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The Mediating and Moderating Effects of the Digital Economy on $PM_{2.5}$: Evidence from China

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Abstract: Environmental issues are fundamentally problems of development mode and life style. Meanwhile, the digital economy is an important means of optimizing the economic structure and achieving high-quality economic development, thereby changing the way of production and life, which can improve the aforementioned environmental challenges. Therefore, this research investigates how the digital economy can bring new ideas for reducing pollution in depth. Based on panel data from 285 prefecture-level cities in China, this paper examines the impact of the digital economy on $PM_{2.5}$. We construct the evaluation system of China's digital economy development from the three aspects of digital penetration, digital human resources, and digital output. We use the digital economy comprehensive index with digital financial inclusion index as the main component to test the robustness. The results show that the increase of the digital economy reduces $PM_{2.5}$ emissions in Chinese cities. In addition, we also explore technological innovation as a mediating channel for the digital economy to influence $PM_{2.5}$ emissions. The digital economy provides a better research environment for technological innovation, conducive to improving cleaner production technology and products. Finally, we find that environmental information disclosure can enhance the impact of the digital economy on $PM_{2.5}$ emissions.

Keywords: digital economy; $PM_{2.5}$ emission; mediation; moderation; technological innovation; environmental information disclosure

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1. Introduction

Advancements in such internet technologies as big data, artificial intelligence, and blockchain have propelled the digital economy and economic growth [1,2]. According to the World Internet Development Report (2018), released during the 5th World Internet Conference, China ranks second in the World Internet Index, just behind the United States. China attaches great importance to developing the digital economy, and the government has issued many related policy documents. Under these policy incentives, China's digital economy had grown from RMB 11 trillion at the beginning of the 13th Five-Year Plan to RMB 45.5 trillion yuan in 2021 (data comes from the National Bureau of Statistics of China). New digital technology and the Internet have drastically reduced search, entry, transportation, and reproduction costs, unleashing enormous potentials for enhancing economic efficiency. There is no doubt that the digital economy impacts every aspect of our lives [3]. If we consider the digital economy as encompassing all economic activities that use or are facilitated by digitized data, then it is essentially the entire economy.

Meanwhile, global environmental problems have gradually been exposed. In recent years, air pollution represented by haze pollution has occurred frequently and affected a wide area, seriously endangering public health. According to the latest "2021 China Ecological and Environmental Status Bulletin" released in May 2022, 35.7% of 339 prefecture-level and above cities still exceed the standard for ambient air quality. The average number of days exceeding the standard in 339 cities was 12.5% of days analyzed. Among them, the number of days with $PM_{2.5}$, O_3, PM_{10}, NO_2, and CO as the primary pollutants accounted for 39.7% of the total number of days exceeding the standard. High concentration of $PM_{2.5}$ is one of the important reasons for the formation of haze weather and the reduction of ambient air quality. $PM_{2.5}$ has been reduced for six consecutive years since the start of the 13th Five-Year Plan period, from 46 micrograms per cubic meter to 30 micrograms per cubic meter. Even so, the current level of air pollution in China is still more than three times higher than the guideline value identified by the World Health Organization (average annual concentration of no more than 10 micrograms per cubic meter). Therefore, alleviating and solving the problem of $PM_{2.5}$ pollution remains the top priority in China's environmental protection battle.

The ecological environment problem is fundamentally a problem of development mode and life style. The digital economy is a significant means to optimize and upgrade the economic structure and achieve high-quality economic development in the new era, thereby changing the way of production and life, which can improve the above problems. Chinese government departments have introduced a series of policies to promote the deeper integration of the digital economy and traditional industries, improve the quality and efficiency of social production, and guide the green economic transformation. For example, it is clearly proposed to accelerate the digital transformation of production mode in the latest "14th Five-Year Plan for Green Industrial Development" released in November 2021. Specifically, industrial Internet, big data, 5G, and other next-generation information technologies should be employed to improve energy, resource, and environmental management, deepen the digital application of production and manufacturing processes, and enable green manufacturing. As can be seen, China's green development, pollution prevention, and control efforts depend heavily on the digital economy. Therefore, it is sensible to further examine whether or not the digital economy could potentially have reduction effects on pollution emissions.

Currently, the relationship between the digital economy and environmental pollution has gradually drawn the attention of academics, but the literature is still inconclusive with mixed results. On the one hand, some academics have conducted in-depth research on the relationship between the digital economy and environmental pollution, and the conclusions mainly include the following three aspects. First, most scholars believe that the digital economy brings environmental purification and reduces pollution. High resource allocation efficiency of the digital economy [4,5] and the use of digital auxiliary platforms with less waste of resources [6–8], second-hand goods platforms, and product recycling [9] are all beneficial for reducing pollution emissions. In addition, Li et al. studied the micro-energy network architecture of enterprise zero carbon emission, and demonstrated that this architecture can greatly reduce the emission of air pollutants [10]. Lee et al. also verified the carbon reduction effect of the digital economy in the transportation sector [11]. Second, some studies found that the digital economy exacerbates environmental pollution. Sui and Rejeski pointed out that each potential positive impact of the digital economy is coupled with a potentially overwhelming negative impact as well [12]. For example, moving business online can reduce waste such as printed catalogues, retail space, and transportation requirements, but we have to manufacture more energy-intensive computers instead. Meanwhile, information and communications technology (ICT) with a large amount of electricity and carbon-intensive materials as intermediate production also has limited impacts on carbon reduction [13–16]. Third, some studies argue that there is a nonlinear relationship between the digital economy and environmental pollution, and the related environmental impacts are also characterized by heterogeneity. For example, Xu et al. found that there is a reverse and complex spatio-temporal evolution of the digital economy and environmental pollution in Chinese cities [17]. Lee et al. focused on the relationship between digital financial inclusion and carbon neutrality and found that the marginal impact of digital financial inclusion on carbon intensity first decreases and then increases [18]. Regarding the heterogeneous impact of the digital economy on the environment, it mainly includes regional heterogeneity [19], the differences between resource-based and non-resource-based cities [20]. On the other hand, some literature also explores the specific mechanism of how the digital economy affects the environment, and mainly includes mediating effects and moderating effects. Specifically, the relevant mediating effects are primarily that the digital economy can influence economic growth, financial development, and industrial structure upgrading, thereby reducing carbon emissions [21]. Additionally, technological innovation and human capital [22], energy efficiency [23], and resource allocation [24] also play mediating roles. The moderating effect mainly includes R&D investment [25] and environmental regulation [26].

