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The impact of the digital economy on environmental pollution: a perspective on collaborative governance between government and Public

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The rapid development of the digital economy is driving transformative changes in a multifaceted collaborative environmental governance system. From the perspective of collaborative governance between government and the public, this study employs double fixed-effects models, spatial econometric models, and instrumental variables methods to empirically explore how the digital economy influences environmental pollution, using panel data from 30 provinces in China spanning 2011 to 2022. The results demonstrate that the digital economy significantly lowers environmental pollution. The primary mechanism is through the government's environmental governance behaviors, which are positively moderated by public environmental concerns, enhancing effectiveness. Additionally, the digital economy induces a spatial spillover effect on environmental pollution. This promotion of collaborative management between the government and the public is poised to become a pivotal direction in future environmental governance.

KEYWORDS

digital economy, environmental pollution, environmental governance, coordinated governance, spatial spillover

1 Introduction

As one of the world's largest energy consumers and carbon emitters, improving environmental pollution in China holds significant importance for the global environment. Yet, China's environmental challenges are extremely severe. To tackle this, it's crucial to actively embrace the new development concept, focus on building and enhancing an ecological civilization system, and unwaveringly pursue a green, circular, and low-carbon economic growth path.

The digital economy, which involves economic activities created by connecting individuals, organizations, and information systems via digital technology, is rapidly evolving (Carlsson, 2004; Sturgeon, 2021; Zhen et al., 2021; Zou and Deng, 2022). The influence of the digital economy on environmental pollution is a key focus among scholars. The digital economy reduces environmental pollution by fostering technological innovation and refining industrial structures (Zhang et al., 2023). It also enhances the integration of the real economy with industry using production factors such as knowledge, information, and IT, playing a vital role in boosting production efficiency (Pan et al., 2022), reducing carbon emissions (Xie et al., 2024), and advancing green transformations (Liu and Zhao, 2024). Technologies like artificial intelligence, big data, and industrial robots are reshaping industrial chains (Moyer and Hughes, 2012)and enhancing green total factor productivity (Chen et al., 2023; Wang et al., 2024), thus driving high-quality development (Wang et al., 2024). From this perspective, studying the impact of the digital economy on environmental pollution and the underlying mechanisms behind it is of significant importance for achieving green and sustainable development.

However, the synergistic mechanisms between government environmental governance and social public participation have not received adequate attention, presenting an opportunity to expand this area of research. The use of big data platforms and Internet technology can enhance the informatization of government environmental oversight, the scientific basis of environmental protection decisions, and deepen social participation (Wei and Zhang, 2023). These advancements improve the government's capacity to manage the environment and further reduce environmental pollution levels. Notably, a diverse and shared environmental governance model is emerging in China, where the government leads and public participation supports. Public involvement acts as an informal environmental regulation (Tan and Eguavoen, 2017), compelling local governments to focus on environmental protection and increase invest-ments in environmental pollution control (Ge et al., 2021), which contributes to environmental improvement (Wang et al., 2023).

This study investigates how the development of digital economy impacts regional environmental pollution governance through collaborative efforts between the government and the public. The findings indicate that the digital economy significantly reduces environmental pollution levels. This reduction prompts local governments to increase investments in environmental pollution control, enhance their focus on environmental governance, and enforce environmental protection penalties, thereby improving regional environmental quality. These conclusions remain robust after various analyses, including the instrumental variable method and substituting explanatory variables. Public environmental concern also positively moderates the relationship between the digital economy and environmental pollution, indicating that the digital economy enhances environmental governance effectiveness through increased government and public interaction and participation.

The potential marginal contribution of this paper is twofold: Firstly, we use the co-management by multiple environmental stakeholders as the entry point, positioning the digital economy, governmental environmental governance, public environmental concern, and environmental pollution prevention within the same analytical framework to systematically assess the governance effects of the digital economy on environmental pollution. This encourages us to consider the synergistic effects of government environmental governance and social public participation, offering a fresh perspective for deeply understanding how the digital economy contributes to green development. Secondly, this paper delves into the specific transmission mechanisms through the interaction between local governments and the public, aiming to explore the long-term mechanisms of environmental governance facilitated by collaborative efforts between the government and the public.

The structure of the paper is as follows: Section 1 introduces the study. Section 2 reviews relevant literature and presents theoretical analyses. Section 3 outlines the research design, including variable selection, data sources, and model construction. Section 4 analyzes empirical results, covering baseline regression outcomes, impact mechanisms, moderating effects, and tests for spatial effects. Section 5 conducts robustness tests, utilizing approaches like the instrumental variables method, substitution of explanatory variables, and heterogeneity analysis. Finally, Section 6 offers conclusions and policy recommendations.

2 Theoretical mechanism and research hypothesis

2.1 The development of digital economy can reduce environmental pollution

The rapid advancement and widespread adoption of digital information technologies—such as the Internet, big data, and artificial intelligence—not only inject new momentum into economic development but also facilitate the restructuring of the environmental governance system encompassing government, businesses, and society. This restructuring supports the economy's transition to green and low-carbon operations. Specifically, within enterprises, the innovative breakthroughs in digital technology serve as a key driver for eco-friendly economic practices. As primary agents of pollution control, businesses utilize digital technologies to gather information and consolidate resources, enabling informed production decisions and enhancing operational efficiency (Zhang Rongwu et al., 2022). Moreover, the digital economy enhances knowledge dissemination efficiency in electronic equipment, communication networks, and information processing, encouraging enterprises to adopt green production models. This undoubtedly fosters technological innovation and industrial upgrading, ultimately contributing to both pollution reduction and green development (Xu et al., 2023).

