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Research on the Impact of Digital Economy on the Level of Collaborative Governance of Pollution Reduction and Carbon Abatement

-- Based on the Mediating Effect of Industrial Structure Upgrading

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Abstract

In the coordinated process of advancing the construction of "Digital China, the digital economy is increasingly becoming an important force supporting high-quality development. Simultaneously, it provides an innovative approach to addressing the synergistic issues between traditional pollution control and carbon emission reduction. This study, based on panel data from 266 Chinese cities from 2014 to 2023, examines how the development of the digital economy affects the synergistic governance of pollution control and carbon emission reduction. To explore its potential mechanisms, this study incorporates industrial structure upgrading as a mediating factor in the analysis. This paper employs a two-way fixed effects model combined with a mediating effect framework. The study concludes that the development of the digital economy significantly improves the synergistic governance of pollution control and carbon emission reduction. Mechanism analysis shows that industrial structure upgrading plays a significant mediating role in this relationship. Further heterogeneity analysis reveals that the positive impact of the digital economy is more significant in resource-based cities and cities with relatively low levels of economic development. This study provides empirical evidence at city level, illustrating how the digital economy promotes coordinated pollution and carbon control. Furthermore, this study provides policy implications for promoting the development of the digital economy and optimizing industrial structure.

Keywords

Digital Economy; Pollution Reduction and Carbon Mitigation; Industrial Structure Upgrading; Mediating Effect.

1. Introduction

Carbon dioxide and pollutant emissions pose long-term threats to ecosystem balance and human health, and human beings still face severe environmental governance pressure. Data from the International Energy Agency (2024)[10] shows that China's carbon dioxide emissions from fuel combustion reached 11.13 billion tons in 2023. Data from the Ministry of Ecology and Environment of China (2024)[18] indicates that approximately 40.1% of Chinese cities failed to meet national ambient air quality standards in 2023. Against this backdrop, promoting coordinated governance of pollution reduction and carbon emission reduction has become an important policy path and a necessary strategic choice for alleviating environmental constraints. The Intergovernmental Panel on Climate Change (2023)[11] explicitly emphasized that the world must accelerate emission reduction efforts. The State Council of the People's Republic of China (2026)[23] further proposes to continuously deepen synergistic pollution reduction and carbon mitigation, multi-pollutant synergistic control and regional synergistic governance. Coordinated governance is widely considered a key pathway to achieving this goal.

Digital economy injects new momentum into economic growth and provides an important pathway for promoting coordinated governance of pollution reduction and carbon emission reduction (Han et al., 2025)[7]. Digital technology is a crucial driver of urban low-carbon transformation, enhancing environmental oversight and optimizing energy and resource allocation to effectively improve the synergistic efficiency of pollution control and carbon reduction (Che et al., 2026)[2]. Digital transformation promotes industrial transformation towards high-end green development through multiple channels, including scale expansion, improving position in global value chains, and optimizing energy consumption structures, thereby reducing carbon emission intensity at its source (Jin et al., 2024)[12].

Currently, digital economy, pollution and carbon reduction have attracted widespread attention in academia. Regarding digital economy, existing research mainly explores its measurement methods and development levels (Hou et al., 2025; Li et al., 2025)[9,16], multi-dimensional collaborative governance models (Du & Hou, 2026; He et al., 2025)[5,8], and its economic and environmental impacts (Li & Yang, 2026; Wang & Wang, 2025)[13,24]. Previous studies about pollution and carbon emission reduction have primarily assessed the governance performance (Li et al., 2026; Xiao et al., 2025)[14,29], explored regional collaborative governance networks (Sun et al., 2025; Zhang et al., 2025)[23,30], and identified key influencing factors and mechanisms (Liang et al., 2024; Wang et al., 2025)[17,26]. However, some gaps remain. Existing research has not clearly elucidated the specific pathways through which the digital economy impacts environmental governance, and ignore industrial upgrading in this process. In practice, digital economy can improve resource allocation efficiency (Shen et al., 2024)[20]. Simultaneously, industrial upgrading helps eliminate outdated production capacities with high pollution, promotes the development of green and low-carbon industries, and provides support for the coordinated governance of pollution reduction and carbon emissions (Ren et al., 2025)[19]. Given these shortcomings, this study mainly concerns the impact of digital economy on the coordinated governance of pollution reduction, and further investigates whether industrial upgrading plays a mediating role in this process. The findings are expected to enrich the understanding of how the digital economy empowers environmental governance.

