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Does Digital City Construction Contribute to Air Pollution Control? Evidence from China

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Abstract: With the quick advancement of new generation information technologies like the Internet, big data, cloud computing, artificial intelligence, and blockchain, digitalization is emerging as a crucial tool for restructuring factor resources, reshaping the economic landscape, and altering competitiveness. However, there is no literature on the impact and mechanism of digitalization on environmental pollution management. Thus, this study measured the level of digital development in each province using principal component analysis based on panel data of 30 Chinese provinces during 2006–2019. On this basis, the impact of digitalization on haze and its mechanisms were explored using regression models and mediating effect models, respectively. The findings demonstrate that (1) haze pollution may be reduced through digital progresses, and there is an inverse U-shaped non-linear link between them, that is, as digital technology is refined, its impact on haze pollution shifts from facilitation to suppression; (2) digital development can reduce haze pollution by promoting technological innovation and improving the efficiency of environmental management; and (3) there is regional heterogeneity in the influence of digitalization on air pollution. In heavily polluted areas, the suppression effect of digital technology on air pollution is more than three times that of other areas. The goal of this study is to investigate how digitalization affects haze pollution and its mechanisms, as well as to offer some scientific guidance for China's efforts to build a "Digital China" under the banner of digitalization.

Keywords: digital city construction; air pollution; technological innovation; environmental governance effect; China

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1. Introduction

The rapid economic growth in China during the past 40 years of reform and opening up has put considerable strain on the country's natural environment [1], especially in recent years, with the frequent and influential air pollution problems arousing widespread concern in the whole society. According to the Ministry of Ecology and Environment, 53.4% of China's prefecture-level cities had substandard air quality in 2019, and 337 prefecture-level cities accumulated 1666 heavily polluted days for the year. The annual average concentration of $PM_{2.5}$ nationwide in 2019 was 36 micrograms per cubic meter, well above the safety value set by the World Health Organization (10 micrograms per cubic meter). The increase in environmental pollution has brought about a series of social development problems. The heavy deterioration of air quality on the one hand leads to a decrease in urban attractiveness, a decrease in factor inflow, and a restriction in the development of agglomeration effects [2], resulting in a slowdown in human capital accumulation and insufficient innovation dynamics, which seriously restricts the quality of China's economic and social development. According to the World Bank Organization, environmental issues cause China to lose up to 10% of its yearly gross domestic product (GDP). On the other hand, severe air pollution continues to affect the physical health of the population and reduces life expectancy [3–6]. Therefore, in recent years, the prevention and management of air pollution has been highly valued by Chinese government at all levels, and governance measures have been introduced such as the Ambient Air Quality Standards, the Action Plan for the Prevention and Control of Air Pollution, and the Three-Year Action Plan for the Promised Blue Sky Defense, to strengthen supervision and enforcement efforts in an effort to continuously improve China's air quality [7]. By the end of 2021, the annual average $PM_{2.5}$ concentration in 339 cities nationwide was 30 μg per cubic meter, a decrease of about 40% from 2015, but more than one-third of cities still failed to meet air quality standards, which means that China's air pollution management situation is still grave [8]. Therefore, a critical issue that China must quickly address in the course of green growth is how to enhance the ecological environment while guaranteeing the smooth functioning of the economy.

The term "digital city construction" refers to raising the level of informationalization of a city by utilizing digital technology to analyze and manage all city operations, including human, material, financial, and informational resources, in order to maximize resource allocation and advance the city's overall development [9]. The construction of digital cities is an important part of the construction of digital China, and is the first practice of the construction of digital China. Accurately grasping the new features, new rules and new trends of digital cities, and scientifically planning the practical path of digital city construction have become the key measures for governments around the world to improve the quality of services, enhance the credibility of the government, and build a service-oriented government that satisfies the people. Building a digital city is not simply a matter of integrating information technology, but of taking full advantage of information technology within the framework of the country's overall development, especially internet technology and the accurate usage of multifaceted data to inform decisions on all aspects of social life and to support the efficient functioning of the city. Digital technologies based on information and the internet are currently leading new social changes [10–12]. China, the greatest developing nation in the world, has started building new infrastructure to hasten the advancement of digital technologies like 5G, data centers, cloud computing, and the Internet of Things (IoT). Digitalization not only enables dynamic environmental monitoring and information technology for government environmental supervision, but also promotes deeper public participation in environmental protection and the intelligence of the environmental protection industry. Specifically, the use of digital technologies such as big data and cloud computing has enabled real-time dynamic monitoring of environmental information covering air, rivers, and soils, providing a basis for identifying problems and solving them, and providing technical support for the government's environmental decisions [13–16]. By enabling resource scheduling, information linkage, and resource sharing, as well as by providing information support for the government to improve regulatory efficiency and strengthen the effectiveness of regulatory enforcement, the level of environmental information applications has increased with the maturation of information technology. The public may now obtain environmental information, raise their level of knowledge, and take part in environmental conservation thanks to the development of digital technology. The "Internet+" has significantly altered the environmental protection industry, providing opportunities for businesses to pursue product innovation, create clean production techniques, achieve green and low-carbon enterprise development, and promote economic restructuring of the industry by accelerating the industrialization of environmental technology advancements to achieve industrial upgrading and resource recycling. Digitalization is consequently viewed as a crucial tool for attaining a "win-win" scenario in terms of economic growth and environmental preservation in the goal of sustainable development. It is thus clear that digitalization is becoming an important driver of quality urban and regional development in the future, which is an urgent requirement for action on climate change. Discovering the impact of digital development on air pollution at the regional level and its mechanisms will, on the one hand, provide an in-depth study of urban digitalization and, on the other hand, provide empirical research to reduce regional disparities and achieve a common wealth and a sustainable city of the future. Based on the above analysis, this study explores two questions: whether digital city construction can have an impact on regional air pollution control, and how such an impact exists. To address these two questions, this paper examines the effects of digitalization on regional air pollution and its mechanisms utilizing inter-provincial-level panel data, regression models, and mediating effects models in China from 2006 to 2019. The conclusions have significant ramifications for managing and enhancing local environments as well as creating long-term sustainable development plans.