In terms of governmental environmental governance, digital technology facilitates the development and application of ecological and environmental data, effectively collecting, integrating, and sharing critical information like pollution levels and environmental carrying capacity. This data supports dynamic assessments and supervision of governmental environmental efforts, improving pollution perception and early warning capabilities (Fang et al., 2024), and enhancing the precision and effectiveness of environmental supervision. This provides a robust data foundation for crafting environmental policies and refining the ecological regulation framework, thereby elevating the government's role in environmental management (Shin and Choi, 2015).

Regarding public supervision and participation, the digital economy simplifies ac-cess to environmental information and raises public environmental awareness by enhancing public service platforms and fostering information exchange between the government and the community. The public can engage in environmental oversight through avenues such as social media, ensuring adherence to environmental regulations and governance policies, and supervising pollution activities and enforcement. This transformation of environmental consciousness into action facilitates collaborative governance of environmental pollution by both government and the public (Yang et al., 2020).

In conclusion, the development of digital economy impacts environmental pollution by promoting green production in enterprises, refining governmental environmental regulatory frameworks, and enhancing social and public oversight. Based on these insights, this paper proposes the following research hypothesis:

Hypothesis 1: The development of digital economy will reduce environmental pollutant emissions, i.e., digital economic development contributes to effective environmental pollution management.

2.2 Government and Public synergy mechanism

2.2.1 Government environmental governance mechanism

Reducing environmental pollution is a systematic project requiring the participation and synergy of multiple actors, including the government, enterprises, and the public. From the perspective of interactive synergy between the government and the public, analyzing the impact of the digital economy on the environmental governance behaviors of local governments can deepen our understanding of China's environmental pollution governance model.

Firstly, the digital economy enables the government to efficiently collect, integrate, and share environmental data, scientifically assess government environmental governance performance, and enhance the accuracy and effectiveness of environmental supervision, thus boosting the government's regulatory capacity (Zhao Shuliang et al., 2023). Additionally, the government can use digital technology to expand communication channels for knowledge diffusion, support environmental regulation, and improve policy formulation and implementation, which also increases government transparency (Peng et al., 2023), and improves environmental governance (Ahlers and Shen, 2018).

Secondly, investment in environmental pollution management reflects the commitment and effort of local governments in environmental governance. The digital economy drives local governments to increase their investments in environmental governance through digitized knowledge, information, technology, and other production factors, thereby elevating the level of ecological and environmental governance (Su et al., 2018; Zhu and Li, 2020).

Thirdly, the digital economy aids the development and utilization of environmental data and information, reducing information asymmetry between various government departments, businesses, and the public. This breaks down data barriers, forms a comprehensive ecological and environmental data system, and improves the transparency of local government environmental protection (Ahlers and Shen, 2018). The digital economy also enhances government environmental supervision and law enforcement capabilities, enabling the government to impose penalties on non-compliant businesses (Wu et al., 2024), strengthen the investigation and handling of environmental violations and penalties (Li Mingxian et al., 2023; Liu et al., 2024), and deter environmental non-compliance by businesses, which in turn reduces environmental pollution emissions.

Based on the above analysis, the following hypothesis is proposed:

Hypothesis 2: The digital economy affects environmental pollution governance through the pathways of government environmental governance attention, environmental pollution governance investment, and environmental protection administrative enforcement efforts.

2.2.2 Regulatory effect of Public environmental concern

Social public participation, supplementing environmental regulation, supervises and influences local government environmental governance behaviors. With the rapid advancement of digital technology, the public can share social resources and create public service platforms using the Internet and big data. This platform model enables the public to easily access environmental information, express their opinions, and voice their dissatisfaction with pollution issues and demand for environmental quality improvement (Tan and Eguavoen, 2017). The theory of government responsiveness suggests that government environmental governance behaviors are influenced by and respond to regional public opinion, aligning environmental policies with public preferences (Arantes, 2023). In response to public environmental demands, the government reduces Environmental pollution by increasing attention to environmental governance, boosting investment in pollution control, and imposing administrative penalties for environmental protection (Sun et al., 2023; Liu et al., 2024).

On the other hand, under the Chinese environmental governance model, public satisfaction with environmental governance is a crucial metric for assessing local government performance. The digital economy promotes public environmental demands, participation, and supervision, compelling higher-level governments to motivate and oversee lower-level government environmental policies and behaviors, which assists in reducing local environmental pollution (Niu et al., 2024). As the primary responder, local governments attend to public environmental demands and actively respond through their governance practices, adjusting their environmental policy preferences, which undoubtedly enhances the environmental governance performance of local governments. The digital economy influences local government environmental policy adjustments and governance behaviors by elevating public environmental concerns and transforming public demands into active participation in environmental protection activities (Arantes, 2023).

The above logical mechanism is summarized as follows: The digital economy contributes to the interaction between the government and the public, influences public environmental awareness and behavior, and guides the public to pay attention to and participate in the process of environmental governance, thus fostering a governance system that is scientific in decision-making, refined in supervision, and convenient in service. By influencing local government environmental governance behaviors, public environmental demands compel local governments to enhance their focus on environmental governance, increase investments in environmental pollution control and enforcement, and ultimately aid in regional environmental pollution control.

As a result, the following hypothesis is derived:

Hypothesis 3: Public environmental concern positively moderates the relationship between the digital economy and environmental pollution, enhancing the impact of digital economy on government environmental regulation.

TABLE 1 Comprehensive Evaluation Indicator System for the development of digital economy.