2. Methodology and Data

2.1. Hypotheses Development

Digital economy can directly contribute to the improvement of synergistic pollution reduction and carbon mitigation governance. First, digital economy reduces carbon emissions and environmental pollution based on the innovative application of low-carbon and environmental protection technologies (Zhao et al., 2026)[33]. Second, the digital economy contributes to supply chain restructuring and strengthens collaborative linkages among upstream and downstream firms (Li & Xu, 2026)[15]. With the support of data-driven technologies, traditional supply chain systems can be reorganized and upgraded through digital means. It accurately predicts market demand on the demand side to avoid overproduction and resource waste, realizes intelligent control of production processes on the production side to reduce energy loss and pollutant emissions in production, optimizes logistics paths through intelligent scheduling on the transportation side to reduce carbon emissions in transportation, and achieves zero-inventory and low-inventory operations through digital management on the inventory side to reduce resource consumption in warehousing. Therefore, this study proposes the following hypothesis: H1: The development of the digital economy has made a significant contribution to promoting coordinated governance of pollution and carbon emission reduction.

Digital economy can reduce CO2 emissions and environmental pollutants. First, the deep integration of digital technology with high-energy-consuming industries has accelerated their intelligent transformation and green development. This process helps to improve efficiency, reduce resource dependence (Fan & Li, 2026)[6]. In addition, digital technology innovations have effectively reduced energy intensity and carbon emissions by influencing industrial structure upgrading paths such as energy resource allocation and utilization efficiency (Wang et al., 2023)[27]. In this process, the scale and composition of regional energy consumption are gradually adjusted, further promoting the rational evolution of industrial structure. Therefore, this study proposes the hypothesis: H2: Industrial structure upgrading is an intermediary mechanism through which the digital economy influences coordinated pollution reduction and carbon emission reduction governance. Schematic diagram of hypothesis is presented in Figure 1.

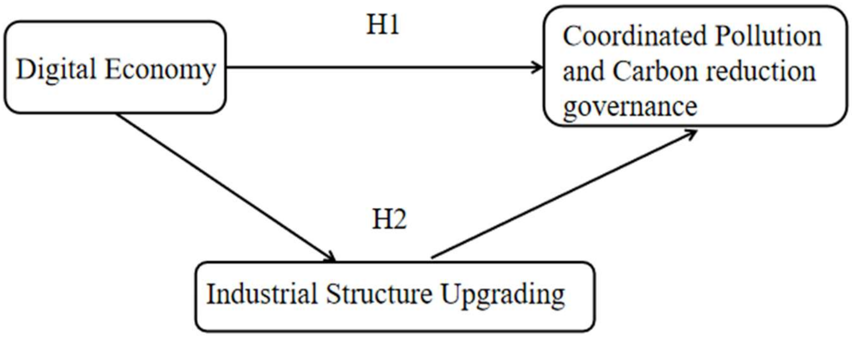

Figure 1. Research Hypothesis

2.2. Model Specification

2.2.1. Benchmark

To examine specific influence of digital economy, this study establishes a baseline regression model.

$$CPC_{it} = \beta_0 + \beta_1 DE_{it} + \sum_{k=1}^{6} \beta_k Controls_{it,k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where i denotes the city, t denotes the year, and k denotes the number of control variables. CPC represents the level of synergistic pollution reduction and carbon mitigation governance, DE represents the level of digital economy development, and Controls represents control variables, including population stock, population quality, market demand, technological level, urban-rural structure and economic development level. μ_i captures city fixed effects. λ_t represents the time fixed effect, used to control all annual-level macro shocks and policy effects that do not change with cities. ε_{it} represents the random error term. In addition, β_0 is the constant term. β_1 and $\sum_{k=1}^{6} \beta_k$ are the estimated coefficients of variables.

2.2.2. Mediating Effect Model

This study draws on the mediation analysis method proposed by Wen and Ye (2014)[28] and incorporates industrial structure upgrading into the empirical framework to further identify the potential mechanisms within digital economy, coordinated emission reduction and pollution control.

