the transformation of the energy structure. At the level of household consumption, the widespread application of digital platforms (such as online shopping and virtual meetings) has not only subtly changed people's consumption habits but also accelerated their pace of life. By reducing resource consumption in daily life, these digital platforms lay a solid foundation for the promotion of green and low-carbon lifestyles. Meanwhile, the popularity of mobile payment methods represented by WeChat Pay and Alipay has led to profound changes in the consumption model, driving households to shift towards more environmentally friendly and low-carbon consumption patterns.

In summary, digital technologies empower the environmental coordinated governance system from three dimensions: (1) Optimization of macro-level governance, which improves the precision of environmental regulation through the construction of a digital government; (2) Innovation in micro-level production, which achieves an increase in total factor productivity relying on the industrial internet platform; (3) Green transformation at the consumption end, which guides low-carbon consumption behaviors through the digital consumption ecosystem. Based on this, this paper proposes the following core hypothesis:

Hypothesis 1: The digital economy can effectively promote the realization of the synergistic effect of pollution reduction and carbon emission reduction.

2.2 Indirect Impact of Digital Economy on Pollution-Carbon Synergy

2.2.1 Green Technological Progress

As a crucial path to alleviate environmental pressure, the progress of green technology holds significant importance. Its mechanism of action is mainly reflected in the following aspects: First, knowledge reserve serves as the core driving force for technological innovation. With the acceleration of the digitalization process, the efficiency of information transmission has been significantly improved. This enables enterprises to more conveniently access cutting-edge knowledge and skills, accelerate the cycle of technological innovation, expand its scope of influence, and enhance its spill-over effect, thereby effectively reducing R & D costs. Moreover, by leveraging big-data technology, enterprises can accurately perceive market changes, reduce the misalignment between R & D and market demand caused by information barriers, and optimize resource allocation to improve innovation efficiency^[21]. In the context of financial market imperfection, digital inclusive finance constructs an environmental credit profile of enterprises through blockchain credit-reporting technology, alleviating the information asymmetry between banks and enterprises and guiding financial resources towards the field of green technology R & D. Meanwhile, the characteristics of technology-intensive industries spawned by the development of the digital economy create a talent-siphoning effect, promoting the upgrading of the human-capital structure towards a high-skill and innovative direction. Specifically: (1) The effect of suppressing technological innovation costs: Digital technology reduces the cost of R & D trial-and-error, facilitating breakthroughs in key technologies such as carbon capture and new energy; (2) The effect of optimizing the allocation of innovation factors: The industrial internet platform enables the cross-regional collaborative allocation of R & D resources, improving the efficiency of technology transfer; (3) The effect of human-capital upgrading: The industrial agglomeration of the digital economy drives up the return on investment in higher education, accelerating the reserve of innovative talents.

Based on this, this paper proposes the following hypothesis regarding the transmission mechanism:

Hypothesis 2: The digital economy significantly promotes the realization of the synergistic effect

of pollution reduction and carbon emission reduction through the triple transmission paths of the effect of suppressing technological innovation costs, the effect of optimizing the allocation of innovation factors, and the effect of human-capital upgrading.

2.2.2 Industrial Structure Upgrading

The rapid development of the digital economy has played an important role in promoting the optimization and upgrading of the industrial structure. Based on the theoretical framework of new structural economics, the evolution of the industrial structure towards the middle and high ends empowers the environmental coordinated governance system through a dual path. Specifically, digital industrialization reconstructs the value chain of traditional industries through the innovative diffusion of digital technology clusters (such as industrial internet and blockchain). On the one hand, it gives rise to new business forms such as the platform economy and the sharing economy, promotes the precise matching of demand on the consumer side, and realizes the improvement of total factor productivity. On the other hand, it optimizes the energy consumption structure through a real-time monitoring system and reduces the energy consumption intensity per unit of GDP. Industrial digitization, relying on technologies such as 5G and the Internet of Things, transforms all factors of traditional industries, generating three aspects of synergistic effects: (1) The green reconstruction of production processes is achieved through digital twin technology, reducing the dependence on fossil energy; (2) A cross-regional supply chain collaboration platform is constructed to break through the barriers to factor circulation; (3) A digital financial credit reporting system is developed to guide capital flows into the field of low-carbon technologies. This composite mechanism of "technological innovation - model transformation - factor reorganization" ultimately forms a multiplier effect on the synergistic effect of pollution prevention and carbon emission reduction. It also effectively resolves the contradiction between fairness and efficiency for enterprises, promotes the transformation of traditional manufacturing industries into knowledge-intensive industries, enhances the market competitiveness of traditional industries, and thus contributes to the optimization and

upgrading of the industrial structure^[22].