This paper has the following innovations: first, it constructs a new, multi-dimensional indicator system for digital development, mainly including four aspects: digital infrastructure, digital economy, digital industry, and digital application, which provides a reference for constructing development indicators for digital city construction. Second, the inclusion of digital city development into a thorough economic-energy research framework not only offers a fresh viewpoint on local environmental governance but also expands the field of environmental economics study. Finally, this paper takes digital city construction as an entry point in the context of digital China, and explores the effectiveness of digitalization in combating environmental pollution. In addition to extending the field of study on urban and environmental economics, this study also offers a solid scientific foundation for the use of digital platforms and technologies in environmental rehabilitation. For example, our findings demonstrate the effectiveness of digitalization in tackling haze pollution, thus encouraging countries around the world to actively explore new environmental governance models that combine modern information technology with environmental governance, especially for developing countries that are in transition or facing serious environmental pollution problems (e.g., India, Iran, etc.).

Section 2 reviews the literature on air pollution. Section 3 analyses the mechanisms of digitalization and air pollution. Section 4 describes the data and methods used. Section 5 presents the results and discussion of the empirical analysis, and the final section concludes with a summary and policy recommendations.

2. Literature Review

Currently, numerous academics have researched different aspects of air pollution, and their results all indicate that the most harmful substance affecting air quality is $PM_{2.5}$ [17,18]. The factors that contribute to the continuous increase in $PM_{2.5}$ concentrations can be attributed to natural and social factors, which cover regional economic development, industrial structure, environmental regulations, and urbanization [18–21]. The influence of information technology on environmental pollution is receiving increasing attention as a result of the advancement of information technology, such as the Internet, but the relationship between the two mentioned above is still somewhat controversial due to different research backgrounds, research fields, and research methods.

First, some scholars argue that the information technology on which digitalization is based can exacerbate air pollution in a region. Both Sadorsky [22] and Park [23], for example, highlight the fact that the manufacturing process of information and communications technology (ICT) equipment, as well as its operation, consumes large amounts of resources, which undoubtedly increases the region's dependence on fossil fuels. In addition, the disposal of used electronic equipment also increases the risk of environmental pollution. Second, some scholars emphasized the effect of ICT on air quality improvement. For example, the empirical studies of Ozcan and Apergis [24] showed that the development of ICT causes a reduction in air pollution levels. Wu et al. [25] argue that the diffusion of information technology achieves the intelligence of environmental governance, thus reducing the level of resource mismatch and environmental pollution. In addition, the diffusion of advanced technology can be spread through the ICT, which indirectly influences the upgrading of industrial structure and the green transformation of enterprises. Therefore, ICT has a positive impact on regional air pollution. Finally, some scholars have found a non-linear relationship between ICT and air pollution. For example, Higón [26] empirically investigated the possibility that ICT development would initially increase pollution emissions and reduce them later, using both developing and developed countries as samples.

In conclusion, prior research has offered several theoretical frameworks and empirical investigations for the understanding of the connection between ICT and environmental contamination, however there are still gaps. First, some scholars have only emphasized the impact of information technology or Internet technology, ignoring the digital character of environmental governance, and digitalization is not regarded by academics as an emergent component in the study of air pollution in the context of digital China. Second, digital indicators are not sufficiently measured in depth. Scholars ignore the reality that digital growth is a multi-dimensional and comprehensive system and instead use a single indicator to gauge the amount of Internet or information development. Third, the mechanisms by which digitalization affects air pollution are not mentioned. It would be beneficial for different areas to develop acceptable environmental management strategies to reach a "win-win" scenario for both economic and environmental protection by investigating the transmission channels of digital influence on air pollution.

3. Theoretical Framework

Digital technology allows for a natural advantage in the dissemination and sharing of information [27,28]. With the spread and improvement of digital technology, the model of environmental governance is also undergoing significant changes [14,29,30]. At the moment, China uses a composite model to control its environmental pollution, and digital refinement has made this model more effective. The merging of environmental governance with mobile Internet, big data, cloud computing, and other new physical objects has transformed the field's conventional model while also generating effective new ones [14,16]. Digitalization has made it easier for managers to collect environmental information, improving policy decisions as well as management efficiency. At the same time the cloud is free from physical entities and compresses pollution emissions to a minimum [31]. Even the sharing economy has emerged as a result of digitalization, which has decreased the number of journeys made in private vehicles and cut down on energy usage. The use of digital technology thus enhances the effectiveness of resource distribution and curbs haze pollution. This implies that the development of digitalization has a dampening effect on air pollution.

Digital technology itself contains a certain amount of technological innovation, and technological innovation, in turn, can improve air quality by increasing business productivity and offsetting environmental protection costs [32]. The accumulation of innovation capital throughout society in the sharing and transmission of information drives the technological progress of human society. Likewise, one of the most critical ways to advance environmental governance is through technology [33], with digital technology reducing energy consumption in production processes and increasing the intelligence of the environmental industry through technological advances. The improvement of information technology allows for the application of innovative cleaning methods to various systems, increasing the efficiency of resource use in companies and improving the level of air pollution control, thus reducing air pollution [34–36]. In addition, digitalization has brought about huge changes to the environmental industry. The benefits of digital platforms have given businesses the chance to pursue product innovation and environmental improvements. It encourages the economic restructuring of the environmental protection business by hastening the industrialization of scientific and technological advancements in that sector. Thus, digitalization can reduce air pollution by enhancing technological innovation.

Digital technology enables an accurate grasp of the state of the environment through big data, which on the one hand can aid in the scientific decision-making and correct research of policy makers, and on the other hand can avoid the dislocation of subjects in the process of environmental regulation. However, the state of the air is a responsible project that requires not only the intervention of environmental regulators, but also the extensive participation of citizens [37,38]. Digital platforms offer new models in terms of access to information, enhanced participation, and increased awareness [39]. On the one hand, the various information covered by environmental big data can be presented to residents through digital platforms, allowing them to learn about environmental regulation, environmental governance, and the state of environmental change in real time and in all aspects [40–42]; on the other hand, through a variety of informational channels, the public can notice environmental contamination, which plays a critical role in environmental monitoring [38,43,44]. Digitalization can break down the barriers of information asymmetry between environmental subjects and achieve a double insurance of environmental supervision. This not only compensates for the absence of conventional monitoring instruments, but also increases the effectiveness of supervision and enriches new monitoring tools. Thus, digitalization can strengthen the participation of multiple subjects and facilitate a change in the way the government manages the environment, thereby reducing air pollution.