Specifically, the first step examines whether digital economy development exerts a significant influence on industrial structure upgrading. The corresponding model is presented in Equation (2):

$$ISU_{it} = \alpha_0 + \alpha_1 DE_{it} + \sum_{k=1}^{6} \alpha_k Controls_{it,k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Where ISU denotes industrial structure upgrading, α_0 represents the constant term, while α_1 and $\sum_{k=1}^{6} \alpha_k$ indicate the estimated coefficients of digital economy and control variables, respectively.

Then, test direct effect and mediating effect, as shown in Formula (3):

$$CPC_{it} = \gamma_0 + \gamma_1 DE_{it} + \gamma_2 ISU_{it} + \sum_{k=1}^{6} \gamma_k Controls_{it,k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Where γ_0 is the intercept term in the three effects, and γ_1, γ_2 and $\sum_{k=1}^{6} \gamma_k$ are the estimated coefficients of the variables.

2.3. Variable Measurement

2.3.1. Explained Variable

The dependent variable is the level of synergistic pollution reduction and carbon mitigation governance. To quantify this variable, this paper uses a coupling coordination degree model to calculate the degree of coordination between pollution reduction and carbon reduction. Specific measurement procedure is described as follows:

Dependent variable is the level of coordinated governance between pollution reduction and carbon reduction. To quantify this variable, this paper uses a coupling coordination degree model.

(1) Calculation of scores of the two subsystems of the carbon mitigation subsystem and the pollution reduction subsystem

Carbon mitigation subsystem, denoted as U_1, is measured by carbon dioxide emissions, which reflects regional carbon reduction performance and the level of low-carbon development. U_2 is the pollution reduction system, adopting the Air Quality Index (AQI). The measured concentrations of six pollutants including PM2.5, PM10, SO2, NO2, O3 and CO in the region in that year are selected, the corresponding air quality index of each is calculated separately, and the maximum value of the six indices is taken as the AQI of the region in that year. Since the indicators in the two subsystems differ in measurement units and directional attributes, the original data are standardized using the range standardization method. The formulas are shown as follows:

Positive indicator:

$$y_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (4)$$

Negative indicator:

$$y_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (5)$$

(2) Calculate the coupling degree (C), as shown in Formula (6):

$$C = 2 * \left[\frac{(U_1 * U_2)}{(U_1 + U_2)^2}\right]^{1/2} \quad (6)$$

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(3) Calculate the comprehensive development index (T), as shown in Formula (7):

$$T = aU_1 + bU_2 \tag{7}$$

Where a and b are weight coefficients, both set to 0.5 in this paper.
(4) Calculate the coupling coordination degree (CCD), presented in Formula (8):

$$CCD = \sqrt{C \times T} \tag{8}$$

The value range of CCD is [0,1]. A higher value indicates a stronger coordination relationship between the pollution reduction subsystem and the carbon mitigation subsystem, and reflects a higher level of synergistic governance.

2.3.2. Core Explanatory Variable

The main explanatory variable is the level of digital economy development. Drawing on the research of Hou et al. (2025)[9] and Li et al. (2025)[16], this study constructs an evaluation framework that includes four dimensions. Detailed indicators are reported in Table 1.

Table 1. Digital Economy Indicator

First-level Indicator	Second-level Indicator	Unit
Digital Infrastructure	Internet Penetration Rate	%
	Mobile Phone Penetration Rate	%
Digital Industrialization	Number of Employees in Information Transmission, Software and Information Technology Services	Ten thousand persons
Industrial Digitalization	Digital Inclusive Finance Index	Dimensionless
Digital Innovation Capability	Technology Contract Transaction Volume	Ten thousand yuan
	Total Patent Grants	Item

This study employs the entropy-weighted TOPSIS method, which combines objective indicator weighting with multi-criteria decision analysis. Specifically, firstly, the entropy-weighted method is used to assign weights to each indicator based on the degree of information variation in the data. Then, the TOPSIS method is applied to measure the relative closeness of each city to the positive and negative ideal solutions, thereby generating a comprehensive digital economy development index.

Compared with subjective weighting methods such as expert scoring, the entropy weight-TOPSIS method can effectively reduce potential bias arising from human judgment. Moreover, by assessing the relative distance between each sample and the ideal reference points, this method enhances the comparability and interpretability of digital economy development levels across different cities.