Based on this, this paper proposes the following hypothesis regarding the transmission mechanism:

Hypothesis 3: The digital economy significantly promotes the advanced evolution of the industrial structure through the dual paths of "digital industrialization → cultivation of technology-intensive industries" and "industrial digitization → green transformation of traditional industries", and then drives the synergistic effect of pollution reduction and carbon emission reduction through the composite mechanism of optimizing the energy consumption structure and diffusing pollution control technologies.

2.2.3 Public Environmental Oversight

The development of digital technologies provides a new interactive paradigm for public participation in the coordinated governance of pollution prevention and carbon emission reduction. Its mechanism of action is mainly reflected in the following two aspects: First, digital technologies accelerate the speed of information dissemination and increase public attention to environmental issues, thereby awakening social awareness of environmental protection. This exerts pressure on the government's environmental protection policies and enterprises' investments in the field of green technologies. Second, when making investment decisions, as public awareness of environmental protection improves, investors are more inclined to allocate funds to environmentally friendly enterprises. This, to some extent, alleviates the financing difficulties faced by green enterprises and encourages them to carry out green technological innovation, thus playing a regulatory role in the synergistic effect of pollution reduction and carbon emission reduction. Although the direct impact of the public on the synergistic effect of pollution reduction and carbon emission reduction is relatively small, with the government's active promotion of public participation in environmental protection activities and the emergence of digital financial products such as "Ant Forest" on Alipay, the ways and forms of public participation in environmental governance are gradually increasing, and people's environmental awareness is being gradually translated into specific actions^[23]. For example,

many citizens choose to walk instead of using transportation means for commuting in order to accumulate forest energy. Digital technologies possess characteristics such as openness, convenience, and entertainment value in terms of public participation in environmental protection, which can significantly reduce the institutional barriers and implementation costs for the public to participate in environmental governance.

Based on this, this paper proposes the following hypothesis regarding the transmission mechanism:

Hypothesis 4: The digital economy enhances the synergistic effect of pollution reduction and carbon emission reduction through the dual mediating paths of improving the effectiveness of public environmental supervision and increasing the willingness of the public to participate in low-carbon behaviors.

3. Research Design

3.1 Model Specification

3.1.1 Baseline Regression Model

To verify the mechanism of the development of the digital economy on the synergistic effect of pollution reduction and carbon emission reduction, based on the dynamic panel data of the nine provinces in the Yellow River Basin from 2012 to 2022, this paper constructs the following two-way fixed effects model:

$$Se_{it} = \alpha_0 + \alpha_1 dig_{it} + \alpha_2 controls_{it} + \mu_i + \vartheta_t + \varepsilon_{it} \quad (1)$$

In Equation (1): Se_{it} denotes the pollution-carbon synergy efficiency of city i in period t ; dig_{it} represents the digital economy development level of city i in period t ; $controls_{it}$ denotes a set of control variables, including population density (Ln pd), urbanization level (UI), human capital level (Hucap), financial development degree (Fdd), science and education expenditure level (Se), and industrial upgrading level (Iu); α_0 , α_1 , α_2 are parameters to be estimated; μ_i captures city fixed effects; ϑ_t captures time fixed effects; ε_{it} denotes the random disturbance term.

3.1.2 Mediation Effect Model

Based on theoretical analysis, this study empirically examines the mechanisms through which the digital economy influences pollution-carbon synergy, focusing on three dimensions: green technological progress, industrial structure upgrading, and public environmental oversight.