In conclusion, Figure 1 of this study presents a theoretical framework for the effect of the development of digital cities on haze pollution.

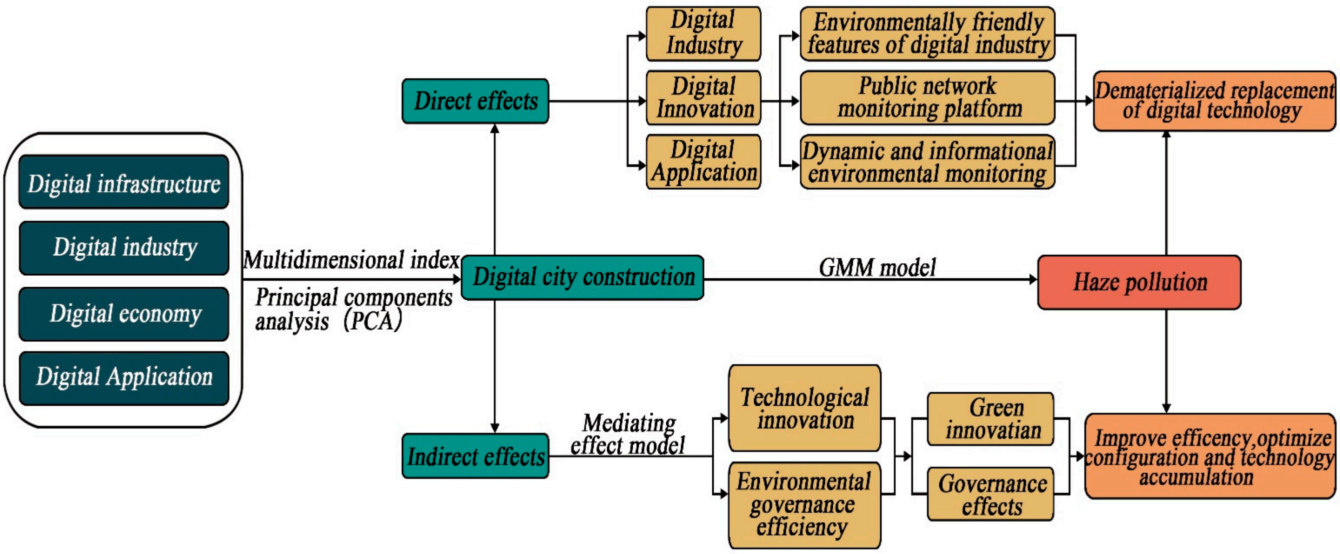

Figure 1. Conceptual framework of the impact of digitalization on haze pollution.

4. Data and Methods

4.1. Data

4.1.1. Air Pollution Indicator

Previous literature has pointed out that the most hazardous substance affecting air quality is $PM_{2.5}$, so in this study we used the annual average $PM_{2.5}$ concentrations in each region as a quantitative indicator of air pollution. Based on the annual global $PM_{2.5}$ concentration maps published by the Center for International Earth Science Information Network (CIESIN), we calculated the annual average $PM_{2.5}$ concentrations for each province in China from 2006 to 2019. It should be particularly emphasized that the haze pollution data we obtained are consistent with the haze analysis launched by the Ministry of Environment for China; in addition, this dataset has been widely used in other studies, so the data is highly reliable [45–47].

4.1.2. Digitalization Level (DIGL)

Because there is currently no comprehensive index or assessment criteria to evaluate the extent of digitalization, it is complex and complicated to define. Based on the existing research content and our previous research results [9], the quantitative index system of digitalization measurement contains a total of 14 indicators in four categories, including digital infrastructure (DIGI), digital economy (DIGE), digital industry (DIGD), and digital application (DIGA), as shown in Table 1, and the digital development level of each province from 2006 to 2019 is shown in Figure 1.

Table 1. Comprehensive quantification system of the digitalization level.

First-Level	Second-Level Indicator	Third-Level Indicator	Unit
Digitalization level (DIGL)	Digital infrastructure construction (DIGI)	Internet penetration rate	%
		Number of Internet broadband access ports	10^4
		Number of Internet domain names	10^4
		Length of fiber optic cable lines	10^4 km
	Digital economy (DIGE)	Number of employed persons in units related to information technology, transmission, and software services	10^4
		Software business revenue	10^4 yuan
		Export value of high-tech products as a percentage	%
	Digital industry (DIGD)	R&D expenditure of industrial enterprises above the scale as a percentage	%
		Total telecommunication business	10^8 yuan
		Number of high-tech enterprises	-
	Digital application (DIGA)	Enterprise informatization level	%
		E-commerce transaction volume	10^8 yuan
		Total express delivery business	10^4
		Number of digital TV subscribers	10^4

4.1.3. Other Variables

In addition to $PM_{2.5}$ and digital variables, this study includes some other variables. We use total population (TOP), GDP per capita (GDP), and R&D intensity (TEC) to represent population, wealth, and technology, respectively [48,49]. In addition, previous studies have found that the industrial structure (INS), urbanization (URB), trade openness (TRA), green area per capita (GRC), transport infrastructure (TRI), and population density (POD) can affect $PM_{2.5}$ concentration, so we controlled for these variables in our empirical study [50–56]. Finally, we explored the mechanism of digitalization affecting $PM_{2.5}$ changes by using environmental governance effects (EGE) and technological innovation (TEI) as mediating variables. For this study, the data from 30 provinces in China (including autonomous regions and municipalities) from 2006 to 2019 were chosen. The website of the National Bureau of Statistics, the China Statistical Yearbook, China Construction Yearbook, and China Science and Technology Yearbook were utilized to gather the macro data for the study. Please consult Table 2 for information on all variables.