2.3.3. Mediating Variable

Industrial structure upgrading, represented by ISU, is the mediating variable. Based on the Petty-Clark Theorem, industrial evolution during economic development is typically characterized by a gradual decline in the relative contribution of the primary industry and a corresponding increase in the shares of the secondary and tertiary industries (An et al., 2025)[1]. Accordingly, this paper constructs the industrial structure upgrading index by assigning weights to the GDP shares of the three industries.

$$ISU_{it} = 1 \times W_{1it} + 2 \times W_{2it} + 3 \times W_{3it} \quad (9)$$

Where W_{1it}, W_{2it} and W_{3it} denote the respective proportions of value added from the primary, secondary, and tertiary industries in regional GDP. Referring to An et al. (2025)[1], weights of 1, 2, and 3 are assigned to the three industries in sequence. A higher weight indicates a higher level of industrial technology intensity and added value. Higher weights indicate greater contribution of industrial technology intensity and added value.

2.3.4. Control Variables

This study controlled for six factors: population size, population quality, market demand, technological level, urban-rural structure, and economic development level. Considering the research of Ding et al. (2024)[4], Zhang et al. (2024)[32], and Zhao et al. (2026)[33], these variables were selected to better identify the net effect. Specific information is presented in Table 2.

Table 2. Specific Information of Control Variables

Variable	Indicator	Description
Population Stock (PS)	Registered Population Size (10,000 persons)	Reflects the total regional population and basic carrying pressure, affecting energy consumption, pollutant emissions and carbon emissions, and is a basic constraint for environmental governance.
Population Quality (PQ)	Proportion of Higher Education Population (%)	Reflects the knowledge reserve and environmental protection awareness of regional residents. A high level of human capital helps promote green consumption preferences and low-carbon technology adoption.
Market Demand (MD)	Total Imports (CNY)	Reflects the intensity of regional consumption demand for external goods and services. Changes in import demand indirectly affect domestic production structure and energy consumption structure, affecting regional environmental governance.
Technological Level (STL)	R&D Expenditure (CNY)	Technological investment is an important guarantee for the R&D of clean production technology, pollution control technology and low-carbon technology.
Urban-Rural Structure (URS)	Urbanization Rate (%)	Depicts the regional urban-rural development pattern. The urbanization process reshapes energy consumption structure, pollutant emission characteristics and environmental governance model.
Economic Development Level (EDL)	Per Capita GDP (CNY)	Differences in regional economic development stages should be controlled.

2.4. Data Sources

The empirical analysis is based on panel data for 266 prefecture-level cities in China from 2014 to 2023. The dataset is compiled from several official and authoritative databases and statistical publications, including EDGAR, the China Environmental Monitoring Station, the State Intellectual Property Office and statistical information released by local statistical authorities.

3. Results

3.1. Descriptive Statistics

In order to preliminarily examine the statistical distribution and fluctuation characteristics of the variables used in the empirical analysis, this study presents descriptive statistics in Table 3.

Table 3. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
SPC	2660	0.892	0.06	0	0.99
DE	2660	0.039	0.064	0.004	0.862
PS	2660	453.5	330.244	20.25	3416
PQ	2660	221.812	267.858	2.117	2034.597
MD	2660	50331.506	214521.93	0.068	3082763.4
STL	2660	163463.37	483741.31	753	5549817
URS	2660	0.597	0.139	0.246	1
EDL	2660	62587.584	34395.043	11214	264699

3.2. Evolution Trend

Using Stata 14.0, this study conducts kernel density estimation for the sample years of 2014, 2017, 2020, and 2023. The estimation are presented in Figure 2, which suggest that the peak of the curve for digital economy gradually increases over time, while the distribution center moves continuously to the right. This suggests that China's urban digital economy has maintained a steady upward trend. With the wider application and diffusion of digital technologies, the initial disparities among regions have been gradually reduced. Meanwhile, the distribution range of the kernel density curve tends to narrow, indicating that the differences in governance levels among sample cities have declined. Overall, the distribution pattern becomes more concentrated and balanced, reflecting a gradual convergence in regional synergistic governance performance.