Drawing on the mediation effect testing methods proposed by Wen Zhonglin et al.²⁴, the following mediation models are constructed:

$$M_{it} = \beta_0 + \beta_1 dig_{it} + \beta_2 controls_{it} + \mu_i + \theta + \varepsilon_{it} \quad (2)$$

$$SE_{it} = \alpha_3 + \alpha_4 dig_{it} + \alpha_5 M_{it} + \alpha_6 controls_{it} + \mu_i + \theta + \varepsilon_{it} \quad (3)$$

In Equations (2) and (3): Equation (2) captures the impact of the digital economy on the mediator variables. Equation (3) examines the combined effects of the digital economy and mediator variables on pollution-carbon synergy. M_{it} denotes the mediator variables: green technological progress (Inn), industrial structure upgrading (Ind), and public environmental oversight (Bdidx). $\beta_0, \beta_1, \beta_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$, represent parameters to be estimated. If $\beta_1, \alpha_4, \alpha_5$ are statistically significant, it indicates that the digital economy influences pollution - carbon synergy through these mediator variables.

3.2 Variable Specification

3.2.1 Dependent Variables

Currently, China faces the dual challenges of atmospheric pollution control and greenhouse gas emission reduction. Given that environmental pollutants and carbon emissions share common sources, promoting their synergistic governance holds significant practical importance and urgency. To quantitatively assess emission reduction effects, this study adopts SO₂ emission intensity (SEI), defined as the ratio of urban SO₂ emissions to GDP, and CO₂ emission intensity

(CEI), defined as the ratio of urban CO₂ emissions to GDP, to characterize the mitigation effects of air pollutants and greenhouse gases, respectively. To further quantify the synergistic effect of pollution and carbon reduction at the city level, this study constructs a Pollution-Carbon Reduction Level (PCR) indicator, represented by the interaction term of SO₂ emission intensity and CO₂ emission intensity. Since both indicators are inverse metrics (where higher values indicate poorer performance), their multiplicative term comprehensively reflects the overall emission reduction outcomes. This approach aligns with the systemic characteristics of coordinated pollution-carbon governance, as it captures the intertwined nature of these dual objectives²⁵. The specific formulas are as follows:

$$PCR = SEI \times CEI \quad (4)$$

3.2.2 Explanatory Variable

The digital economy development index serves as the core explanatory variable. Drawing on the research framework of Zhao et al.²⁵ and considering data availability, this study constructs an evaluation index system for digital economy development levels from two dimensions: digitalization input and digitalization output. Four secondary indicators were selected to establish this system, and the entropy method was employed to measure its development level. The specific evaluation index system for digital economy development is presented in Table 1.

Table 1: Digital Economy Development Level Evaluation Indicator System

first-level index	Second-level index	Third-level index	Unit	Criterion Attribute
Digitalization Investment	Digital Infrastructure	Number of Internet access ports	10,000 units	+
		Number of Internet broadband access subscribers	10,000 households	+
		Number of domain names	10,000 units	+
		Mobile base station density	units/km ²	+
		Mobile phone penetration rate	units/100 ppl	+
		Long-distance optical cable length per unit area	10,000 units/km	+
	Digital Innovation Capability	Full-time equivalent of R&D personnel in large-scale industrial enterprises	person-years	+
		R&D expenditure in large-scale industrial enterprises	10,000 yuan	+
		Number of R&D projects	items	+

		(topics) in large-scale industrial enterprises		
		Total value of technology contracts concluded	10,000 yuan	+
		Number of patents granted	items	+
Digitalized Outcome	Digital Industrialization	Software business revenue as a percentage of GDP	%	+
		Information technology service revenue as a percentage of GDP	%	+
		Number of employees in the information service industry	10,000 people	+
		Telecommunications business volume as a percentage of GDP	%	+
	Industrial Digitalization	Proportion of Enterprises with E-commerce Transaction Activities	%	+
		Share of Enterprise E-commerce in GDP	%	+
		Number of Computers per 100 Employees in Enterprises	people	+
		Number of Websites per 100 Enterprises	unit	+
		Digital Inclusive Finance Index	/	+

3.2.3 Mediator Variables

Based on the theoretical framework of new structural economics, this paper constructs an index system of triple effects: (1) Technological innovation effect is measured by the number of authorized green utility model patents. This index reflects the actual application level of environmentally friendly technologies such as clean production technologies and carbon capture technologies; (2) Industrial structure effect is constructed by taking the natural logarithm of the weighted sum of the proportions of the three industries (with a weight of 1 for the primary industry, 2 for the secondary industry, and 3 for the tertiary industry). This index reflects the characteristics of the advanced evolution of the industrial structure; (3) Public supervision effect uses the annual search volume data of the keyword "environmental pollution" from the Baidu Index platform. After standardization processing, it reflects the degree of public concern about environmental issues. Among them, the green patent data comes from the patent database of the National Intellectual Property Administration, the industrial structure data is sourced from the China Statistical Yearbook, and the search index data is obtained through the Baidu Index API interface.