It is worth noting that only a few scholars have focused on the connection between the digital economy and $PM_{2.5}$, and the majority of the aforementioned literature uses carbon emissions to represent the level of environmental pollution. For example, Qi et al. found that the digital economy has a stronger improvement effect on the SO_2 concentration than its improvement effect on the $PM_{2.5}$ and NO_2 concentrations [27]. Che and Wang also verified the haze reduction effect brought by the development of China's digital economy and analyzed the heterogeneity characteristics of the haze reduction effect [20]. However, the above studies either have too broad research objectives, considering many pollutants, or do not fully consider the relevant mediating effects, moderating effects, and other influencing mechanisms.

In short, although extensive research has been carried out in the relevant field, there exists no study paying attention to the comprehensive effect of the digital economy on $PM_{2.5}$ and its influencing mechanism. Compared to prior research, this paper advances the literature as follows: (1) Previous studies generally focused on the environmental effects of the digital economy, but few studies focused on the analysis of $PM_{2.5}$ emissions. This paper integrates the digital economy and $PM_{2.5}$ emissions into a unified research framework, which is consistent with China's development idea of supporting the deep integration of the digital economy and ecological civilization construction. (2) Cities are playing an ever-more-important role in intelligent innovation and pollution avoidance as digital and smart cities emerge. However, previous studies lack empirical evidence at the city level in China. This paper uses panel data from 285 prefecture-level cities in China from 2005 to 2018 to explore the impact of digital economy development on $PM_{2.5}$, and our sample helps fill the aforementioned gap. (3) This paper investigates the influence mechanism of the digital economy on $PM_{2.5}$ emissions, including the mediating effect of technological innovation and the moderating effect of environmental information disclosure. Our research will provide more precise development guidance for harnessing the digital economy to reduce $PM_{2.5}$ pollution.

The rest of this paper is arranged as follows: Section 2 sorts out the theory development. Section 3 states the econometric model, variables, data, and its source. Section 4 presents the empirical analysis and test results. Section 5 analyzes further discussion. Section 6 shows the conclusions and implications of this paper.

2. Theory Development

2.1. The Environmental Effects of the Digital Economy

With the development of digital technologies [28] and digital industries [29] such as the Internet and e-commerce, the digital economy has evolved into a brand-new sector of the economy and society, providing fresh insights for environmental governance, energy conservation, and emission reduction. This paper supposes that the digital economy alleviates $PM_{2.5}$ mainly from production and living:

(1) From the perspective of the industrial upgrading effect, the digital economy provides enterprises with internet technologies and platforms to upgrade industrial structure through industrial digitalization and digital industrialization, to reduce $PM_{2.5}$ emissions. On the one hand, industrial digitalization can comprehensively transform traditional industries by using modern information technology. Only by comprehensively introducing new production materials such as procedures, systems, and

models, as well as new production means including data and digitally transforming traditional industries, can we explore the hidden low-pollution development potential of traditional industries, and then improve the digital economy's low-pollution level. For example, the energy management and operation technology of the energy Internet can be used to promote the adjustment of the energy structure of traditional industries [30]. On the other hand, digital industrialization, as a fundamental component of the digital economy, includes the electronic information manufacturing industry, telecommunications industry, software industry, and information service industry, etc. It has the advantages of being green and low-pollution when compared to traditional industries such as the manufacturing industry.

(2) In terms of the resource allocation effect, the digital economy can alleviate $PM_{2.5}$ by optimizing resource allocation and improving resource utilization efficiency. Internet technology breaks traditional geographical boundaries and can maximize the integration of resources [30] to improve the efficiency of economic development. Specifically, relevant digital service platforms can monitor the manufacturing process in real-time and assess the operational status of its equipment, assisting enterprises in improving energy efficiency and lowering energy costs [31]. Further, the construction of a digital platform can also promote the coordination between upstream and downstream enterprises of the industrial chain or different industrial chains, thereby accelerating the optimal allocation and integrated development of industrial chain resources and achieving the goal of $PM_{2.5}$ reduction and efficiency increase.

(3) From the standpoint of life and consumption style, the expansion of the digital economy has facilitated the public's online work and lifestyle, reduced the usage of daily travel and transportation, and effectively reduced pollution emissions in the process of life. E-commerce realizes consumers shopping online to reduce the transportation costs and the pollution emissions of carrying goods from supermarkets [32]. Through centralized distribution, e-commerce can also increase the number of goods per delivery, i.e., reduce the number of deliveries, thereby reducing emissions of traffic pollutants [33]. Internet goods are stored centrally in warehouses and transported by trucks, resulting in far less energy consumption and pollution than consumers going to shopping malls individually [34]. In addition, the development of smart drone technology supports enterprises to use drones to deliver goods directly to their homes, further reducing vehicle emissions [35]. Digital technologies such as the Internet and cloud computing can achieve online and paperless offices through electronic information carriers, thus reducing energy consumption and haze pollution [36].