Primary indicator	Secondary indicator	Description of indicator	Unit
Digital infrastructure	Internet penetration	Number of internet broadband access ports	Ten thousand units
		Number of internet broadband subscribers	Ten thousand households
		Number of internet domains	Ten thousand units
	Mobile phone penetration	Mobile phone base station density	Units per square kilometer
		Mobile phone penetration rate	Devices per 100 people
	Breadth of information transmission	Length of long-distance optical cables per area	Kilometers per square kilometer
Digital industrialization	Software and IT services	Revenue from software business as a percentage of GDP	%
		Number of employees in IT and software services	Ten thousand people
	Level of electronic information manufacturing	Revenue from electronic information manufacturing as a percentage of GDP	%
		Total volume of telecommunications business as a percentage of GDP	%
		Per capita telecommunications business volume	Yuan per person
	Development level of postal and telecommunications	Total postal services per capita	Yuan per person
		Per capita postal business volume	Ten thousand items
		Corporate e-commerce transaction volume	Hundred million yuan
Industrial digitization	Enterprise digital development	Proportion of enterprises engaged in E-commerce transaction	%
		Number of computers per 100 people in enterprises	Units
		Number of websites per 100 enterprises	Units
	Digital inclusive finance	Digital inclusive finance index	—
Digital innovation capacity	R&D level in enterprises	Full-Time equivalent R&D personnel in large-scale industrial enterprises	Person-year
		R&D expenditure in industrial enterprises above a designated size	Ten thousand yuan
		Number of R&D projects in large-scale industrial enterprises	Projects
	Technological innovation capacity	Total amount of technology contracts	Ten thousand yuan
		Number of patent applications granted	Items

2.3 Spatial spillover effects

The spatial spillover effect of the digital economy and environmental pollution is a crucial prerequisite for spatial measurement research. The spatial spillover effect of the digital economy has been extensively studied (Li Guangqin et al., 2023; Hou et al., 2023; Xu, 2024), with scholars exploring its impacts on rural revitalization (Li Guangqin et al., 2023) and industrial green innovation (Li Mingxian et al., 2023).

Conversely, the spatial spillover effect of environmental factors has also garnered significant attention (Liu et al., 2020; Zhang Maomao et al., 2022; Zhao Feng et al., 2023). This includes research on water pollution (Liu, et al., 2020), the interplay between urbanization and environmental pollution (Zhao Feng et al., 2023), the relationship between industrial agglomeration and environmental pollution (Zhang Maomao et al., 2022), and the mismatch of land resources contributing to environmental issues (Wan and Shi, 2022). Given that both the digital economy and environmental pollution exert influences on surrounding areas, it is conceivable that the digital economy might also impact environmental pollution in neighboring regions through spatial spillovers.

Thus, the following hypothesis is proposed:

Hypothesis 4: The digital economy will exert spatial spillover effects on environmental pollution.

3 Research design

3.1 Variable selection

3.1.1 Explained variable

Environmental pollution level (Pol). The entropy weighting method is used to calculate a comprehensive environmental pollution index for regional industrial wastewater, sulfur dioxide

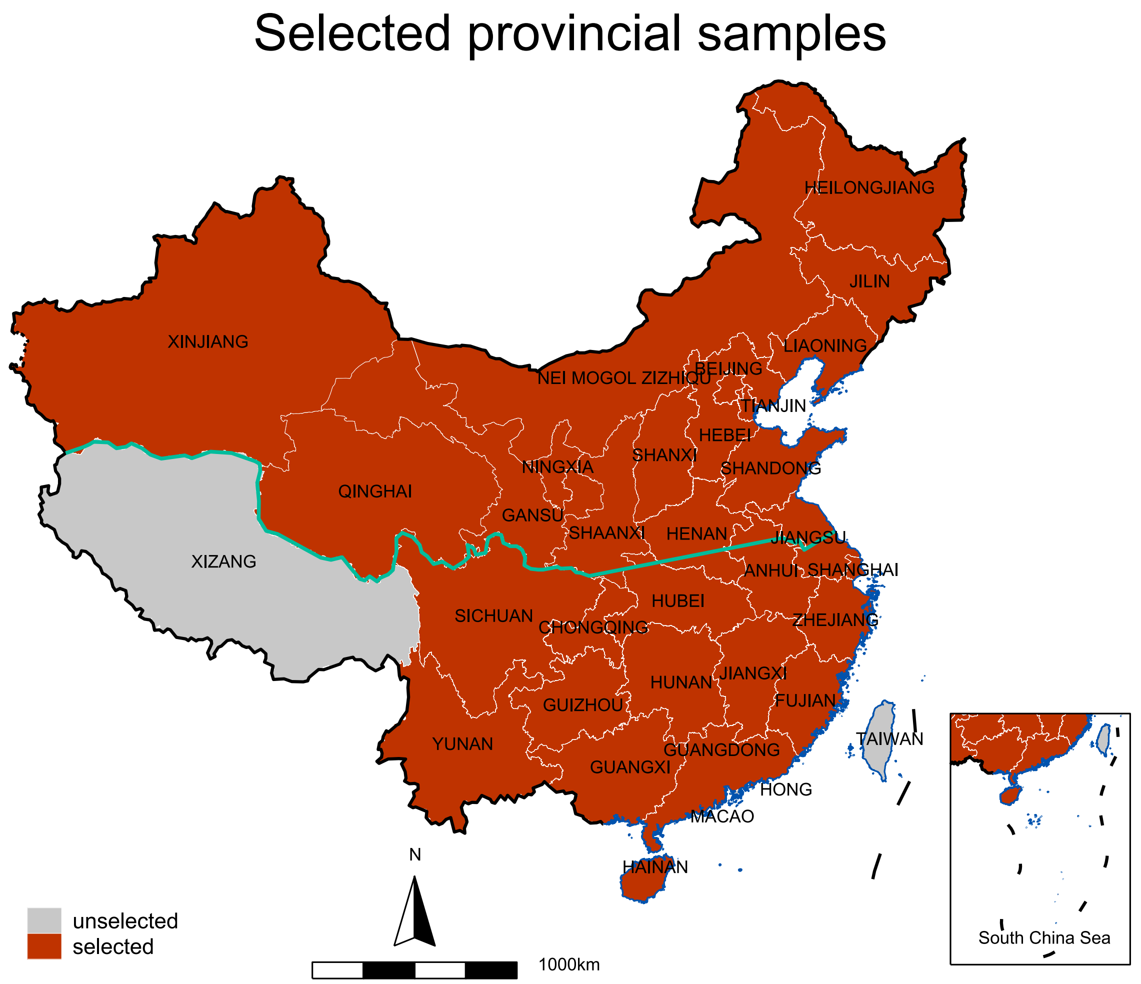

FIGURE 1
Selected provincial samples.

emissions, and solid waste emissions as a measure of the level of environmental pollution in each region.