3.2.4 Control Variables

Population density (Ln_{pd}): Measured by the logarithmic transformation of the geometric mean of the number of permanent residents and the built-up area, reflecting the impact of regional population distribution on environmental pressure.

Urbanization level (U_I): Measured by the proportion of urban population to total population, which reflects the environmental impact of spatial agglomeration effects.

Human capital level (H_{ucap}): Represented by the proportion of tertiary education students, reflecting the supportive role of education levels in technological innovation.

Financial development degree (F_{dd}): Constructed as a financial deepening index (the ratio of deposits and loans of financial institutions to GDP), measuring the impact of capital allocation efficiency on green investment.

Science and education expenditure (S_e): Represented by the proportion of government expenditure on science and technology in total fiscal expenditure, reflecting the guiding role of government R&D investment in technological progress.

Industrial upgrading level (I_u): Measured by the

proportion of secondary industry added value to GDP, reflecting the intensity of environmental regulation during the industrialization process.

3.4 Data Sources

Based on the principle of panel data integrity, this study constructs a dynamic panel dataset for the nine provinces in the Yellow River Basin. (1) The spatial scope is limited to the nine provinces specified in the Plan for Ecological Protection and High-Quality Development in the Yellow River Basin; (2) The time span is set as 2012–2022 to match the statistical cycle of core digital economy indicators (e.g., digital infrastructure index); (3) To meet data integrity requirements, after addressing missing values through multiple imputation, samples with a missing rate exceeding 15% for key variables (e.g., green patent authorizations, digital economy development index) are excluded. The final dataset is an unbalanced panel containing 11 annual observations and 9 provincial units. SO₂ emission data are sourced from the China Urban Statistical

Yearbook. CO₂ emissions are calculated using the IPCC method (a standard approach developed by the Intergovernmental Panel on Climate Change for estimating greenhouse gas emissions such as CO₂ from energy consumption, based on measured and calculated data of energy use), with relevant data drawn from the China Energy Statistical Yearbook and the China CO₂ Accounting Database (CEADS). The digital inclusive finance index in the digital economy level indicators is obtained from the Peking University Digital Inclusive Finance Index, while other data are from the China Statistical Yearbook. Interpolation methods are used to supplement partial missing values.

4 Empirical Results and Discussion

4.1 Baseline Regression Analysis

As shown in Table 2, the baseline regression model demonstrates the statistically significant influence of digital economy development on the co-benefits of pollutant emission reduction and carbon mitigation.

Table 2 Baseline Regression Results

Variables	(1)	(2)
Digital	11.53** (4.12)	23.64***(3.177)
lnpd		-5.002(5.390)
UI		-67.48***(10.21)
Hucap		132.6(70.43)
Fdd		-1.951***(0.333)
Se		40.98*(20.41)
Iu		-0.0809**(0.0236)
_cons	2.116*** (6.51)	63.83*(24.60)
N	99	99
R ²	0.269	0.847
Province	Yes	Yes
Year	Yes	Yes

Note: Robust standard errors are reported in parentheses; *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. The same applies hereafter.

This study employs a two-way fixed effects model to validate the environmental synergistic governance efficiency of digital economy development. The regression results (Column 1 of Table 1) show that the regression coefficient of the digital economy level is significantly positive at the 5% significance level. After adding control variables, the regression results (Column 2 of Table 1) are significant at the 1% level, indicating

that the digital economy has a statistically significant positive driving effect on the synergistic efficiency of pollution reduction and carbon emission reduction, supporting the core assertion of Hypothesis 1.