(4) Regarding pollution prevention, the digital economy can innovate the mode of haze pollution governance. Digital technology can collect haze information in real-time, and even establish environmental information-sharing platforms among researchers, governments, enterprises, and residents to improve the efficiency of environmental management [37]. In recent years, the governance of haze pollution has shifted from a single government to a diversified society [38]. Specifically, the atmosphere is a flowing element, which is not limited by the administrative boundary. Big data technology can provide data and decision-making support for regional atmospheric environmental quality management, inter-regional coordination, and the cooperation mechanism. For example, Shenzhen, as the central city of the Greater Bay Area, has taken the initiative to coordinate with Shenzhen–Hong Kong, Shenzhen–Dongguan, and Shenzhen–Huizhou to build a joint prevention and control mechanism with the help of digital technologies. In short, the integration of information technology and environmental governance makes this comprehensive governance mode more effective, forming an effective new mode of haze pollution governance [39].

To sum up, the existing literature and related abatement practices show that the digital economy can reduce $PM_{2.5}$ emissions by promoting industrial structure upgrades, optimizing resource allocation, improving life and consumption patterns, and innovating government pollution control patterns. Therefore, Hypothesis 1 is given as follows:

Hypothesis 1. *The development of a Chinese city's digital economy has the potential to reduce $PM_{2.5}$ emissions.*

2.2. Technological Innovation as the Mediator

On the one hand, as a representative of innovation-driven economy, the digital economy has propelled technological innovation to unparalleled heights. This paper supposes that numerous aspects of the digital economy serve to advance technological innovation. More specifically, knowledge accumulation is the fundamental component of technological innovation [40], which can be accelerated by depending on the digital economy's beneficial role of increasing the effectiveness of new knowledge transmission. The digital economy expands market borders, fosters a rush of fresh ideas, and creates new industries, products, and business models. The stock of useful innovation knowledge can be increased by integrating and classifying fragmented information knowledge as well as by weeding out information knowledge that is not innovative. For example, Litvinenko studied the impact of the digital economy on the innovation of mining technology. He concluded that the digital economy integrates resources, increases the stock of knowledge, and provides solid conditions for technological innovation [41]. In addition, we believe that traditional economic forms cannot effectively organize the dispersed "tacit knowledge" of individuals together, but the widespread use of digital technology and modern information networks provides an efficient means of disseminating this dispersed "tacit knowledge". The rapid expansion of knowledge via the network will enable more individuals to develop new "tacit knowledge". Further, network effects result in the accumulation of shared knowledge and skills, which ultimately promotes the continuous improvement of technological innovation. Not only that, the above information sharing effect and knowledge integration effect of the digital economy also benefit enterprises to carry out green technology innovation [42].

On the other hand, traditional technology innovation and green technology innovation are both conducive to environmental pollution control [43,44]. Regarding traditional technological innovation, technological progress will improve productivity and resource usage efficiency and reduce factors input in the production process, and therefore lessen the production's negative effects on the environment. Meanwhile, traditional technological innovation can improve the treatment efficiency of pollutants by strengthening the terminal treatment [45]. For example, cities with high levels of technological innovation are more likely to have intelligent pollution monitoring platforms and help companies improve their pollution treatment capabilities. In addition, traditional technological innovation can also promote cleaner production technology and the research of environmental protection products, enabling enterprises' green transformation. Thus, green technology innovation is a vital element for improving environmental quality. First, similar to traditional technological innovation, green technological innovation can also save production factors, thereby reducing energy use. Furthermore, the development, use, and updating of clean technology can achieve the goal of technological transformation of equipment with high energy consumption. Therefore, production equipment becomes more high-quality, efficient, and low-consumption, and thus, it promotes energy conservation and emission reduction. Based on the above theoretical basis, a few studies have indeed verified the emission reduction effect of green technology innovation by analyzing the relationship between green technology innovation and NOx and PM_{10} concentrations [46] and $PM_{2.5}$ [47].

In short, it can be concluded that the digital economy helps to promote technological innovation, and technological innovation will have a beneficial impact on reducing pollution. Therefore, technological innovation will play a mediating role between the digital economy and $PM_{2.5}$ emissions. Hypothesis 2 is given as follows.

Hypothesis 2. *Technological innovation is a mediating variable in the impact of the digital economy on $PM_{2.5}$.*

2.3. The Moderating Effect of Environmental Information Disclosure

The expansion of the digital economy fosters the diffusion of all types of information and facilitates the general public's access to information. As a means of environmental governance in the new era, environmental information disclosure profoundly impacts China's economy, society, and environment [48,49]. In detail, online disclosure of environmental information can effectively guide the public to pay attention to environmental conditions, supervise enterprise production behavior, and enhance the emission reduction effect of the digital economy on $PM_{2.5}$. Furthermore, people can gain a deeper understanding of environmental damage, acquiring pollutant discharge monitoring information and environmental publicity more conveniently, and raise their level of environmental awareness. For example, Kansiime et al. found that farmers would gain a better comprehension of green production after browsing a large amount of environmental pollution information on the Internet [50]. Zhao et al. proposed that releasing more green production information can increase farmers' green production behaviors, confirming the impact of environmental information disclosure on people's awareness of environmental protection [51]. Obviously, the development of the digital economy facilitates the disclosure of environmental information, and the disclosure of environmental information has the potential to change people's perceptions of environmental pollution. In other words, environmental information disclosure can help to moderate the environmental effects of the digital economy.