4.2. Methods

4.2.1. Basic Model

The theoretical foundation of this study was derived from a very well-liked model, namely the IPAT model [57–60], A quantitative relationship model representing the impact of human activities on the environment (I represents environmental pressure, P represents population, and A represents wealth). The model presentation is specified as follows:

$$PM_{2.5} = F(TOP,GDP,TEC) \tag{1}$$

In this equation, TOP stands for population, GDP stands for wealth, and TEC stands for technological progress. As mentioned earlier, the change in $PM_{2.5}$ is affected by various other factors, so this paper considers other influencing factors as well in the research framework, and the model was improved further as follows:

$$PM_{2.5} = F(TOP, GDP, TEC, \text{Other variables}) \tag{2}$$

The other variables in Equation (2), i.e., represent the various factors that affect the levels of $PM_{2.5}$. Based on this, we added a digital proxy scalar to Equation (2) as another key factor affecting $PM_{2.5}$ levels, and the obtained model is shown below.

$$PM_{2.5} = \beta_0 + \beta_1 TOP_{it} + \beta_2 GDP_{it} + \beta_3 TEC_{it} + \beta_4 DIGL_{it} + \alpha_i + v_t + \varepsilon_{it} \quad (3)$$

where $B_0 \sim \beta_4$ represent the coefficients of each variable; α_i and v_t represent the inter-provincial and time effects, respectively; and ε_{it} represents the random error term. In addition, we also included the quadratic term of the digitalization indicator in the model as a way to test the non-linear relationship between it and $PM_{2.5}$ emissions. Due to the fact that not all factors impacting $PM_{2.5}$ emissions were chosen, some significant explanatory variables may have been missed, which might have caused a link between the independent variables and the error terms and, consequently, endogeneity. Based on this, we constructed a Generalized Method of Moments (GMM) model based on instrumental variables for the empirical analysis.

Table 2. The descriptive statistics of variables mentioned in this paper.

Variables	Symbol	Obs.	Mean	Std. Dev.	Min	Max	Unit
Digitalization level	DIGL	420	0.141	0.118	0.019	0.822	-
Digital infrastructure construction	DIGI	420	0.072	0.047	0.003	0.274	-
Digital economy	DIGE	420	0.022	0.026	0.001	0.161	-
Digital industry	DIGD	420	0.014	0.023	0.001	0.175	-
Digital application	DIGA	420	0.032	0.032	0.001	0.230	-
$PM_{2.5}$	$PM_{2.5}$	420	41.517	14.617	9.566	85.628	mg/m^3
Population density	POD	420	2820.336	1214.976	597	6307	
Urbanization rate	URB	420	54.651	13.549	27.461	89.600	%
Transport infrastructure	TRI	420	14.241	4.648	4.045	26.211	$person/m^2$
Energy consumption	ENC	420	4.209	2.645	1.032	15.677	kwh/person
Total population	POP	420	4479.481	2685.198	545.450	11433.477	ten thousand person
GDP per capita	GDP	420	42357.391	26631.844	6103	164563	yuan
R&D intensity	TEC	420	1.491	1.094	0.201	6.311	%
Industrial structure	INS	420	1.188	0.662	0.527	5.234	-
Technological innovation	TEI	420	38347.378	65051.132	97	527390	-
Trade openness	TRA	420	3069	3650	126	17874	
Green area per capita	GRC	420	15.581	12.582	1.905	64.985	$person/m^2$
Environmental governance effects	EGE	420	4.621	3.069	1	17	-

4.2.2. Transmission Mechanism

In this part of the study, we focus on the mechanisms by which digitalization affects $PM_{2.5}$ emissions. We mentioned in the previous analysis that digitalization can influence the level of $PM_{2.5}$ concentrations through environmental governance effects as well as technological innovation. The mediating effect refers to the indirect effect that a factor can have on another factor through an intermediate variable [61]. In order to be able to detect the mediating effect of environmental governance as well as technological innovation, a standardized mediating effect model was created. The model equation is shown below.

$$Y = \alpha X + \varepsilon_1 \quad (4)$$

$$M = \beta X + \varepsilon_2 \quad (5)$$

$$Y = \alpha' X + \gamma M + \varepsilon_3 \quad (6)$$

This paper explores the annual average $PM_{2.5}$ concentration as the dependent variable Y, the EGE and TEI as the mediating variable M, and DIGL as the independent variable X to build a mediating effect model.

5. Results and Discussion

5.1. Trends in DIGL and $PM_{2.5}$ over Time

Figure 2 quantifies the development level and average annual growth rate curves of digitalization in 30 Chinese provinces in 2006, 2009, 2012, 2015, and 2018, respectively. From the figure, it can be found that some provinces in the eastern coastal region have a good digitalization foundation such as Shanghai, Guangdong, Jiangsu, Beijing, and Tianjin, which also have the best economic foundations in China. In contrast, the digitalization foundation in the central and western regions is weaker, thus forming a digitalization pattern in which the east is strong, and the west is weak. Nevertheless, the average annual growth rate of digitalization in the central and western provinces is high and even exceeds that of some eastern provinces, indicating that the digitalization level of the central and western provinces has developed rapidly in the past 10 years and regional disparities in digitalization are progressively closing. The central and western regions will see more fast development in their degree of digitalization in the future due to the steady movement of digital industries and infrastructure from coastal to interior areas, giving them a significant latecomer advantage.