In addition, the urbanization level (UI) shows a negative correlation at the 1% significance level, suggesting that the improvement of the urbanization level has, to some extent, inhibited

pollution reduction and carbon emission reduction. The reason may be that when promoting economic development, various regions actively advance the urbanization process. However, a higher urbanization level poses a certain threat to regional pollution reduction and carbon emission reduction. For example, industries with high pollution, high energy consumption, and high emissions may be introduced. The degree of financial development (Fdd) is significantly negative at the 1% level. Financial development usually implies an increase in economic activities and more efficient use of resources. However, this development is often accompanied by an increase in energy consumption, leading to an increase in pollutants and a rise in carbon emissions. The level of science and education expenditure (Se) is significantly positive at the 10% level, indicating that the support and emphasis on science and education can play a positive role in promoting pollution reduction and carbon emission reduction. The reason for this result may be that the focus on science and education can provide necessary research and development funds for research institutions and enterprises, promoting

innovation in fields such as clean production technology, energy-saving technology, and environmental protection technology. The research, development, and application of these technologies help reduce energy consumption and carbon emissions.

4.2 Mechanism Analysis

Based on the synergistic governance effect of the digital economy verified by the benchmark regression, this study further employs the non-parametric Bootstrap method (with 500 repeated samplings) to test the statistical significance of the three transmission paths, namely the progress of green technologies, the upgrading of the industrial structure, and public environmental supervision. Based on the synergistic governance effect of the digital economy verified by the benchmark regression, this study further employs the non-parametric Bootstrap method (with 500 repeated samplings) to test the statistical significance of the three transmission paths, namely the progress of green technologies, the upgrading of the industrial structure, and public environmental supervision.

Table 3 Bootstrap Mediation Test Results

Variables	(1) Green Technological Progress	(2) Industrial Structure Upgrading	(3) Public Environmental Supervision
Bootstrap Test	0.44*	1.56**	0.05*
Confidence Interval	[0.02,1.29]	[0.36,2.27]	[0.005,0.63]

First, this study constructs a transmission path model of "digital economy development → green technological progress → synergistic effect of pollution reduction and carbon emission reduction." Column (1) of Table 3 reports the results of the Bootstrap mediation test, where the Bootstrap test value for green technological progress is 0.44, with a confidence interval of [0.02, 1.29]. The results show a positive relationship between digital economy and the synergistic effect at the 10% significance level. This indicates that the digital economy exerts a positive impact on the synergistic effect of pollution reduction and carbon emission reduction by promoting green technological progress, which supports Hypothesis 2. The digital economy accelerates information circulation, reduces

technological R&D costs, and improves innovation efficiency, thereby fostering green technological progress and providing strong support for pollution reduction and carbon emission reduction.

Second, this study constructs a transmission path model of "digital economy development → advanced evolution of industrial structure → synergistic effect of pollution reduction and carbon emission reduction." The Bootstrap test value for industrial structure upgrading is 1.56, with a confidence interval of [0.36, 2.27], which is significantly positive at the 5% significance level. The digital economy, driven by the twin forces of digital industrialization and industrial digitization, promotes the optimization and upgrading of industrial structure, reduces dependence on fossil

energy, facilitates the clean transformation of energy consumption structure, and thereby enhances the synergistic effect of pollution reduction and carbon emission reduction. This finding supports Hypothesis 3.

Finally, this study constructs a transmission path model of "digital economy development → enhanced public environmental supervision effectiveness → synergistic effect of pollution reduction and carbon emission reduction." Column 3 of Table 3 shows that the Bootstrap test value is 0.05, with a confidence interval of [0.005, 0.63], which is also significantly positive at the 10% significance level. The digital economy lowers the thresholds and costs for public participation in environmental governance, enhances public awareness of environmental protection, and broadens avenues for public engagement in environmental governance through channels such as digital financial products, thereby strengthening public supervision over the synergy between pollution reduction and carbon emission reduction. This result supports Hypothesis 4.

4.3 Robustness

To validate the reliability of the benchmark regression results, this study conducts robustness tests using two methods based on the time-lag effect characteristics of the dynamic panel model. First, considering the lagged impact of the digital economy, the study tests with the core explanatory variable lagged by one period (Column 1 of Table 4). The results show that the coefficient of the digital economy development level is significantly positive at the 1% significance level, indicating a significant intertemporal driving effect of the digital economy on the synergistic effect of pollution reduction and carbon emission reduction. Meanwhile, addressing potential disturbances in the policy environment caused by the exogenous shock of the COVID-19 pandemic that emerged in 2020, the study identifies outliers through a t-test and excludes data from 2021–2022 (Column 2 of Table 4). The estimation results show that the digital economy coefficient remains significant at the 1% level. This finding not only aligns with the causal inference logic of dynamic panel data but also reinforces the policy implications of the digital economy's synergistic governance effect through the exogenous shock test.