Additionally, the moderating effect of environmental information disclosure is also shown in its capacity to moderate the impact of the digital economy on public behavior. Environmental information disclosure can increase the impact of the digital economy on public behavior, enabling people to make environmentally friendly decisions in the process of production by enterprises and farmers, and daily consumption by residents. For example, reducing the use of private cars and increasing the use of public transportation can effectively reduce $PM_{2.5}$ emissions [52]. Therefore, this paper proposes research Hypothesis 3:

Hypothesis 3. *Environmental information disclosure plays an enhanced moderating effect in the process of the digital economy affecting $PM_{2.5}$.*

3. Materials and Methods

We divide the verification into three stages. First, we will test Hypotheses 1to verify whether the digital economy will reduce $PM_{2.5}$. Second, Hypothesis 2 will be tested to verify whether technological innovation is a significant mediator of the digital economy's impact on $PM_{2.5}$. Third, Hypothesis 3 will be tested to examine the moderating role of environmental information disclosure in the process of the digital economy affecting $PM_{2.5}$.

3.1. Empirical Model

To test hypotheses 1, we constructed the following econometric model:

$$\ln PM2.5_{it} = \beta_0 + \beta_1 Digit_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where i refers to the observation city and t refers to the observation year. ln*PM2.5* is $PM_{2.5}$ emissions. *Digit* denotes the degree of the digital economy, the variable of interest. X is a series of control variables which includes real income per capita (ln*Rpgdp*) and its square term (ln*RpgdpS*), the degree of export opening-up (*Open*), governmental research and development expenditure rate (*RD*), foreign direct investment (*FDI*), industrial structure (*Ins*), and energy consumption (ln*Coal*). Additionally, μ_i is the city-fixed effect, γ_t is the time-fixed effect, and ε_{it} is the error term. β_1 is the coefficient for *Digit*. If the results show that β_1 is significantly negative, the digital economy can reduce $PM_{2.5}$. If β_1 is positive, Hypothesis 1 is overturned, meaning neither Hypothesis 2 nor Hypothesis 3 remain true.

Further, Hypothesis 2 is examined according to the mediation models. The mediation effect indicates that the influence of an independent variable on a dependent variable is transmitted through a third variable named the mediator [53]. This paper uses the causal steps approach to test the mediating effect [54]. We constructed the mediation model as follows:

$$M_{it} = \alpha_0 + a_1 Digit_{it} + \alpha_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{2}$$

$$\ln PM2.5_{it} = \varphi_0 + \varphi_1 Digit_{it} + \varphi_2 M_{it} + \varphi_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{3}$$

where *M* represents the mediating variable, namely, technological innovation, and the other variables have the same meanings as Equation (1). Equation (2) aims to test the relationship between the digital economy and mediating variables, expecting that the estimated coefficient for$\alpha_1$is positive. Equation (3) examines whether *Digit* and *M* are significantly related to ln*PM2.5*, expecting that the estimated coefficients of φ_1 and φ_2 are negative. The above three Equations (1)–(3) constitute a complete mediation test. As a result, the testing process of the mediating effect is mainly divided into three steps. In the first step, a basic regression on Equation (1) is performed. If the estimated coefficient of β_1 is significant, there is a mediating effect; otherwise, there is a masking effect. The second step is to examine the coefficients of α_1 and φ_2. If both α_1 and φ_1 are significant, then φ_1 will be further tested. If at least one of the two is not significant, then the Sobel test or Bootstrap test will be performed. The third step is to test the coefficient of φ_1. If the coefficient of φ_1 is not significant, there is a complete mediating effect, while the direct impact is not significant. On the contrary, if the coefficient of φ_1 is significant, compare the coefficient's signs of φ_1 and $\alpha_1 * \varphi_2$. If both of them have the same sign, and φ_1 is smaller than β_1, there is a partial mediating effect. The proportion of the above mediating effect can be represented by $\frac{\alpha_1 * \varphi_2}{\beta_1}$.

Finally, Hypothesis 3 is tested using the moderation model. Based on Equation (1), this paper introduces *PITI*, when the value of *PITI* is 1, it indicates that the supervision situation of pollution source of city *i* is disclosed in *t* year. When the value of *PITI* is 0, the situation is the opposite. To test the moderating effect of environmental information disclosure, this paper introduces the interaction term *Digit_PITI* about the digital economy and environmental information disclosure. The moderation model was constructed as follows:

$$\ln PM2.5_{it} = \omega_0 + \omega_1 Digit_{it} + \omega_2 Digit\_PITI_{it} + \omega_3 PITI_{it} + \omega_4 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{4}$$

where *Digit_PITI* is the variable we are interested in. The other variables have the same meanings as Equation (1).

3.2. Variables and Data Selection

3.2.1. Explained Variable

The explained variable is $\ln PM_{2.5}$, which represents the level of $PM_{2.5}$ in China. The $PM_{2.5}$ concentration data come from Dalhousie University's Atmospheric Composition Analysis Group. The source data were raster processed and then matched with a vector map of Chinese prefecture-level cities to obtain annual $PM_{2.5}$ mean data. The explained variable uses a logarithmic form in the following empirical research part to reduce the estimation bias caused by the sample dispersion.