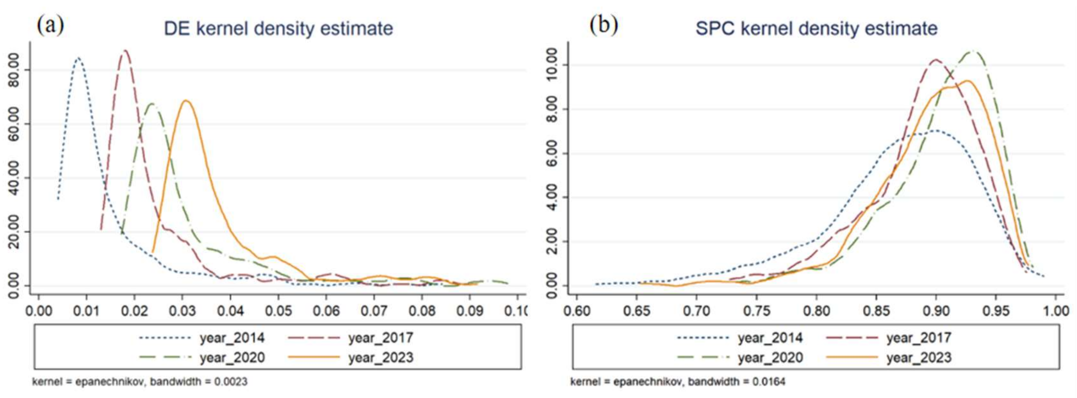

Figure 2. Kernel Density Estimation Curves

3.3. Benchmark Regression Results

Regression analysis of the constructed OLS model is carried out based on Stata 14.0.

According to the benchmark regression results, the estimated coefficient of DE is 0.131 and is significantly positive at the 5% level, providing empirical support for Hypothesis H1. This finding suggests that the development of the digital economy can significantly enhance synergistic pollution reduction and carbon mitigation governance. Furthermore, applying digital technologies into environmental governance can help overcome information asymmetry and coordination barriers that exist in traditional governance systems. By improving the matching efficiency between environmental governance demand and governance capacity, digital technology contributes to a substantial improvement in the overall effectiveness of coordinated pollution and carbon reduction governance.

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Table 4. Benchmark Results

VARIABLES	SPC
DE	0.131**
	(0.0617)
PS	-4.47e-05
	(3.03e-05)
PQ	-3.24e-06
	(1.06e-05)
MD	1.36e-08
	(1.60e-08)
STL	-1.78e-09
	(5.03e-09)
URS	0.0383*
	(0.0227)
EDL	-4.38e-07***
	(7.13e-08)
Constant	0.885***
	(0.0193)
R-squared	0.160

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

3.4. Robustness Tests

3.4.1. Replacement of Explanatory Variable

To further verify the reliability of the baseline regression results, following the method of Zhang et al. (2025) [31], the core explanatory variable "digital economy" was replaced with the digital infrastructure index DI, and the empirical model was re-estimated. After the replacement, the estimated coefficient of digital infrastructure was found to be 0.0194, which was statistically significant at the 1% significance level. This result is consistent with the direction of baseline regression and has a higher significance level. Therefore, the conclusion still holds after replacing the core explanatory variable.

3.4.2. Exclusion of Special Years

Considering that the COVID-19 pandemic from the end of 2019 to 2020 might have caused abnormal fluctuations in the sample data, thus affecting the identification of the overall effect, this study excluded the observations from 2019 and 2020 and re-estimated the mode. The coefficient of the core explanatory variable was found to be 0.1452, and remained positive at the 5% significance level. After removing potential interference from the pandemic, each unit increase in the level of digital economy development still significantly improved the level of urban coordinated emission reduction governance by 0.1452 units. The estimated coefficients remained relatively stable, and the direction and significance of the effect were consistent with the baseline. Therefore, the baseline conclusions are robust and reliable.

4. Further Analysis: Mediation and Heterogeneity

4.1. Heterogeneity Analysis

4.1.1. Resource-based and Non-resource-based Cities

First, following official standards of China (2013)[21], all cities were distinguished into resource-based cities and non-resource-based cities. Two-way fixed effects regressions are conducted separately for the two subsamples. Resource-based cities are those whose leading industries are closely associated with the exploitation of natural resources. This group includes 107 cities,

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including Daqing, Datong, and Karamay. In contrast, non-resource cities refer to those cities whose main economic activities do not rely on mining, forestry, and other natural resources. These cities have diversified industrial systems and their economic growth is less dependent on local resource endowments. This group contains 159 cities, including Beijing, Shanghai, and Chongqing.