3.1.2 Main explanatory variable

The explanatory variable in this paper is the digital economy (Dtf). Currently, defining the connotation of the digital economy is challenging, with many scholars understanding it as the sum of economic activities based on modern information technology (Carlsson, 2004; Sturgeon, 2021; Zhen et al., 2021; Zou and Deng, 2022). In this paper, we build on the work of Wang et al. (2021) to construct a digital economy development index using the entropy weight method. We select indicators from four dimensions: digital infrastructure, digital industrialization, industrial digitization, and digital innovation capability. The specific indicators are presented in Table 1.

3.1.3 Mechanistic variables

This study identifies three core mechanistic variables to dissect the behavioral patterns of local governments in environmental governance. First, the degree of pre-existing attention to environmental governance (en) is quantified by analyzing the frequency of environmental and haze-related terms in the annual work reports of provincial governments. Secondly, the financial commitment to environmental pollution control (ei) is gauged by the total provincial investment in this area. Finally, the post-action intensity of enforcing environmental regulations (ez) is measured through the tally of environmental administrative penalty cases. These variables are designed to provide a comprehensive evaluation of the government's dedication and efficacy in environmental protection.

3.1.4 Moderating variable

The moderating variable, public environmental concern (pf), is represented by the Baidu haze search index. This choice is primarily due to Baidu's status as the largest Chinese search engine, which offers extensive coverage and high data availability, allowing for detailed regional analysis based on search frequency and trends. Haze, as an environmental issue, tends to register a higher level of public awareness compared to other issues like environmental pollution, making it an ideal measure of environmental concern.

TABLE 2 Descriptive statistics.

Variable type	Variable name	Variable symbol	Mean	Standard deviation	Minimum	Maximum
dependent variable	environmental pollution Level	Pol	0.795	0.564	0.164	3.643
independent variable	the digital economy	Dtf	0.114	0.102	0.014	0.599
mechanistic variables	government environmental governance attention	en	0.345	0.311	0.017	1.773
	environmental pollution control investment	ei	5.414	2.978	2.108	21.132
	government environmental enforcement effort	ez	0.839	0.647	0.256	3.605
moderating variable	public environmental awareness	pf	0.311	0.368	0.002	2.031
control variables	financial freedom	ff	0.491	0.188	0.151	0.931
	financial development level	fin	0.041	0.013	0.020	0.085
	infrastructure	inf	0.004	0.003	0.001	0.013
	healthcare level	sin	39.064	9.856	16	75
	technology input	tec	111.379	60.476	16.635	324.157
	education level	edu	277.555	85.769	108.2	561.3
	elderly dependency ratio	old	38.553	7.367	19.3	56.7
	child dependency ratio	chi	22.986	6.208	9.9	36.4

3.1.5 Control variables

In a bid to thoroughly examine the digital economy's influence on environmental pollution, this study introduces various control variables: fiscal freedom (ff), gauged by the ratio of fiscal revenue to fiscal expenditures; financial development level (fin), defined by the urban financial employment per 10,000 people; infrastructure (inf), assessed through the ratio of highway kilometers to developed area; medical care level (sin), measured by the number of practicing assistant physicians per 10,000 people; science and technology investment (tec), represented by the ratio of industrial enterprises' R&D expenditures to regional GDP; education level (edu), based on the average higher education enrollment per 10,000 population; old-age burden (old), using the elderly dependency ratio; and parenting burden (chi), determined by the child dependency ratio.

3.2 Model Setting

Based on the results of the Hausman test (test value of 39.472, p-value of 0), the fixed effect model is deemed appropriate. Given that the data are panel data, and drawing on the methodology of Zhang et al. (2023), a double fixed-effect model is employed to analyze the impact of the digital economy on environmental pollution. The specific model (1) is presented as follows.

$$\mathrm{Pol}_{i,t} = \alpha_0 + \alpha_1 Dtf_{i,t} + \alpha_2 Z_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \tag{1}$$

In Eq. 1, Poli,t represents the level of environmental pollution in province i during period t; Dtfi,t denotes the level of the digital economy in province i during the same period; the vector Zi,t includes a series of control variables for environmental pollution; μi symbolizes the individual fixed effect, while δt controls for the time fixed effect; εi,t is the random disturbance term.

Secondly, to explore the mechanisms through which the digital economy impacts environmental pollution, a transmission effect model is introduced as depicted in Eqs 2, 3. Here, itvi,t represents a series of mechanism variables through which the digital economy influences environmental pollution.

$$Itv_{it} = \beta_0 + \beta_1 Dtf_{i,t} + \beta_2 Z_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \tag{2}$$

$$Plo_{i,t} = \gamma_0 + \gamma_1 itv_{i,t} + \gamma_2 Z_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \tag{3}$$

Thirdly, to assess the moderating effect of public environmental concern on the mechanism variables, this effect is captured in Eq. 4.

$$Itv_{i,t} = \eta_0 + \eta_1 Dtf_{i,t} + \eta_2 Dtf_{i,t}{}^{*}pf + \eta_3 Z_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \tag{4}$$

Additionally, the explanatory variables and the cross-multiplication term of each control variable with the spatial weight matrix are integrated into Eq. 1 to construct the Spatial Durbin Model (SDM), as detailed in Eq. 5. Here, φ2 represents the spatial spillover coefficient, and W is the spatial weight matrix.

$$Pol_{i,t} = \varphi_0 + \varphi_1 Dtgf_{i,t} + \varphi_2 WDtf_{i,t} + \varphi_3 Z_{i,t} + \varphi_4 WZ_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \tag{5}$$

3.3 Data sources and descriptive statistics

Drawing on the approach of Zhang et al. (2023), 30 provinces in China (excluding Tibet, Taiwan, Hong Kong, and Macau) are selected as the research sample, covering the period from 2011 to 2022. The

TABLE 3 Main results.