3.2.2. Explaining Variables

The digital economy is calculated using a comprehensive method as this study's core independent variable. Since the official composite index has not yet been released, calculating the digital economy level is a challenge. The digital economy has a wide range of meanings and implications. Therefore, this study constructs the measurement system of Chinese cities' digital economy level from three dimensions of digital penetration, digital human resources, and digital output, as shown in Table 1. In detail, digital penetration indicates the extent to which the development of the digital economy affects daily life and production. Digital human resources are used to measure the degree of digitalization of enterprises, and digital output can reflect the development of digital industrialization to a certain extent.

Table 1. Evaluation system of digital economy level.

Target Level	Criterion Level	Index Level
Digital economy development level	digital penetration	the number of mobile phone users the number of Internet users
	digital human resources	the number of information industry employees
	digital output	per capita postal business volume per capita telecom business volume

Further, this paper uses the entropy weight method to calculate the digital economy level of 285 prefecture-level cities in China from 2005 to 2018. The detailed calculation process is as follows:

Firstly, each indicator of the digital economy is standardized to getx'_{ij}. Meanwhile, we calculate the proportion of the index value z_{ij} of the evaluation sample i under the evaluation index j.

$$x'_{ij} = x_j - x_{min} / x_{max} - x_{min},\ z_{ij} = x'_{ij} / \sum_{i=1}^{m} x'_{ij} (0 \le z_{ij} \le 1; i = 1, 2, 3, \cdots, n) \quad (5)$$

where x_j is the original value of the digital economy evaluation index j; x_{max} and x_{min} represent the maximum and minimum values, respectively, of the digital economy evaluation index j over the sample period.

Secondly, according to the theory of information entropy [55] and the proportion of the index value z_{ij}, we calculate the digital economy entropy e_j of the evaluation index j and digital economy utility value d_j.

$$e_j = \frac{1}{lnm} \sum_{i=1}^{m} z_{ij} lnz_{ij},\ d_j = 1 - e_j \quad (6)$$

Thirdly, we calculate the weight w_j of the evaluation index j. The greater the weight of the index, the more remarkable its contribution to the evaluation results.

$$w_j = d_j / \sum_{j=1}^{n} d_j \quad (7)$$

Finally, according to the weight of each evaluation index w_j, the total score of the evaluation sample i can be calculated, i.e., the digital economy-level s_i of the prefecture-level city i is,

$$s_i = w_j x'_{ij} \quad (8)$$

3.2.3. Mediating Variable

To verify whether technological innovation is a significant mediation channel for the impact of the digital economy on $PM_{2.5}$, this paper takes *Cxz* as mediating variable. The data of China's regional Innovation and Entrepreneurship Index (*Cxz*) come from the Enterprise Big Data Research Center of Peking University. The index includes five dimensions: the number of new micro-enterprises, access to foreign investment, access to venture capital, patent output, and trademark output, which can more objectively and comprehensively reflect the quality of innovation in China.

3.2.4. Moderating Variable

This paper adopts the Pollution Information Transparency Index (*PITI*) jointly released by IPE and NRDC to represent environmental information disclosure [52]. Specifically, the

Pollution Information Transparency Index was jointly developed by the Institute of Public & Environmental Affairs (IPE) and the Natural Resources Defense Council (NRDC) to establish a baseline for the first year of China's environmental information disclosure and to record every step of the country's information transparency. Its first report, announced in 2008, included a composite score for 113 prefecture-level cities, increasing the total number of cities studied to 120 since 2013.

3.2.5. Control Variables

In order to eliminate omitting variable bias, this study controls a series of other variables that might influence $PM_{2.5}$. The control variables include: (1) Real income per capita (ln*Rpgdp*) and its square term (ln*RpgdpS*), which can be used to investigate the relationship between economic growth and $PM_{2.5}$ [56] under the framework of the environmental Kuznets effect. The real income per capita is obtained by dividing the real GDP by the population, and the real GDP is calculated according to the constant price in 2005; (2) The degree of export opening-up (*Open*) [57], calculated by dividing the export amount by GDP, where the export value is converted into RMB using the current year's exchange rate; (3) Governmental R&D expenditure rate (*RD*), obtained by dividing governmental R&D expenditure by GDP; (4) Proportion of foreign direct investment (*FDI*) [58], obtained by dividing foreign direct investment by GDP, where the foreign direct investment is converted into RMB using the current year's exchange rate; (5) Industrial structure (*Ins*), obtained by dividing the added value of the secondary industry by GDP; (6) Energy consumption (ln*Coal*), expressed in the natural logarithm of coal consumption. Since cities don't disclose their coal consumption data directly, we take the proportion of each prefecture-level city's GDP in the whole province as the weight, multiply it by the province's coal consumption, and the result represents each prefecture-level city's coal consumption.

3.3. Sources of Data

This study used a panel dataset of 285 cities from 2005 to 2018 as a sample. These cities are located in 30 provinces, except for the ones in Tibet. In addition to ln*PM2.5*, the data mainly come from China Statistical Yearbook, China Urban Statistical Yearbook, China Regional Economic Statistical Yearbook, China Energy Statistical Yearbook, and Easy Professional Superior (EPS) data platform. These statistical yearbooks are widely used to analyze China's environmental and economic issues [59,60]. Table 2 is a summary of descriptive statistics for the main variables.

Table 2. The statistical description of main variables.