Table 4 Robustness Test Results

Variables	(1) (Lagged by One Period)	(2) (Excluding Last Year)
L.Digital	24.594***(7.36)	
Lnpd	-9.429(-1.64)	1.804(0.20)
UI	-59.522***(-4.82)	-75.105***(-5.08)
Hucap	93.472(1.19)	109.969(0.97)
Fdd	-1.715***(-5.07)	-1.717***(-3.67)
Se	33.115*(1.72)	2.353(0.06)
Iu	-0.080***(-4.04)	-0.079**(-2.57)
Digital		27.486***(4.62)
Observations	90	81
R ²	0.875	0.927
Province	Yes	Yes
Year	Yes	Yes

4.4 Heterogeneity

The emerging economic paradigm dominated by data factors drives the synergistic effects of

environmental governance to exhibit characteristics of regional gradient differentiation through multi-level transmission mechanisms. The regression results are presented in Table 5.

Table 5 Heterogeneity Test Results

Variables	(1) (Low-Economy)	(2) (High-Economy)	(3) (Low-Density)	(4) (High-Density)

	Group)	Group)	Group)	Group)
Digitl	-9.1116	6.4556***	116.5571**	0.0230
	(-0.2607)	(9.4614)	(2.0842)	(0.0134)
Ln pd	1.3663***	-0.2032**	1.9841***	0.3919**
	(3.3395)	(-2.4917)	(4.0991)	(2.0314)
Ul	-26.4015***	-6.8375***	-22.7868**	-0.4793
	(-3.9691)	(-9.8104)	(-2.7616)	(-0.2372)
Hucap	-4.1e+02***	117.5754***	-5.3e+02***	59.4395***
	(-3.2703)	(16.0910)	(-3.9060)	(2.8442)
Fdd	-1.6005***	-0.1791*	-0.5771	0.8261***
	(-3.0931)	(-1.7889)	(-0.9221)	(3.2060)
Se	-25.0503	1.6399	-69.3324	14.0414
	(-0.3736)	(0.4288)	(-0.8950)	(1.0875)
Iu	-0.0091	-0.0194**	0.0734	-0.0022
	(-0.1660)	(-2.5129)	(1.0581)	(-0.1113)
_cons	22.8440***	3.6862***	10.2537	-4.3520**
	(4.3713)	(5.0174)	(1.6596)	(-2.3961)
N	55	44	55	44
R ²	0.7147	0.9477	0.7857	0.6367

4.4.1 Heterogeneity with economic development Level

Based on the 2022 regional gross domestic product (GDP) data officially released by each province, a median grouping method is used to construct an analytical framework for economic level heterogeneity. Specifically, using the median GDP of 3.28 trillion yuan (the value corresponding to Shaanxi Province) among the nine provinces as the threshold, provinces with a GDP exceeding 3.28 trillion yuan (Shanxi, Sichuan, Henan, Shandong) are classified into the high-economic-level region group, while those with a GDP of ≤ 3.28 trillion yuan (Qinghai, Ningxia, Gansu, Inner Mongolia, Shaanxi) are classified into the low-economic-level region group. A grouped regression model is employed to systematically examine the heterogeneity of core driving factors and their influence mechanisms across different economic gradient regions.

The results show that the digital economy has a more pronounced effect in high-economic-level regions compared to low-economic-level regions. One possible reason for this result is that high-economic-level regions possess more complete digital economy infrastructure, such as high-speed networks and data centers, which provide favorable conditions for the application of digital technologies. Meanwhile, these regions also have

relatively advanced digital technology development levels, enabling more effective use of technologies such as big data, cloud computing, and artificial intelligence for environmental monitoring, management, and governance—thereby improving the efficiency of pollution reduction and carbon emission reduction. In contrast, low-economic-level regions lag behind in digital economy infrastructure and technological capabilities, limiting the application of digital technologies in pollution and carbon reduction. This explains why the effects of pollution reduction and carbon emission reduction are less evident in these areas.