Variable	Pol				
	(1)	(2)	(3)	(4)	(5)
Dtf	−1.087***	−1.078***	−1.254***	−1.442***	−1.328***
	(0.270)	(0.274)	(0.262)	(0.265)	(0.264)
ff		−0.987***	−0.926***	−0.984***	−0.849***
		(0.302)	0.287	(0.282)	(0.277)
fin		−2.995***	−3.107***	−5.709***	−5.948***
		(1.515)	(1.445)	(1.495)	(1.465)
inf			9.429	6.381	9.960
			(11.584)	(11.329)	(11.259)
sin			−0.011***	−0.010***	−0.008***
			(0.002)	(0.002)	(0.002)
tec				−0.001***	−0.002***
				(0.001)	(0.001)
edu				−0.002***	−0.002***
				(0.001)	(0.001)
old					−0.025***
					(0.006)
chi					0.017***
					(0.010)
_cons	0.400***	1.346***	1.970***	3.082***	3.299***
	(0.078)	(0.243)	(0.253)	(0.336)	(0.343)
region effects	yes	yes	yes	yes	yes
time effects	yes	yes	yes	yes	yes
N	360	360	360	360	360
adj R^2	0.880	0.917	0.925	0.931	0.934

Note: *, **, *** indicates significant at the 10%, 5%, 1% level, the brackets are robust standard.

selected provinces are shown in Figure 1. The data for the dependent variables are sourced from the China Environmental Yearbook. Composite indicators for the dependent variables are derived from the digital finance Index of Peking University, the China Statistical Yearbook, and the respective statistical yearbooks of each province. The data for the control variables are also obtained from the China Statistical Yearbook and the provincial statistical yearbooks. Descriptive statistics for each variable are presented in Table 2.

4 Empirical analysis

4.1 Benchmark regression

Table 3 illustrates the results of a regression analysis on the impact of the digital economy on environmental pollution. As control variables were incrementally added to the regression model, the estimated coefficient for the core explanatory variable, the digital economy index (Dtf), consistently showed a significant negative effect. This strongly supports the hypothesis that the digital economy significantly mitigates or reduces environmental pollution, confirming Hypothesis 1.

Among the control variables, fiscal freedom's impact on environmental pollution is also negative, suggesting that increased fiscal freedom provides local governments with more resources to combat environmental pollution. Financial development negatively correlates with environmental pollution; higher financial development levels likely channel more funds towards sustainable practices, thereby reducing pollution levels. However, the influence of infrastructure development on environmental pollution was found to be statistically insignificant. Medical care levels also negatively affect environmental pollution, implying that higher levels of healthcare lead to greater public awareness and concern for health, which in turn discourages environmental pollution. The impact of investments in

TABLE 4 Mechanism analysis.

Variable	en	Pol	ei	Pol	ez	Pol
	(6)	(7)	(8)	(9)	(10)	(11)
	2.413***		4.294***		2.083***	
Dtf	(0.082)		(0.991)		(0.321)	
		−0.541***				
en		(0.093)				
				−0.109***		
ei				(0.014)		
						−1.161***
ez						(0.281)
_cons	−0.768***		18.610***	5.211***	1.296***	3.002***
	(0.107)		(1.287)	(0.423)	(0.417)	(0.363)
control variables	yes	yes	yes	yes	yes	yes
region effects	yes	yes	yes	yes	yes	yes
time effects	yes	yes	yes	yes	yes	yes
N	360	360	360	360	360	360
adj R2	0.979	0.936	0.967	0.941	0.926	0.929

science and technology on environmental pollution is also negative, reinforcing the idea that technological advancements drive energy efficiency and pollution reduction. Similarly, higher education levels correlate with reduced environmental pollution, as they foster more expertise in pollution prevention and control. The old-age dependency ratio negatively affects environmental pollution. Elderly populations, being more health-sensitive, tend to reside in areas with better environmental conditions, thus places with higher elderly care levels experience lower pollution. In contrast, the child dependency ratio has a positive impact on environmental pollution. In regions with higher fertility rates, which typically have more outdated production methods, environmental pollution is more severe.

4.2 Mechanism analysis

Hypothesis 2 asserts that the development of the digital economy impacts the level of environmental pollution through pathways such as increased government focus on environmental governance, greater investment in pollution control, and more stringent environmental administrative law enforcement. This section provides an empirical examination of these mechanisms, with regression outcomes detailed in Table 4. Results from columns (7), (9), and (11) reveal that the digital economy substantially enhances government attention to environmental governance, boosts investment in environmental pollution control, and strengthens environmental administrative law enforcement. Furthermore, data from columns (6), (8), and (10) indicate that public environmental concern, environmental regulation level, green innovation level, and industrial structure significantly diminish environmental pollution levels. Consequently, the digital economy mitigates environmental pollution through mechanisms that influence government attention, investment in pollution control, and the enforcement of environmental laws, thus confirming Hypothesis 2.

TABLE 5 Test of moderating effect of public environmental concern.