Variables	N	Mean	Sd	Min	Max
$\ln PM_{2.5}$	3990	3.660	0.498	1.141	4.702
Digit	3990	0.044	0.055	0.003	0.601
ln*Rpgdp*	3990	10.119	0.701	4.483	13.706
Open	3990	14.533	31.612	0.001	882.756
RD	3990	0.271	0.563	0.000	20.408
FDI	3990	0.023	0.023	0.000	0.288
Ins	3990	48.275	10.893	14.400	90.970
ln*Coal*	3990	6.537	0.943	3.298	8.994
Cxz	3920	51.952	28.064	1.365	100
PITI	3990	0.421	0.494	0	1

4. Results

4.1. Results for the Benchmark Model

In accordance with the F-test and Hausman test results, two-way fixed effect modes were selected, and the empirical results of Equation (1) are shown in Table 3. Column (1) is the linear regression that only has the core explaining variable *Digit*. The coefficient is significantly negative at the 1% level. After controlling both city and time-fixed effects in Column (2), the significance of the coefficient remains unchanged and the value is −0.741. Similarly, Column (3)'s consideration of a series of control variables also does not change the significance of the coefficient, and the value of β_1 becomes −0.693, indicating the digital economy's negative effect on $PM_{2.5}$. Finally, this paper introduces ln*Rpgdps* to test the environmental Kuznets curve in China and ob-tains the regression results in Column (4) of Table 3. The results in Column (4) show that at the 1% significance level, each unit increase in the digital economy's develop-ment level results in a 63.4% reduction in $PM_{2.5}$ emissions.

Table 3. Results of the baseline model.

Variables	(1)	(2)	(3)	(4)
Digit	−1.845 ***	−0.741 ***	−0.693 ***	−0.634 ***
	(−7.78)	(−4.52)	(−4.19)	(-3.93)
ln*Rpgdp*			−0.076 ***	0.181 **
			(−3.21)	(2.16)
ln*RpgdpS*				−0.014 ***
				(−2.93)
Open			−0.000	−0.000
			(−0.95)	(−0.95)
RD			−0.013	−0.012
			(−1.38)	(−1.38)
FDI			0.911 ***	0.898 ***
			(3.77)	(3.76)
Ins			−0.003 ***	−0.004 ***
			(−3.47)	(−3.85)
ln*Coal*			0.090 ***	0.097 ***
			(3.34)	(3.50)
Constant	3.741 ***	3.423 ***	3.775 ***	2.551 ***
	(359.39)	(283.52)	(14.53)	(5.92)
City Effects	YES	YES	YES	YES
Year Effects	NO	YES	YES	YES
Observations	3990	3990	3990	3990
R-squared	0.033	0.489	0.512	0.514

Note: *** and ** represent significance at 1% and 5% levels, respectively. The *t*-statistic in parenthesis.

Regarding the other control variables, first, the coefficients of ln*Rpgdp* and ln*RpgdpS* to ln$PM_{2.5}$ are significantly positive and negative, respectively. The results indicate that there is an inverted U-shaped relationship between per capita real income and $PM_{2.5}$ emissions, i.e., an environmental Kuznets curve exists in prefecture-level cities in China. Second, the coefficient of *FDI* is significantly positive at the 1 % level, indicating that the introduction of foreign direct investment may aggravate China's pollution problem, which is consistent with the pollution paradise hypothesis. Third, the coefficient of *Ins* is significantly negative at the 1% level, indicating that the optimization of industrial structure is conducive to $PM_{2.5}$ reduction. Fourth, the coefficient of ln*Coal* is significantly positive at the 1% level, which means that increased coal consumption will exacerbate $PM_{2.5}$ emissions. This conclusion is consistent with most existing studies [61,62]. Finally, the coefficients of *Open* and *RD* are all not significant, indicating that both export opening-up and R&D expenditure do not affect $PM_{2.5}$ emissions.

4.2. Robustness Analysis of the Benchmark Model

This paper further conducts the robustness test using the benchmark model by Winsorize and changing explanatory variables, and the results are presented in Table 4. Firstly, to avoid the bias caused by extreme values, this paper eliminates 10% of the extreme value data and re-estimates the original model. Column (1) of Table 4 reports the results of the benchmark model after excluding the extreme values, and the coefficient of *Digit* is significantly negative at 5% level, which verifies the robustness of the corresponding conclusions. Then, we change the core explanatory variable to conduct the robust test. Specifically, according to the study of Zhao et al. [63], the digital economy composite index ln*INT*, with the digital financial inclusion index as its main component, is used in this paper to replace the originally explained variables. The results in Columns (2) and (3) of Table 4 show that the coefficient of ln*INT* is significantly negative, and is consistent with the regression coefficients described above. Therefore, we confirmed that the digital economy does exert a significant negative effect on $PM_{2.5}$ emissions, and the empirical results of this paper are robust and reliable.

Table 4. Results of robustness test.

Variables	(1)	(2)	(3)
	Winsorize	**Changing Explaining Variable**	
Digit	−1.180 **		
	(−2.19)		
ln*INT*		−0.023 **	−0.016 *
		(−2.15)	(−1.85)
Control vairables	YES	YES	YES
Constant	3.186 ***	3.595 ***	10.002 ***
	(9.69)	(36.56)	(4.78)
City Effects	YES	YES	YES
Year Effects	YES	YES	YES
Observations	2519	2208	2208
R-squared	0.595	0.692	0.708

Note: ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively. The *t*-statistic in parenthesis.