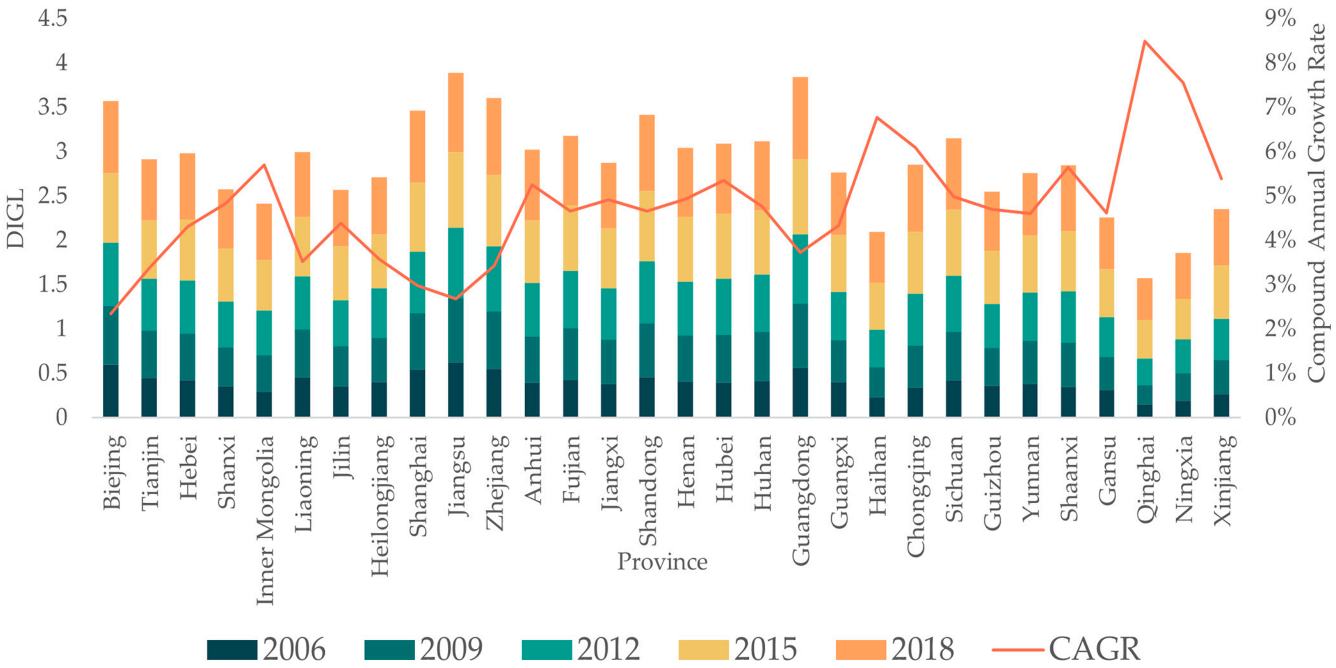

Figure 2. Temporal trends of digital development and its average annual growth rate in 30 provinces (autonomous regions and municipalities).

Figure 3 quantifies the changes in $PM_{2.5}$ concentrations and the curves of the annual average rate of change for 30 Chinese provinces in 2006, 2009, 2012, 2015, and 2018. Overall, the haze pollution situation was more severe in the eastern regions compared to the western regions, such as the Beijing–Tianjin–Hebei urban agglomeration, which had the highest $PM_{2.5}$ concentrations, although it is also known for being the most economically developed region. In contrast, the central and western areas had less haze pollution and less environmental stress. From 2006 to 2018, $PM_{2.5}$ emissions were gradually decreasing in various provinces across the country, indicating a gradual improvement in the haze situation. With the increasing environmental pressure, the government has gradually adopted pollutant emission limits as a constraint target and has continuously strengthened its environmental responsibility. After a decade-long change in development philosophy and the implementation of reform measures, pollutant emissions have been effectively controlled and the effect of environmental management has been enhanced. The $PM_{2.5}$

concentration continues to show a negative growth, indicating that China's environmental problems are being continuously improved.

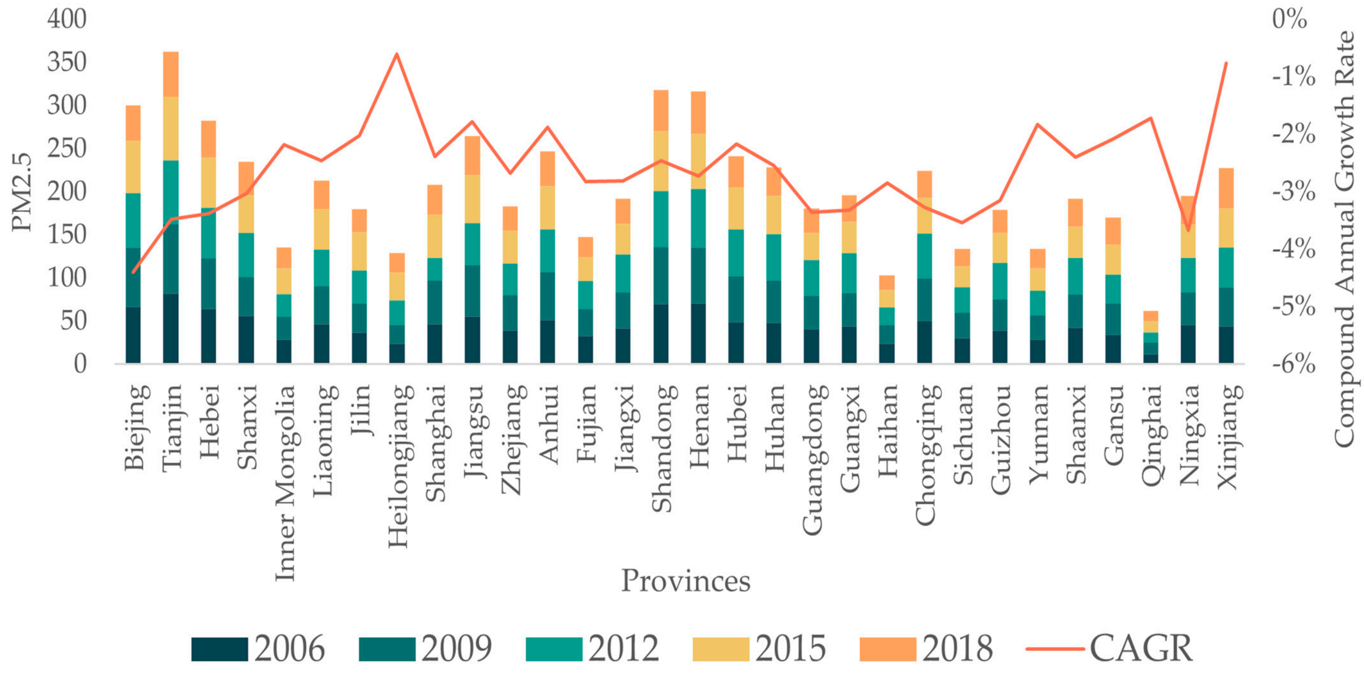

Figure 3. Temporal trends of $PM_{2.5}$ and its average annual growth rate in 30 provinces (autonomous regions and municipalities).