4.4.2 Heterogeneity with Geographic Spatial

Using the 2022 population and geographic spatial data of the nine provinces in the Yellow River Basin, an analytical framework for regional heterogeneity is constructed based on the mean of geographically weighted population density. By calculating the basin-wide average population density (total population/total area = 117.85 persons per square kilometer) as the classification threshold, the nine provinces are divided into two spatial clusters: the high-density group (Henan, Shandong, Shanxi, Shaanxi, Sichuan) with a population density ≥ 117.85 persons/km² and the low-density group (Gansu, Inner Mongolia, Qinghai, Ningxia) with a population density < 117.85 persons/km². This double-sample

classification strategy aims to reveal the coupling relationship between population agglomeration characteristics and regional development factors through a spatial heterogeneity model.

The regression results show that the impact of digital economy development on the synergistic effect of pollution reduction and carbon emission reduction exhibits significant population density threshold characteristics. One possible reason for this result is that high-population-density areas often face rigid constraints in industrial structure, energy structure, and other aspects, making adjustments more difficult. In contrast, low-population-density areas have greater room for adjustment in industrial and energy structures, making it easier to achieve pollution and carbon reduction through measures such as optimizing industrial structure and developing clean energy. Secondly, in low-population-density regions, the relatively smaller population and slower pace of life facilitate the cultivation and enhancement of public environmental awareness. Meanwhile, high-population-density areas face greater challenges in fostering public environmental awareness due to their large populations and fast-paced lifestyles.

5 Conclusions and Suggestions

5.1 Conclusions

Based on panel data from nine provinces in the Yellow River Economic Belt spanning 2012–2022, this study systematically investigates the impact of the digital economy on the synergistic effects of pollution reduction and carbon mitigation, along with its underlying mechanisms. Through theoretical analysis and empirical verification, the following key conclusions are drawn:

(1) The digital economy significantly promotes synergistic pollution reduction and carbon mitigation. Empirical results demonstrate that digital economy development exerts a statistically significant positive impact on the synergistic effects of pollution reduction and carbon mitigation in the Yellow River Economic Belt. Through its efficient, green, and sustainable characteristics, the digital economy enhances government governance efficiency, optimizes enterprise production efficiency, and drives the green transformation of residents' lifestyles—thereby effectively facilitating the coordinated

reduction of air pollutants and greenhouse gases. This finding validates Hypothesis 1, confirming that the digital economy can promote synergistic pollution reduction and carbon mitigation effects.

(2) The digital economy promotes the synergy between pollution reduction and carbon emission reduction through multiple mechanisms. Further analysis reveals three key mechanisms by which the digital economy achieves this synergy:

Green Technological Progress: The vigorous development of the digital economy restructures the configuration of innovation factors. By enabling the rapid flow of information elements and continuously reducing the marginal cost of technological R&D, it significantly enhances the operational efficiency of the green technology R&D system. The new talent demands generated by the digital economy drive the upgrading of human capital quality, forming a virtuous cycle between technological iteration and talent optimization. Such structural changes provide new momentum to break through bottlenecks in environmental governance technologies, particularly driving revolutionary progress in the coordinated governance of carbon pollutants. This mechanism validates Hypothesis 2.

Industrial Structure Upgrading: Digital industrialization has given rise to technology-intensive industrial clusters such as big data centers and artificial intelligence, increasing the share of core digital economy industries and weakening the path dependence of economic growth on fossil energy. Industrial digitization, through industrial internet platforms, reconstructs production processes, reducing energy consumption per unit of added value in key industries and increasing the proportion of clean energy consumption. The synergistic effect between the low-carbon transformation of energy consumption structure and the diffusion of pollution control technologies ultimately enhances the efficiency of coordinated pollution and carbon reduction governance. Driven by the twin forces of digital industrialization and industrial digitization, the digital economy promotes the optimization and upgrading of industrial structure, reduces dependence on fossil energy, guides energy consumption toward clean energy, and thereby enhances the synergistic effect of pollution and carbon reduction. This conclusion supports Hypothesis 3.

Public Environmental Supervision: The development of digital technologies lowers the thresholds and costs for public participation in environmental governance, enhances public awareness of environmental protection, and broadens avenues for public engagement through channels such as digital financial products—thereby strengthening public supervision over the synergy between pollution reduction and carbon emission reduction. This mechanism validates Hypothesis 4.