4.3. Endogeneity Analysis

Given that the concept of the digital economy is broad and encompasses all aspects of life, the relevant regression estimates may have endogeneity issues. To solve the endogenous problem, this paper selects the first-order lag of *Digit* and Total Business Volume of Telecommunications and Postal Services (*Post*) [64], as two instrumental variables of the digital economy. *Post* is chosen as an instrumental variable for the following reasons. On the one hand, the greater the number of telecommunications and postal services, the higher the degree of economic digitalization. On the other hand, there is no apparent correlation between the amount of postal service use and $PM_{2.5}$. Further, we use the two-stage least square method to conduct the endogeneity test, and the regression results are shown in Table 5. Specifically, the F statistic rejects the null hypothesis that "weak instrumental variables exist". LM test results show that there is no insufficient recognition problem of instrumental variables, so the selection of both instrumental variables is reasonable. It can be found that the digital economy still has a significant reduction effect on $PM_{2.5}$ emissions after controlling the endogeneity problem by selecting instrumental variables, which again verifies the robustness of the previous regression results.

4.4. Influence Mechanism Analysis

This paper studies the influence mechanism of the digital economy on $PM_{2.5}$ from two aspects: technological innovation as the mediating variable and environmental information disclosure as the moderating variable.

4.5. Results for the Mediation Model

Considering that Hypothesis 1 has been verified, i.e., the first step of the mediation test has been completed. Next, this paper needs to further complete the regression of Equations (2) and (3) to verify the mediating effect of technological innovation. All regression results are shown in Columns (1)–(3) in Table 6.

Table 5. Results of endogeneity test.

Variables	IV: First Order Lag of *Digit*		IV: *Post*	
	(1)	(2)	(3)	(4)
Digit	−3.827 ***	−0.839 ***	−3.922 ***	−0.631 **
	(−10.71)	(−3.86)	(−8.50)	(−2.54)
ln*Rpgdp*		0.148 **		0.181 ***
		(2.49)		(2.88)
ln*RpgdpS*		−0.012 ***		−0.014 ***
		(−3.51)		(−3.85)
Open		−0.000 *		−0.000
		(−1.81)		(−1.63)
RD		−0.009 *		−0.012 **
		(−1.90)		(−1.96)
FDI		0.650 ***		0.898 ***
		(4.11)		(5.58)
Ins		−0.003 ***		−0.004 ***
		(−4.75)		(−6.22)
ln*Coal*		0.089 ***		0.097 ***
		(5.63)		(6.44)
City Effects	YES	YES	YES	YES
Year Effects	YES	YES	YES	YES
Observations	3705	3705	3990	3990
F test	1572.21	1562.02	1264.54	1135.95
(*p*)	(0.000)	(0.000)	(0.000)	(0.000)
LM test	65.570	66.193	38.068	33.611
(*p*)	(0.000)	(0.000)	(0.000)	(0.000)

Note: ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively. The *z*-statistic in parenthesis.

The empirical results of Equation (2) in Column (2) demonstrate that the coefficient of *Digit* to *Cxz* is significantly positive at the 1% level, which means that the development of the digital economy is significantly conducive to technological innovation. The results of Equation (3) in Column (3) show that the coefficient of *Cxz* to $\ln PM_{2.5}$ is significantly negative at the 1% level, which indicates that the progress of technological innovation is conducive to pollution reduction, and this conclusion is consistent with most existing studies. Based on the aforementioned test procedures of the mediation model, since the above coefficients are both significant, it has been concluded that the digital economy could help with $PM_{2.5}$ reduction through the mediating effect of technological innovation.

The following analysis is about the relationship between total, direct, and indirect effects. First, the coefficient of *Digit* to $\ln PM_{2.5}$ is −0.798, which represents the total reduction effect of digital economy. Second, after adding the mediating variable *Cxz*, the coefficient of ln*Digit* to $\ln PM_{2.5}$ is −0.78, which represents the direct effect of digital economy. The difference in value between the total effect and the direct effect is the indirect effect, i.e., the indirect effect of the digital economy on $PM_{2.5}$ through technological innovation is −0.024. The proportion of the mediating effect on the total effect is 3%. In summary, the digital economy not only has a significant direct $PM_{2.5}$ reduction effect, but also can exert a significant indirect effect through technological innovation. Therefore, hypothesis H_2 is proven.

Table 6. Results of mediation and moderation test.

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
	Mediating Effect			**Moderating Effect**	
	First Step	**Second Step**	**Third Step**	**ln$PM_{2.5}$**	
	ln$PM_{2.5}$	***Cxz***	**ln$PM_{2.5}$**		
Digit	−0.798 ***	24.44 ***	−0.780 ***	−0.600 ***	−0.582 ***
	(−4.92)	(3.54)	(−4.88)	(−2.77)	(−2.68)
Cxz			−0.001 ***		
			(−2.83)		
Digit_PITI_c				−0.425 **	−0.390 **
				(−2.39)	(−2.18)
PITI				−0.003	0.002
				(−0.15)	(0.13)
ln*Rpgdp*	0.185 **	10.94	0.193 **	−0.005 ***	0.167 **
	(2.21)	(0.82)	(2.23)	(−4.18)	(2.24)
ln*RpgdpS*	−0.014 ***	−0.312	−0.014 ***		−0.013 ***
	(−2.98)	(−0.52)	(−2.98)		(−3.05)
Open	−0.000	0.003	−0.000	−0.000	−0.000
	(−0.96)	(0.37)	(−0.97)	(−0.99)	(−0.98)
RD	−0.012	−0.083	−0.012	−0.012	−0.012
	(−1.38)	(−0.17)	(−1.44)	(−1.38)	(−1.38)
FDI	0.885 ***	35.32 **	0.912 ***	0.822 ***	0.872 ***
	(3.62)	(2.33)	(3.69)	(3.56)	(3.55)
Ins	−0.004 ***	0.014	−0.004 ***	−0.004 ***	−0.004 ***
	(−4.04)	(0.16)	(−4.02)	(−3.67)	(−3.93)
ln*Coal*	0.108 ***	6.024 ***	0.112 ***	0.106 ***	0.110 ***
	(3.96)	(3.35)	(4.09)	(3.93)	(4.04)
Constant	2.482 ***	−70.05	2.430 ***	3.402 ***	2.561 ***
	(5.85)	(−0.95)	(5.47)	(17.88)	(6.69)
City Effects	YES	YES	YES	YES	YES
Year Effects	YES	YES	YES	YES	YES
Observations	3920	3920	3920	3920	3920
R−squared	0.516	0.030	0.517	0.516	0.517
Mediating effect		Significant			