5.2. Benchmark Model

In the benchmark model, we first explored the effect of digitalization on $PM_{2.5}$ emissions. The results are shown in Table 3. In the absence of any control variables, digitalization was positively correlated with $PM_{2.5}$, while the square of digitalization was significantly negatively correlated with $PM_{2.5}$, which indicates that there is a non-linear relationship between the effect of digitalization on $PM_{2.5}$, i.e., the relationship between digitalization and $PM_{2.5}$ shows an inverted U-shaped curve. Even with the inclusion of control factors, the non-linear association between digitalization and $PM_{2.5}$ was still present and significant. Second, to address the potential endogeneity issue, we used the analytical results of the GMM model for comparative analysis. From the fourth column of Table 3, we can see that the p-value of Wald χ^2 was less than 0.000, demonstrating that the model is valid, and the p-value of Hansen test was greater than 0.05, indicating that the chosen instrumental variable is valid. The GMM results showed that digital city construction can significantly affect $PM_{2.5}$ emissions, and this effect shows a non-linear relationship of increasing and then decreasing. The possible reason for this is that at the initial stage of digital city construction, the massive construction of infrastructure causes huge energy consumption, which accelerates the increase in regional haze pollution [26]. In addition, at this stage there are problems such as weak regulation and imperfect regulatory technologies [62]. Therefore, at this stage, it is difficult for digitalization to suppress the large-scale haze pollution. At the second phase of digital development, combining the improvement of technology and the completion of infrastructure, on the one hand, the update of technology promotes the innovation of enterprise technology, accelerating green and low-carbon development, and achieving improvements in resource utilization efficiency as well as in energy-saving and emission reduction efficiency, thus reducing haze pollution. The increasing popularity of digital technology has improved the level of application of environmental information, realized resource sharing and information linkage [14,16], compensated for the lack of regulatory tools and the inefficiency of regulatory enforcement, and proposed a certain aspect of support for reducing environmental pollution [63].

Table 3. The results of the benchmark model.

Variables	Static Panel Model (OLS) $PM_{2.5}$	$PM_{2.5}$	GMM Model $PM_{2.5}$
DIGL	58.373 ** (5.655)	43.598 ** (2.926)	4.244 * (2.220)
sDIGL	−80.477 ** (−9.177)	−69.837 ** (−7.355)	−3.415 ** (−2.969)
GDP		22.047 ** (5.153)	0.039 (0.200)
POP		−62.946 ** (−2.938)	0.176 (1.653)
TEC		4.361 (0.774)	0.771 ** (7.894)
POD		0.816 (0.293)	−0.189 ** (−2.949)
URB		−43.509 ** (−3.810)	−0.150 (−1.314)
TRI		−0.485 (0.124)	0.136 (2.565)
TRA		5.294 (1.261)	0.434 ** (5.422)
ENC		7.839 (1.384)	0.010 (0.131)
GRC		−3.002 (−0.763)	−0.203 ** (−3.199)
INS		7.222 (1.659)	0.189 * (2.192)
_cons	36.974 ** (12.445)	87.441 ** (5.292)	−1.004 * (−2.321)
F-value/Wald $\chi 2$	194.099 ** [0.000]	41.607 ** [0.000]	309.524 ** [0.000]
R^2/Hansen test	0.500	0.566	0.588 [0.451]
Control variables	No	Yes	Yes
N	420	420	420

Note: * and ** indicate significance at the 5% and 1% levels, respectively. The numbers in () are the t values of the associated statistics, whereas the numbers in [] are the p values.

5.3. Robustness Test

The results of the regression analysis after handling the extreme values and modifying the sample interval are summarized in Tables 4 and 5, respectively. The results of both the panel regression and GMM model indicate that the association between digitalization and $PM_{2.5}$ emissions is non-linear and inverted U-shaped, with the influence of digitalization indicators being highly positive and the square of digitalization coefficients being strongly negative. After reaching its maximal influence on $PM_{2.5}$ emissions, digitalization progressively diminished and then began to suppress $PM_{2.5}$ emissions. The findings of the control variables did not significantly alter the results, and the robustness test results agreed with the regression results obtained from the benchmark model. Consequently, this paper's findings are reliable.

5.4. Mechanism Analysis

Table 6 presents the statistical results from the mediating effects model with technological innovation as the mediating variable. Additionally, the model is useful since it does not contain 0 in the 95% confidence interval of the mediating effect that was derived using the Bootstrap approach. The results in column (1) of the table indicate a non-linear relationship between digitalization and $PM_{2.5}$ emissions, which is consistent with our previous results using static panel regressions. From the results in column (2) we find that the relationship between digitalization and the mediating variable of technological innovation showed a significant positive relationship, suggesting that the development of digital technology can promote technological innovation. In column (3), we discover that the mediating variable's coefficient was strongly negative, showing that technological innovation can help digitalization lower regional $PM_{2.5}$ emissions. Therefore, the transmission mechanism that digitalization can influence regional $PM_{2.5}$ emissions through technological innovation is valid.

Table 4. Robustness analysis results after removing the extreme values.

Variables	**Static Panel Model (OLS)**		**GMM Model**
	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{2.5}}$
DIGL	75.652 ** (5.24)	62.279 ** (32.564)	1.227 * (2.078)
sDIGL	−93.551 ** (−8.532)	−98.967 ** (−7.284)	−2.229 ** (−3.720)
GDP		19.466 ** (4.678)	0.382 (1.465)
POP		−27.495 (−1.400)	0.479 ** (5.552)
TEC		7.513 (1.235)	0.804 ** (8.727)
POD		−0.303 (−0.082)	0.029 (0.524)
URB		−18.886 ** (−2.992)	−0.196 (−1.156)
TRI		4.401 (1.551)	0.184 ** (3.174)
TRA		5.557 (0.686)	0.273 ** (4.958)
ENC		9.997 (1.552)	0.128 (1.438)
GRC		−8.882 (−1.338)	−0.145 * (−2.147)
INS		6.428 (1.610)	0.039 (0.624)
_cons	32.102 ** (8.270)	42.531 ** (3.890)	−0.104 (−1.424)
F-value/Wald $\chi 2$	192.517 ** [0.000]	71.556 ** [0.000]	245.346 ** [0.000]
R^2/Hansen test	0.531	0.554	0.281 [0.626]
Control variables	No	Yes	Yes
N	380	380	380

Note: * and ** indicate significance at the 5% and 1% levels, respectively. The numbers in () are the t values of the associated statistics, whereas the numbers in [] are the p values.