Results show that, for resource-based cities, the estimated coefficient of the digital economy is 1.5098 and is significantly positive at the 1% level. This indicates that digital economy development has a pronounced positive effect on synergistic pollution reduction and carbon mitigation governance in resource-based cities. While for non-resource-based cities, it is 0.0657 and not statistically significant, suggesting that governance-enhancing effect is weak in this type of city.

One possible explanation is that Resource-based cities have always relied on resource-intensive industries. These industries are often associated with high energy consumption, heavy pollution, and strong dependence on traditional production modes. Consequently, these cities face greater pressure in terms of environmental governance and industrial transformation. Although digital technologies may still improve environmental supervision and governance precision in non-resource-based cities, their marginal contribution to coordinated pollution and carbon governance is comparatively limited.

4.1.2. High-economic and Low-economic Cities

In this study, the 266 prefecture-level and above cities are ranked in descending order according to per capita GDP. Based on this, the top 50% of cities in terms of GDP per capita were categorized as cities with higher levels of economic development, including Beijing, Shanghai, and Chongqing; the bottom 50% were categorized as cities with lower levels of economic development, including Qiqihar, Ulanqab, and Lishui. Two-way fixed effects regressions are then conducted separately for the two subsamples.

Regression results indicate that, among cities with a high level of economic development, the estimated coefficient of the digital economy is 0.0171, but it does not pass the statistical significance test. This indicates that the positive effect of the digital economy is not evident in economically developed cities. In contrast, for cities with a relatively low level, the coefficient is 1.6335 and is significantly positive at the 1% level, indicating that digital economy development exerts a stronger promoting effect on synergistic pollution reduction and carbon mitigation governance in less developed cities.

The finding implies that the governance-enhancing effect is more pronounced in cities with lower levels of economic development. Although these cities often face greater pressure from environmental governance and industrial transformation, they also possess latecomer advantages in digital development. Through using digital technologies, traditional industries can be rapidly empowered toward greener transformation, and the efficiency of resource allocation can be substantially improved.

By contrast, cities with higher levels of economic development generally have a more solid foundation for environmental governance, leaving relatively limited room for further optimization in pollution reduction and carbon mitigation. In these cities, the role of digital technology may be more concentrated on improving economic efficiency rather than directly enhancing environmental governance performance. Consequently, the marginal contribution of the digital economy to synergistic pollution and carbon governance is relatively weakened.

4.2. Mechanism Test

A mechanism test is carried out with ISU as the mediating variable.

Table 5. Mechanism Test

	baseline	mediator	full
VARIABLES	SPC	ISU	SPC
ISU			0.0523***
			(0.0140)
DE	0.131**	-0.190**	0.141**
	(0.0617)	(0.0900)	(0.0616)
PS	-4.47e-05	7.32e-05*	-4.85e-05
	(3.03e-05)	(4.42e-05)	(3.02e-05)
PQ	-3.24e-06	1.91e-06	-3.34e-06
	(1.06e-05)	(1.54e-05)	(1.05e-05)
MD	1.36e-08	-6.23e-09	1.39e-08
	(1.60e-08)	(2.34e-08)	(1.60e-08)
STL	-1.78e-09	3.50e-08***	-3.60e-09
	(5.03e-09)	(7.34e-09)	(5.04e-09)
URS	0.0383*	0.0221	0.0372
	(0.0227)	(0.0331)	(0.0226)
EDL	-4.38e-07***	-8.26e-07***	-3.95e-07***
	(7.13e-08)	(1.04e-07)	(7.21e-08)
Constant	0.885***	2.272***	0.766***
	(0.0193)	(0.0282)	(0.0372)
R-squared	0.160	0.469	0.165

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

The results suggest that industrial structure upgrading constitutes a significant mediating mechanism linking the digital economy with synergistic pollution reduction and carbon mitigation governance. In the second-stage regression, the estimated coefficient of DE on ISU is −0.1897, which is significantly negative at the 5% level. This result indicates that, during the current stage of development, the digital economy may exert a certain inhibitory effect on industrial structure upgrading.