(3) The synergistic effect of pollution reduction and carbon emission reduction driven by the digital economy exhibits significant spatial gradient characteristics. Specifically, compared to low-economic-level regions, the digital economy has a more pronounced effect in high-economic-level regions. Geographically, the digital economy demonstrates a more significant synergistic effect on pollution and carbon reduction in low-population-density areas, while its impact on high-population-density areas is less significant. This conclusion reflects the complexity and diversity of the digital economy's role in promoting pollution-carbon reduction synergy.

In conclusion, this paper constructs a three-dimensional collaborative analytical framework of "technological innovation—industrial upgrading—public supervision," revealing that the digital economy enhances the synergistic governance efficiency of pollution and carbon reduction through the composite action mechanisms of technological innovation cost inhibition, industrial structure optimization, and public environmental supervision effects. It also deeply explores the heterogeneity of these impacts across different regions. These findings provide important theoretical foundations and practical guidance for high-quality development and high-level environmental protection in the Yellow River Economic Belt and nationwide.

5.2 Policy Suggestions

Based on the above research findings, this paper proposes the following countermeasures and suggestions:

First, strengthen digital infrastructure construction to consolidate the foundation for collaborative governance. By increasing investment and construction efforts in new digital infrastructure such as 5G networks, big data centers, and

industrial internet across the Yellow River Basin, we can promote the in-depth development of the digital economy. Special emphasis should be placed on economically underdeveloped regions to narrow the regional digital divide and significantly enhance pollution reduction and carbon mitigation synergies. For instance: Establish a "government-led + enterprise-participating" joint investment mechanism to attract social capital through special bonds and public-private partnerships (PPP). Prioritize the deployment of environmental monitoring IT networks in pastoral areas and ecologically fragile zones to construct a pan-regional coverage "digital ecological sensing network". Promote interconnection between government data platforms and enterprise environmental protection data systems to establish a dynamic database of "dual-source inventories" for carbon emissions and pollutants.

Second, construct a three - dimensional driving system of "technology - industry - institution" to amplify the synergistic effects. In terms of technology - driven development, a special fund for green technology research in the Yellow River Basin should be established, with a focus on supporting research and development in areas such as carbon capture, clean energy, and smart environmental protection. An integrated innovation alliance of "production, learning, research, and application" should be established. Regarding industry - driven development, a guide for the integration of the digital economy and high - energy - consuming industries should be formulated to promote the full - chain digital transformation of traditional industries such as steel and chemical industries. Pilot projects for building "zero - carbon digital industrial parks" should be carried out in cities along the Yellow River, and tax deductions should be given to enterprises that use green electricity and achieve carbon traceability. As for institution - driven development, a "digital environmental protection credit evaluation" system should be implemented. The digital performance of enterprises in pollution reduction and carbon mitigation should be included in the credit system, and differential credit policies should be implemented for green technology innovation enterprises.

Third, innovate public participation mechanisms to construct a multi-stakeholder governance

framework. First, develop a "Yellow River Eco-Guardian" public engagement app through digital channels, integrating functions such as pollution reporting, carbon footprint calculation, and green credit redemption. This initiative explores an "environmental behavior-to-digital rights" conversion mechanism to encourage broader resident participation. Furthermore, enhance public capacity through educational empowerment by establishing "digital environmental protection classrooms" in primary and secondary schools across the basin, utilizing VR/AR technologies to simulate ecological damage consequences. For farming and pastoral communities, develop multilingual digital environmental training programs to improve the engagement capabilities of residents in ecologically fragile areas.

Fourth, implement differentiated regional strategies to address heterogeneous constraints. In economically developed areas such as the Guanzhong Plain Urban Agglomeration, pilot "digital twin cities" should be established to simulate and optimize energy systems, transportation networks, and industrial layouts using digital twin technology, thereby creating an "intelligent decision-making hub" for pollution reduction and carbon mitigation. For economically underdeveloped regions, a "digital ecological compensation transfer payment" mechanism could be established, requiring beneficiary regions (e.g., downstream developed cities) to pay digital technology service fees to ecological conservation areas (e.g., upstream pastoral regions). Additionally, developing a "photovoltaic + big data" industry model would leverage the abundant solar resources in northwestern regions to construct green data center clusters.

Conflict of Interest

The authors declare no competing interests.

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