The statistical findings of the study of the mediating effect model using the EGE as a mediating variable are shown in Table 7. It can be found that the coefficient of the mediating variable of EGE was significantly negative, indicating that digitalization can influence $PM_{2.5}$ emissions by enhancing the environmental governance effect. The development of digital technology and the construction of digital platforms have enhanced the collaborative work of environmental pollution regulatory bodies on the one hand and stimulated public participation in environmental pollution management on the other. Thus, digitalization based on information technology and Internet technology might lessen haze pollution through two mediating factors, technical innovation and effective environmental regulation, and this result is consistent with the findings of Varian [27] and Aduretsch [64].

Table 5. Robustness analysis results after adjusting the sample interval.

Variables	Static Panel Model (OLS)		GMM Model
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
DIGL	63.975 ** (5.011)	50.359 * (2.585)	1.237 * (2.081)
sDIGL	−83.186 ** (−7.759)	−73.740 ** (−6.130)	−2.075 ** (−5.055)
GDP		16.241 * (2.074)	0.039 (0.200)
POP		−61.122 * (−2.371)	0.176 (1.653)
TEC		7.122 (1.148)	0.771 ** (7.894)
POD		−0.303 (−0.082)	−0.099 * (−2.083)
URB		−25.107 ** (−2.723)	−0.411 ** (−2.756)
TRI		6.583 (1.307)	0.168 ** (3.325)
TRA		4.174 (0.888)	0.336 ** (6.044)
ENC		7.839 (1.384)	−0.105 (−1.437)
GRC		−5.834 (−1.297)	−0.068 (−1.168)
INS		5.266 (1.139)	0.039 (0.624)
_cons	35.127 ** (9.394)	68.017 ** (3.890)	−1.004 * (−2.321)
F-value/Wald χ2	128.292 ** [0.000]	25.254 ** [0.000]	411.482 ** [0.000]
R^2/Hansen test	0.436	0.488	0.432 [0.272]
Control variables	No	Yes	Yes
N	360	360	360

Note: * and ** indicate significance at the 5% and 1% levels, respectively. The numbers in () are the t values of the associated statistics, whereas the numbers in [] are the p values.

Table 6. Results of the analysis of TEI as a mediating effect.

Variables	M = TEI/Explained Variable = $PM_{2.5}$		
	(1)	(2)	(3)
DIGL	2.037 ** (5.595)	10.952 ** (10.796)	0.390 (1.042)
sDIGL	−1.616 ** (−5.177)	-	−1.487 ** (−5.233)
M			0.150 ** (9.409)
_cons	−0.182 (−1.772)	3.333 ** (11.653)	−0.683 ** (−6.356)
F-value	17.581 ** [0.000]	1808.480 ** [0.000]	43.909 ** [0.000]
Adj R^2	0.079	0.897	0.235
Control variables	No	No	No
N	420	420	420

Note: ** indicate significance at the 1% levels. The numbers in () are the t values of the associated statistics, whereas the numbers in [] are the p values.

5.5. Heterogeneity Analysis

Given that regional growth might have an impact on both the degree of digital technology development and the levels of $PM_{2.5}$, there may be some regional differences in the relationship between the two [65]. In this study, we divided the 30 provinces (municipalities and autonomous regions) of China into eastern and central-western regions and conducted regression analyses, the results of which are shown in Table 8. After controlling for the effects of the relevant variables, we discovered that $PM_{2.5}$ emissions were impacted by digital development in both the eastern and central-western areas. Specifically, in both eastern and western regions, digital development promoted $PM_{2.5}$ emissions in the early stages and suppressed $PM_{2.5}$ emissions in the later stages. It was also found that the more polluted eastern regions were more affected by digital technology than the central and western regions. This is not difficult to understand, as in the eastern region, the pressure of performance assessment on local governments tends to result in a one-sided pursuit of economic growth at the expense of environmental management. As a result, in the beginning stages of economic development, haze pollution became more and more serious as digital technology was constantly updated. As the economy develops further, residents become increasingly aware of the importance and urgency of environmental management, and thus digital technology becomes more and more powerful in suppressing haze pollution. Figure 4 plots the trend of the changes in the quantile regression coefficient of $PM_{2.5}$ concentration. From the trend of the regression coefficients, it can be found that as $PM_{2.5}$ concentrations increase, digitalization became more and more suppressive of $PM_{2.5}$ emissions, indicating that promoting digitalization in areas with serious haze pollution can achieve greater environmental benefits and future development potential, a result that is consistent with the previous regression results.

Table 7. Results of the analysis of EGE as a mediating effect.

Variables	**M = EGE/Explained Variable = $PM_{2.5}$**		
	(1)	**(2)**	**(3)**
DIGL	2.804 ** (5.423)	0.366 ** (5.072)	2.574 ** (5.227)
sDIGL	−2.076 ** (−4.976)	-	−1.791 ** (−4.490)
M			−0.326 ** (−6.050)
_cons	−0.498 ** (3.178)	3.333 ** (11.653)	−0.293 (−1.919)
F-value	18.463 ** [0.000]	1808.480 ** [0.000]	25.848 ** [0.000]
Adj R^2	0.096	0.080	0.185
Control variables	No	No	No
N	420	420	420

Note: ** indicate significance at the 1% levels. The numbers in () are the t values of the associated statistics, whereas the numbers in [] are the p values.

Table 8. Analysis of the regional heterogeneity of digitalization on $PM_{2.5}$ emissions.

Variables	**GMM Model**	
	Eastern Region	**Central and Western Regions**
	$PM_{2.5}$	
DIGL	19.594 * (2.066)	8.225 * (2.215)
sDIGL	−27.156 * (−2.145)	−9.756 ** (−2.643)
POP	0.556 (1.633)	0.780 ** (3.872)
TEC	1.825 ** (3.515)	0.519 ** (3.079)
GDP	0.419 (0.570)	0.772 * (2.327)
_cons	7.720 * (2.130)	−2.196 * (−2.2469)
Wald $\chi 2$	14.569 ** [0.000]	66.654 ** [0.000]
Hansen test	0.037/[0.686]	0.021/[0.868]
Control variables	Yes	Yes
N	182	278

Note: * and ** indicate significance at the 5% and 1% levels, respectively. The numbers in () are the t values of the associated statistics, whereas the numbers in [] are the p values.