Variable	pf	en	ei	ez
	(12)	(13)	(14)	(15)
Dtf	3.019***	0.754***	9.407***	4.586***
	0.138	0.143	2.129	0.681
Dtf* pf		0.730***	2.251***	1.102***
		0.056	0.832	0.266
control variables	yes	yes	yes	yes
region effects	yes	yes	yes	yes
time effects	yes	yes	yes	yes
N	360	360	360	360
adj R2	0.958	0.986	0.967	0.931

4.3 Analysis of the regulatory effects of public environmental concerns

Hypothesis 3 posits that public environmental concern positively moderates the relationship between the digital economy and environmental pollution, enhancing the impact of digital economy on government environmental regulation.

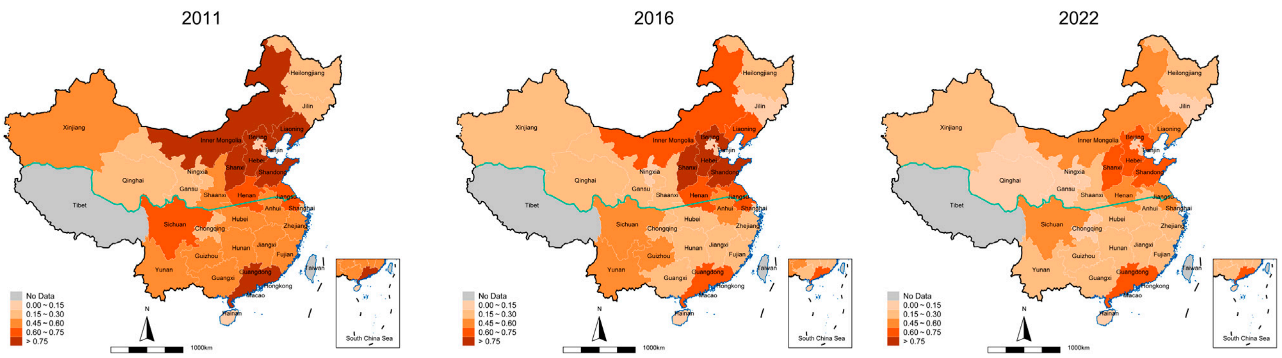

FIGURE 2
Spatial Distribution Map of Environmental pollution.

Table 5, column (12), demonstrates that the impact of the digital economy on public environmental concern is significantly positive at the 1% level, indicating that the digital economy boosts public environmental awareness. Columns (13), (14), and (15) show that after incorporating the interaction term between the digital economy and public environmental concern, the digital economy positively affects local government attention to environmental protection, investment in environmental pollution control, and environmental law enforcement efforts, all significant at least at the 10% level.

Moreover, the interaction term between the digital economy and public environmental concern is significantly positive, highlighting that the digital economy promotes government attention to environmental protection, environmental pollution control investment, and law enforcement efforts by increasing public awareness. In essence, the development of digital economy enhances environmental quality by fostering the synergy of public environmental concerns and prompting local governments to intensify their environmental governance efforts. This process is indicative of China's evolving pattern of diverse and collaborative environmental governance, driven by the government with widespread public involvement, which plays a pivotal role in controlling environmental pollution and outlines the future trajectory of environmental governance. Hypothesis 3 is validated.

4.4 Spatial spillover effect test

Hypothesis 4 believes that the digital economy will have a spatial spillover effect on environmental pollution. This part examines the spatial spillover effect of the digital economy. It is mainly divided into three parts: comparative analysis of spatial distribution maps, spatial autocorrelation test, and spatial econometric regression. The specific process is as follows:

4.4.1 Comparative analysis of spatial distribution maps

Figure 2 shows the spatial distribution of the environmental pollution in 2011, 2016, and 2022. Overall, from 2011 to 2022, the environmental pollution showed a downward trend, indicating that the environmental pollution in China is improving. The provinces with a relatively high degree of environmental pollution are concentrated in the northern part of China, such as Inner Mongolia, Shanxi, and Hebei. The environmental pollution in the eastern coastal provinces is relatively low. The environmental pollution of each province shows certain characteristics of spatial agglomeration.

Figure 3 shows the spatial distribution of the digital economy of various provinces in China in 2011, 2016, and 2022. It can be seen that the level of China's digital economy has achieved relatively large development from 2011 to 2022. Moreover, the development level of the digital economy in northern provinces is lower than that in the south. The development level of the digital economy in southeastern coastal provinces is relatively high, and there is also a certain degree of spatial agglomeration in the development level of the digital economy in space. By comparing Figure 2, it can be found that the environmental pollution of Inner Mongolia, Shanxi, Hebei and other provinces is at a relatively high position in the whole country, and the development level of the digital economy is at a relatively low position in the whole country. The environmental pollution of coastal provinces is at a relatively low level in the whole country, and the development level of the digital economy is at a relatively high position in the whole country. There is a certain correspondence in the spatial distribution between the two. In the following text, the spatial autocorrelation level of the environmental pollution and the development of the digital economy will be further tested.

4.4.2 Spatial autocorrelation test

The premise of the spatial econometric model is the existence of spatial correlation among the study variables. The Moran's Index is used to test the spatial autocorrelation between the digital economy and environmental pollution from 2011 to 2022. Table 6 presents the Moran indices for both digital economy and environmental pollution levels using a geographical distance matrix. The results show significant spatial autocorrelation at the 1% level for the period studied, justifying further spatial econometric regression.