After incorporating industrial structure upgrading into the third-stage regression model, the coefficient of DE remains significantly positive at the 5% level, with an estimated value of 0.1406. Meanwhile, the coefficient of ISU is 0.0523 and passes the 1% significance test, indicating that industrial structure upgrading itself can effectively promote synergistic pollution reduction and carbon mitigation governance. Therefore, Hypothesis H2 is supported. Further from the perspective of effect decomposition, the total effect β_1 is 0.131. The mediating effect exerted by ISU is represented by the product of α_1 and γ_2, about -0.0099. Under the action of the mediating effect, the direct effect is slightly higher than the total effect. This masking effect arises from the relative immaturity of the digital economy in the early stage of development. The high investment and high cost brought by the digital economy force enterprises to carry out green technology R&D, which hinders the development of green technology to a certain extent (Chen et al., 2022)[3]. Since industrial upgrading itself is a key driver of pollution reduction, its negative mediating effect offsets some of the direct emission reduction benefits brought by the digital economy during the transmission process, making the final total effect weaker than the direct effect estimated independently. Overall, the findings suggest that the environmental governance effect of the digital economy is not a simple linear process(Wang et al., 2024)[25]. Instead, it emerges through the interaction between direct

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promotion and indirect restraint. This further reflects the phased adjustment characteristics of China's coordinated development between digital transformation and green transition.

5. Conclusion and Policy Suggestionss

5.1. Research Conclusion

First, benchmark results confirm that digital economy significantly improves the level of synergistic pollution reduction and carbon mitigation governance. After controlling for city fixed effects and year fixed effects, a one-unit increase in the digital economy development level raises the urban synergistic pollution reduction and carbon mitigation governance level by 0.1307 units on average. This finding remains valid after robustness tests, indicating that the benchmark conclusion is reliable.

Second, in response to the masking effect, policy efforts should focus on removing the bottlenecks that restrict the digital economy from empowering green industrial upgrading. Blind expansion of digital industries should be avoided. Instead, attention should be paid to guiding digital technologies into traditional high-pollution industries, so as to promote their low-carbon and intelligent transformation through technological upgrading. Meanwhile, governments should improve policy support for industrial structure upgrading. New business formats such as digital environmental protection, smart energy, and green manufacturing should be actively cultivated. Such policy measures can facilitate the high-end, intelligent, and green-oriented transformation of industrial structure. In addition, a dynamic monitoring mechanism should be established to track the interaction between digital economy development and industrial structure upgrading.

Finally, the heterogeneity analysis indicates that the effect of the digital economy varies significantly across different types of cities. This finding provides empirical evidence for differentiated and targeted policy implementation.

There are still some limitations. First, restricted by data availability, the time span covered by the current analysis is relatively limited, only including observation data for ten years from 2014 to 2023. In the future, data can be obtained from multiple channels to expand the time scale of the study, so as to reveal a more robust and long-term impact effect. Second, this study only includes industrial structure upgrading as a mediating variable into the system for consideration. The digital economy may also affect synergistic pollution reduction and carbon mitigation governance through multiple paths such as empowering technological innovation and inclusive finance.

5.2. Policy Suggestions

First, given the significant positive contribution of the digital economy, local governments should incorporate digital economy development into their green strategic framework. Firstly, local governments should promote the deep integration of digital technologies with traditional industries, utilize intelligent tools such as big data and artificial intelligence to optimize work processes, and support the construction of regional digital environmental governance platforms. Secondly, they should further improve digital infrastructure, narrow the regional digital development gap, increase investment in digital resources in underdeveloped areas, reduce the digital divide, and expand the green enabling effect of the digital economy. Simultaneously, a coordinated evaluation mechanism integrating digital economy development and green transformation should be established.

Second, policy efforts should focus on removing the constraints that hinder the digital economy from empowering green industrial upgrading. At the early stage, local governments are supposed to avoid blind expansion of digital industries. Instead, greater emphasis should be placed on guiding digital technologies into traditional high-polluting sectors. Through technological transformation, digital empowerment can promote the low-carbon and intelligent upgrading of traditional industries, rather than crowding out resources for green technology research and development. At the same time, the policy support system for industrial structure upgrading should be improved. Special support policies can be introduced to cultivate emerging business forms such as digital environmental protection and smart energy, and promote the green, high-end, and intelligent transformation of industrial structure. In addition, a dynamic monitoring mechanism should be established.

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