Note: *** and ** represent significance at 1% and 5% levels, respectively. The t-statistic in parenthesis. *Digit_PITI_c* indicates that the corresponding interaction term is centralized. Due to the lack of technological innovation data of Beijing, Shanghai, Tianjin, Chongqing, and Laiwu, the table removes the data of these cities.

4.6. Results for Moderation Model

This paper is also interested in that whether environmental information disclosure, represented by the Pollution Information Transparency Index (*PITI*), can moderate the $PM_{2.5}$ reduction effect of the digital economy. In this spirit, we take *PITI* as the moderating variable, and construct the interaction term of *Digit* and *PITI*, i.e., *Digit_PITI*. Then we employ the moderating effect model to estimate Equation (4), and the results are shown in Columns (4) and (5) of Table 6. The coefficients of *Digit* and *Digit_PITI* are both significantly negative, indicating that environmental information disclosure strengthens the negative impact of the digital economy on $PM_{2.5}$. Therefore, we believe that compared with cities with no or less disclosure of environmental information, cities with environmental information disclosure have more obvious reduction effects of the digital economy on $PM_{2.5}$ emission.

5. Discussion

As a new form of economic and social development, the digital economy profoundly affects every aspect of society. In order to supplement existing theoretical and empirical studies, this paper investigates the impact of the digital economy on $PM_{2.5}$ pollution and its influencing mechanism in detail. After a series of tests, the research results show that the development of the digital economy can effectively reduce $PM_{2.5}$, which is consistent with the conclusion of scholars who support the digital economy's development [65].

The mediating effect test shows that technological innovation is a significant mediator affecting the impact of the digital economy on $PM_{2.5}$ pollution. The development of the digital economy has dramatically shortened the time and space distances, and integrated resources for industries. Then, it provides a favorable research environment and achievement transformation channels for technological innovation, such as green technology innovation and low-carbon technology innovation. As a result, technological innovation will promote the research and development of cleaner production technology and low-carbon environmental protection products, thereby enhancing the ability to manage pollution and lower $PM_{2.5}$ emissions.

The regression results of the moderating effect model and the corresponding robustness test show that environmental information disclosure can strengthen the reduction effect of the digital economy on $PM_{2.5}$ emissions. The development of the digital economy has dramatically promoted the dissemination of information, and the disclosure of environmental information will raise public concern about environmental pollution and governance. On the one hand, more environmental awareness among the populace will strengthen the social supervision of the government and corporate behavior. Studies have shown that public participation can complement the role of government in environmental governance and pollution reduction [66]. On the other hand, by accessing the disclosed information, the public understands the severity of climate change and air pollution [67].

Through the above analysis and discussion, this paper has obtained the reduction effect of the digital economy on $PM_{2.5}$ pollution and its influence mechanism, and the three hypotheses have been verified. However, there are some limitations to this study. The impact of the digital economy on technological innovation is a long-term process, and the mediating effect of technological innovation should be discussed further. Meanwhile, some scholars found that the information industry has many embodied pollution emissions through input-output studies, which require comprehensive carbon management strategies [68]. In addition, the scope of urban environmental information disclosure needs to be further improved.

6. Conclusions and Policy Implications

Existing studies are insufficient on the impact of the digital economy on $PM_{2.5}$ emissions. Therefore, using the panel data of 285 cities from 2005 to 2018, this paper empirically tests the relationship between the digital economy and $PM_{2.5}$, the mediating role of technological innovation, and the moderating effect of environmental information disclosure. The findings are as follows. (1) The development of the digital economy can significantly reduce $PM_{2.5}$. (2) Technological innovation plays a partial mediating role in the influence of the digital economy on $PM_{2.5}$ pollution. (3) Environmental information disclosure can strengthen the $PM_{2.5}$ reduction effects of the digital economy. The higher the extent of environmental information disclosure, the more pronounced the reduction effect of the digital economy on $PM_{2.5}$.

This study has the following policy implications. Firstly, the government should enhance digital infrastructure construction and increase investment in digitization. More importantly, the government should strengthen the application of the digital economy in pollution prevention and control. Society should improve the governance system of digital and guide enterprises to carry out digital and green transformation. Secondly, local governments and enterprises should be encouraged to make full use of the research environment provided by the digital economy and strengthen knowledge and technology sharing to carry out green technological innovation and research on environmentally friendly products. Finally, in the age of the digital economy, the government should improve the construction of environmental information disclosure network platforms, encourage more cities to disclose ecological information voluntarily, and mobilize the public's enthusiasm to participate in environmental governance.

In conclusion, although this study provides new insights into the influence of the digital economy on $PM_{2.5}$ emissions and provides practical implications, some limitations might deserve further investigation. Considering the important role of enterprises in the digital economy and pollution reduction, this paper only uses cities as a study sample, unable to reveal the influencing mechanism at the enterprises level. Future research can attempt to examine the environmental effects of enterprise digital transformation and carry out analysis on specific cases. Moreover, the existence of other mediating and moderating factors also deserves further study.

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