4.4.3 Spatial econometric regressions

The outcomes from spatial measurement regressions are reported in columns (16) to (19) of Table 7, utilizing four different spatial weight matrices: neighborhood distance,

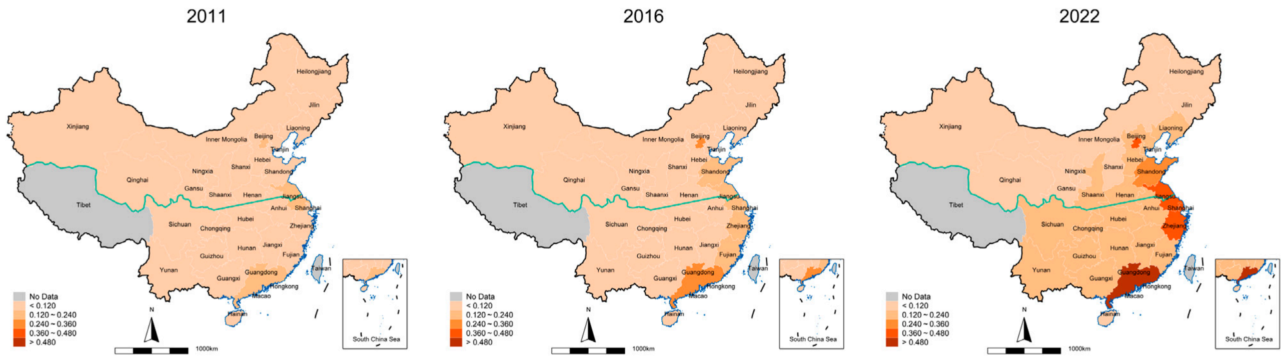

FIGURE 3
Spatial Distribution Map of the Digital economy.

TABLE 6 Results of spatial autocorrelation test.

year	Dtf			Pol		
	Moran's I	Z	p	Moran's I	Z	p
2011	0.097	1.239	0.215	0.349	3.697	0.000
2012	0.195	2.110	0.035	0.347	3.687	0.000
2013	0.188	2.040	0.041	0.184	2.138	0.032
2014	0.185	2.018	0.044	0.195	2.240	0.025
2015	0.196	2.114	0.035	0.195	2.253	0.024
2016	0.212	2.258	0.024	0.183	2.152	0.031
2017	0.220	2.330	0.020	0.182	2.106	0.035
2018	0.195	2.117	0.034	0.176	2.016	0.044
2019	0.211	2.266	0.023	0.145	1.763	0.078
2020	0.194	2.123	0.034	0.138	1.692	0.091
2021	0.186	2.054	0.040	0.125	1.546	0.122
2022	0.162	1.840	0.066	0.106	1.380	0.168

geographic distance, economic distance, and an economic-geographic nested matrix. The results across these matrices are consistent. However, the analysis focuses on the economic-geographic nested matrix shown in column (19), which combines both economic and geographic factors. Note that the spatial econometric model is uniquely characterized, particularly in column (19), rows 3 and 4, which highlight the regression coefficients for the digital economy and its interaction with the spatial weights. The significance of these coefficients primarily indicates whether the digital economy directly influences environmental pollution. However, the actual existence and extent of its spatial impacts require further analysis using spatial econometric modeling techniques, such as partial differentiation; the actual values of the coefficients themselves are less critical here. Detailed examination of the direct and spillover effects is required through partial differentiation, presented in rows 6 and 7 of column (19).

As evident from the third row of column 19, the direct impact of the digital economy on environmental pollution is negative, indicating that the growth of the digital economy within a region is likely to reduce its environmental pollution. Similarly, the fourth row reveals a negative coefficient for the interaction term between the digital economy and the spatial weight matrix. This suggests that while the digital economy may decrease environmental pollution within a region, it can concurrently mitigate pollution in surrounding areas as well. This may stem from the demonstrative effect of the digital economy, where as it prompts an increase in environmental regulatory efforts by local governments, neighboring governments may also face pressure from performance evaluation and public attention, leading to enhanced environmental pollution management. Consequently, when the digital economy reduces environmental pollution in a given region, it tends to have a similar effect in neighboring areas. Thus, Hypothesis 4 is confirmed.

5 Robustness test

5.1 Instrumental variable methods

Drawing on the methodology of Nunn and Qian (2014) and Zhang et al. (2023), we use historical data on post and telecommunications from provinces in 1984 as a basis, combined with the number of Internet users in the country from 2011 to 2022, to construct an instrumental variable. This approach is chosen because the development of the digital economy is closely related to local infrastructure such as postal and telecommunication services, thus satisfying the requirement for correlation between the instrumental variable and the explanatory variables. Additionally, the impact of postal and telecommunication infrastructure on environmental pollution has become negligible over time, meeting the exogeneity requirement of the instrumental variable. Please refer to Table 8 for the relevant regression results.

The results from Table 8 confirm that the digital economy continues to have a significant negative impact on environmental pollution, even after addressing the endogeneity issue.

TABLE 7 Spatial spillover effect test.

Spatial matrix types	Adjacent Distance	Geographic ditance	Economic distance	Economic Geographical nestng
Variable	(16)	(17)	(18)	(19)
Dtf	−0.797***	−0.801***	−0.812***	−0.814***
	(0.267)	(0.270)	(0.271)	(0.274)
W×Dtf	−0.189***	−0.191***	−0.193***	−0.195***
	(0.062)	(0.063)	(0.065)	(0.064)
control variables	yes	yes	yes	yes
direct effect	−0.785***	−0.793***	−0.795***	−0.801***
	(0.273)	(0.276)	(0.277)	(0.279)
spillover effect	−0.093**	−0.095**	−0.096***	−0.098***
	(0.363)	(0.367)	(0.369)	(0.372)
spatial rho	0.144**	0.147***	0.148***	0.150***
	(0.070)	(0.073)	(0.074)	(0.079)
variance $sigma^2$	0.019***	0.019***	0.019***	0.019***
	(0.001)	(0.001)	(0.001)	(0.001)
N	360	360	360	360
adj R^2	0.860	0.862	0.870	0.873

TABLE 8 Robustness check of instrumental variable method.