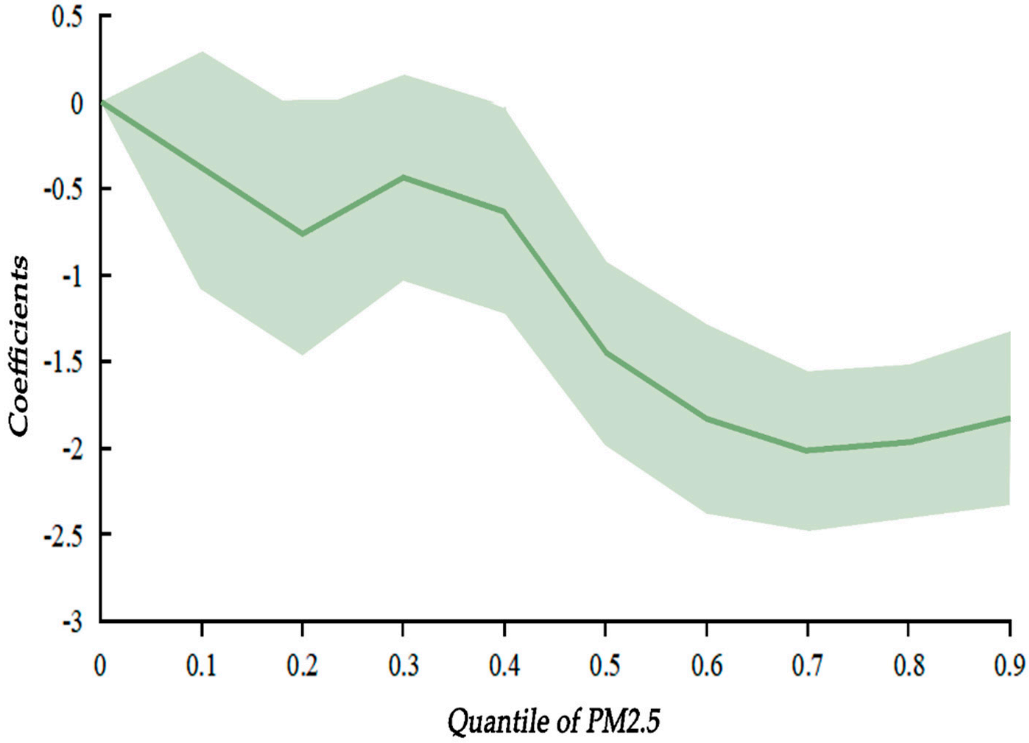

Figure 4. Variation trend of quantile regression coefficient of $PM_{2.5}$.

6. Conclusions and Policy Recommendations

This paper first constructed a comprehensive quantitative index system of digital city construction level, and empirically tested the impact of digital development on air pollution using a GMM model and quantile regression model. Second, to examine the transmission process of digitalization's effects on haze pollution, the mediating effect model was utilized. Finally, the influence of digital development on haze pollution in terms of regional heterogeneity was explored. The following are the study's principal conclusions.

The building of digital cities may greatly reduce haze pollution, and the link between the two exhibits an inverted U-shaped, non-linear relationship. This conclusion has withstood a number of robustness tests. Digital city construction can influence technological innovation and environmental governance effects on haze pollution. Compared to the central and western areas, the eastern region was more affected by the aforementioned consequences of digital development. The implementation of digital development in regions with high environmental pressure can better control haze pollution and thus reduce the negative environmental impact. This research offers insightful recommendations and actions for decision makers to establish future regional environmental management strategies in order to successfully play the crucial role of digitalization in battling haze in the context of digital China. These recommendations, measures, and approaches may contribute positively to China's future development goal of sustainable cities in the face of environmental pressures and economic transformation.

The association between digital development and haze pollution exhibited an inverted U-shaped curve with substantial geographical variation. As Shahnazi [66] mentioned in their study, improving the level of information technology is a key factor to achieve environmental management. Currently, the digital strategy of accelerating digital development and building a digital China has been written into the 14th Five-Year Plan. On this basis, the central government should continue to invest more in new infrastructures such as data platforms to make up for the technical shortcomings of digital development (e.g., data silos, data gaps, and data security) and enhance data service capabilities. In addition, the government should guide enterprises to upgrade digitalization on the one hand, and should guide the flourishing of digitalization-related industries on the other hand to strengthen the transformation and utilization of the results of informatization and industrialization, thereby improving air quality.

Digital development can curb haze pollution through technological innovation. Therefore, local governments should rely on the digital platform, accelerate the improvement of green R&D system, increase R&D investment, promote the transformation of technological innovation end governance to system cycle with the support of data, and use technological innovation to promote green transformation. At the same time, local governments at all levels should rely on data linkage to collaboratively promote the overall improvement of regional green technology innovation and share the results of green technology innovation development and pollution management. Local governments should further promote factor market reform, accelerate the market transformation of R&D resources, promote the establishment and improvement of green technology transfer and transformation market, promote the effective diffusion and application of green and clean technologies, and realize green cycle and low-carbon development.

Digital development can reduce haze pollution by improving the efficiency of environmental management. Local governments should show positive attitudes and support the application of big data and cloud computing technologies in environmental protection. First, local governments should gradually improve the mechanism of accurately targeting public environmental interests based on data collection and research. Second, cross-departmental collaboration based on environmental information sharing should also be emphasized. Finally, a fast and efficient government response mechanism based on real-time perception should be established. The construction of a digital government makes it possible to quickly transmit and interact with data, which greatly compresses the time cost of environmental governance and enhances the ability of intelligent supervision of ecological environment and emergency disposal of environmental risks.

However, there are still some limitations in this study. Our study discusses haze pollution in a non-spatial framework, but ignores the role of space. Haze pollution is characterized by wide coverage, mobility, long hazard cycle, and uneven spatial distribution, and the use of spatial econometric models seems to be more capable of reducing errors in empirical analysis, such as spatial error models, spatial lag models, spatial Durbin models, and semi-parametric geographically weighted regression models. Nevertheless, our study provides an empirical exploration of the relationship between digitalization and air pollution, and the results are still robust and exhaustive, which also provides a basis for the next study of the relationship between digitalization and environmental management based on the comparison of different research methods and the construction of different indicator systems.

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