Variable	Instrumental variable	
	(20)	(21)
Dtf	−0.776***	−1.323***
	(0.332)	(0.317)
region fixed effect	yes	yes
year fixed effect	yes	yes
control variables	no	yes
LM	212.445	216.559
	[0.000]	[0.000]
F	457.848	466.513
	{16.380}	{16.380}
period number	12	12
N	360	360
adj R^2	0.741	0.945

Note:***, **, * denote significance levels at 1%, 5%, and 10%, respectively; figures in parentheses represent robust standard errors, values in square brackets are p-values, and numbers in curly braces are the critical values from the Stock-Yogo weak identification test at the 10% level.

Furthermore, the instrumental variables cleared the LM test with F-values exceeding 10, affirming their statistical validity and appropriateness. These findings robustly support a deeper exploration of the interplay between the digital economy and environmental pollution.

5.2 Replace explained variables

We substituted the main explained variable for its subcomponents sulfur dioxide emissions, water pollutants, and solid pollutant discharge to verify the robustness of our

TABLE 9 Regression with substitute dependent variables.

Variable	Sulfur dioxide emissions	Wastewater discharge	Solid pollutant emissions
	(22)	(23)	(24)
Dtf	−0.602***	−0.75***	−1.63***
	(0.575)	(0.292)	(0.556)
control variables	yes	yes	yes
region effects	yes	yes	yes
time effects	yes	yes	yes
N	360	360	360
adj R2	0.976	0.944	0.919

regression analysis. The modified regression outcomes, presented in Table 9, demonstrate that the results remain robust even after this substitution. This further solidifies the reliability of our regression findings.

5.3 Heterogeneity analysis

At present, various regions in China are at different stages of industrialization and economic development levels, which leads to differences in both environmental pollution and the development of the digital economy. Therefore, in accordance with China's regional planning standards, specifically as shown in Figure 4, it is necessary to analyze the sub-samples from the three regions in order to better understand these differences. The regression results are presented in Table 10.

Table 10 reveals that the impact of the digital economy on environmental pollution is negative across eastern, central, and western regions. However, the most substantial negative impact is observed in the western region, followed by the central and the least in the eastern region. This trend may be attributed to the high level of environmental pollution and the relatively undeveloped the digital economy in the western region, resulting in the largest marginal utility of the digital economy interventions on environmental pollution. In contrast, the digital economy in the eastern region, being more developed and shows a diminishing marginal effect due to lower levels of environmental pollution. Despite this, the development of digital economy remains crucial in the eastern region, which possesses more experience in reducing environmental pollution through digital means. Therefore, the central and western regions could benefit significantly from adopting the eastern region's strategies.

6 Conclusion and policy implications

This study constructs a digital economy development indicator system for 30 provinces spanning from 2011 to 2022, taking into account both government environmental governance and public environmental concerns as the starting points. Utilizing fixed-effect models, spatial econometric models, and an instrumental variable system, it examines the mechanisms of how digital economy development contributes to environmental pollution control. The key findings are as follows: 1) The development of the digital economy significantly reduces environmental pollution, promoting regional green transformation and development. 2) This reduction in environmental pollution is achieved through the government's pre-event focus on environmental governance, in-event investment in pollution control, and post-event enforcement efforts. 3) Public environmental concern positively moderates the relationship between the digital economy and environmental pollution, enhancing the impact of the digital economy on government environmental regulations. 4) The impact of the digital economy on environmental pollution exhibits a spatial spillover effect, where the development of the digital economy reduces pollution in a given region while also lowering pollution levels in surrounding areas.

According to the conclusion, the following suggestions are made:

(1) Vigorously promote the development of the Dtf and improve relevant policies and safeguard systems. Promote the Dtf: strengthen the construction of infrastructure such as 5G and big data, promote the digital transformation of industry, develop new business forms such as platform economy, innovate the application of technology, improve data management and laws and policies, optimize the business environment, train digital talents, narrow the digital divide, and build a healthy and sustainable Dtf ecology.
(2) Give full play to the guiding role of the Dtf in green development through government environmental governance. We will strengthen local governments' attention to environmental governance and enhance their environmental supervision capabilities. We will increase investment in Pol control and improve the government's ability to improve the ecological environment. Strengthen government environmental law enforcement and administrative penalties through information and technology, so as to promote Pol reduction.

FIGURE 4
Regional division of eastern, central and western regions.

TABLE 10 Regional heterogeneity.

Variable	Eastern region	Central region	Western region
	(25)	(26)	(27)
Dif	−0.440***	−1.673***	−4.310***
	(0.153)	(0.639)	(1.977)
control variables	yes	yes	yes
region effects	yes	yes	yes
time efects	yes	yes	yes
the number of regions	11	8	11
N	132	96	132
adjR2	0.976	0.989	0.924

(3) Improve the construction of government public service platforms and improve the channels for the public to express environmental demands. The Dtf will guide the public to pay attention to and participate in environmental governance. With the help of digital technologies and platforms, local governments and social forces are encouraged to interact and cooperate in Pol control, and a collaborative environmental governance system with government supervision as the leading role and public participation as the auxiliary role is better established, so as to improve the public's participation in and supervision of government environmental governance, and thus strengthen the effect of Pol control.

(4) To harness the positive spatial spillover effects of the digital economy on environmental pollution, we should enhance inter-regional communication and cooperation. Through regular dialogues, information sharing, personnel training, and exchange programs, we can facilitate the transfer of technology and expertise from advanced regions to less-developed ones. Additionally, leveraging the technological advantages of the digital economy, we should promote green digital technologies, optimize industrial layouts, and strengthen environmental oversight, ultimately achieving the coordinated development of the digital economy and environmental protection.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://idf.pku.edu.cn/yjcg/zsbg/index.htm.

Author contributions

KL: Conceptualization, Software, Writing–original draft. FM: Data curation, Methodology, Writing–review and editing.

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Conflict of interest

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

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