frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 09 August 2022
doi: 10.3389/fenvs.2022.904254

Exploring the Effect of Digital Economy on PM2.5 Pollution: The Role of Technological Innovation in China

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PM2.5 emission causes serious harm to health and hinders the sustainable development of economy and society. Among all the factors affecting PM2.5 pollution, the role of new economic forms and information technology innovation is lacking. This study aims to explore the impact of digital economy on PM2.5 pollution and its influencing mechanism using data from 281 prefecture-level cities from 2011 to 2016. The empirical results demonstrate that digital economy is conducive to reducing PM2.5 pollution. In other words, the digital economy is conducive to alleviating PM2.5 pollution. Further analysis shows that the digital economy promotes technological innovation, which is an important mediating mechanism affecting PM2.5 pollution. Additionally, the inhibitory effect of digital economy on PM2.5 pollution is more significant in the eastern and central regions. Unfortunately, the negative impact of digital economy on PM2.5 pollution is not significant in the western region. The conclusions provide a new strategy for reducing pollution emissions and improving environmental quality and technological innovation.

Keywords: PM2.5 pollution, digital economy, technological innovation, influencing mechanism, regional heterogeneity

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Specialty section:
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

Received: *25 March 2022*
Accepted: *22 June 2022*
Published: *09 August 2022*

Citation:
Sun X, Chen Z and Loh L (2022) Exploring the Effect of Digital Economy on PM2.5 Pollution: The Role of Technological Innovation in China. Front. Environ. Sci. 10:904254. doi: 10.3389/fenvs.2022.904254

1 INTRODUCTION

In recent years, PM2.5 pollution has become a severe challenge and attracted more and more attention in the world (Liu et al., 2019; Zhou et al., 2019; Zhang M. et al., 2020; Li H. et al., 2021). According to the bulletin on China's ecological environment in 2019, the average concentration of PM2.5 was 36 ug/m3 in 2019, which has decreased significantly compared with 98 ug/m3 in 2013. However, China's air pollution situation is still very serious, and the average concentration of PM2.5 is still much higher than the safety value of 10 ug/m3 given by the World Health Organization (WHO). Literature research shows that haze pollution caused by PM2.5 damages human respiratory and cardiovascular systems and increases the risk of disease (Xie et al., 2019; Zhang et al., 2019). In the long run, air pollution will cause the decline of average life expectancy of residents, impact the accumulation of human capital and significantly hinder the progress of social and economic development (Du et al., 2018; Zhu et al., 2020). It is urgent to comprehensively promote technological innovation and speed up the government's control of air pollution.

The China Government Work Report has repeatedly mentioned to vigorously develop digital economy. According to the data of the White Paper on China's Digital Economy Development (2020), the added value of China's digital economy will reach 3.58 trillion yuan in 2019, accounting for 36.2% of GDP. The digital economy becomes one of the new motivation for driving economic development (Li X. et al., 2021).

On the one hand, the digital economy can not only promote the deep integration of capital, labor, technology and other production factors, stimulate management innovation and technological progress, improve resource utilization efficiency and environmental quality; On the other hand, the digital economy can accelerate economic structure optimization, and reduce resource waste and pollution emissions (Li et al., 2016).

With the rapid development of the digital economy, some scholars have begun to pay attention to the impact of the digital economy on social productivity and factor allocation efficiency. With the penetration of digital economy into industrial development and social life, the environmental and sustainable development effects brought by digital economy have become the focus of research (Ciocoiu, 2011; Li Z. et al., 2021; Zhou et al., 2021; Wang et al., 2022). Initially, the study explored the impact of internet electronic commerce or Internet use on sulfur dioxide or air pollution (Ozcan and Apergis, 2018; Chen and Yan, 2020). Subsequently, the relationship between ICT and environmental pollution or carbon dioxide emission has attracted extensive attention (Khan et al., 2018; Raheem et al., 2020; Bhujabal et al., 2021). The existing literature mainly discusses the impact of digital economy on carbon dioxide emission or low-carbon development. However, the research on how the digital economy affects PM2.5 emissions is still worth supplementing and expanding. The above research literature provides a basis for answering questions and an opportunity for the marginal contribution of this study.

This study raises the following question: What is the relationship between digital economy and PM2.5 pollution? What's the influence mechanism? Is there heterogeneity in the impact of the digital economy on PM2.5 pollution? Therefore, our study attempts to explore the effect of digital economy on PM2.5 pollution and its influencing mechanism. Compared with the existing literature, the contributions of this study mainly include the following aspects. First, the theoretical framework and influence effect of digital economy are very different from traditional economy. This study explores the effect of digital economy on PM2.5 pollution, and effectively complements the research on the influencing factors of air pollution. Secondly, this study also reveals the relationship between the digital economy and air pollution from the perspective of technological innovation, and empirically tests the influencing mechanism. Thirdly, this study investigates the regional heterogeneity and explains the regional differences of environmental benefits produced by digital economy.

The remaining parts of the study is organized as follows: **Section 2** describes a brief literature review and theoretical analysis. **Section 3** provides empirical methods, data, and variable selection. **Section 4** discusses benchmark results, heterogeneity analysis, and robustness test. **Section 5** reports the research conclusions and policy recommendations.

2 LITERATURE REVIEW AND THEORETICAL ANALYSIS

2.1 Literature Review

Based on the existing literature, the current academic research on PM2.5 pollution can be classified into the following categories:

The first kind of literature studies the formation process of PM2.5 pollution from the perspective of natural science, focusing on source emission, meteorological characteristics, human health and chemical mechanism (Karagulian et al., 2015; Lelieveld et al., 2015; Thurston and Newman, 2018). Most of the research results show that PM2.5 emission mainly comes from secondary source emission, biomass combustion, industrial activities, motor vehicle exhaust emission and building dust (Chen et al., 2016; Baasandorj et al., 2017). Bereitschaft and Debbage. (2013) emphasized that the impact of urban land form on PM2.5 has become a new research topic. Yli-Pelkonen et al. (2017) considered the impact of landscape on PM2.5. Contini et al. (2011) and Hagler et al. (2007) believed that factors affecting PM2.5 pollution involve construction activities, motor vehicle use, and industrial production.

The second kind of research gradually studied the socio-economic drivers of PM2.5 emissions. Ji et al. (2018) analyzed the relationship between industrial structure, energy intensity, urbanization and PM2.5 concentration. Wang et al. (2018) discussed the impact of political globalization and democracy on PM2.5 concentration in G20 countries. Lyu et al. (2016) investigated the influencing factors of PM2.5 emission changes in China from 1997 to 2012. Cheng et al. (2017) discussed the key factors of PM2.5 pollution using the data of 285 cities in China from 2001 to 2012. Wang et al. (2021) studied whether the central environmental inspection has effectively improved PM2.5 pollution. Wu et al. (2016) explored the PM2.5 emission influencing factors based on the data of 74 cities. Shi et al. (2017) assessed the impact of the policy on PM2.5 pollution using empirical test methods. Ma et al. (2016) pointed out that urbanization produced various pollution sources and increased PM2.5 pollution. Li et al. (2016) proved that industrialization and urbanization increased PM2.5 pollution.

In addition, some literature has analyzed the relationship between technological innovation and the environment. Iqbal et al. (2021) proposed that environmentally relevant technological innovations are strongly linked to carbon emissions. Anser et al. (2021) found that the relationship between agricultural technology and carbon emissions shows a monotonic increase. Khan et al. (2021) proposed that technological innovation makes a positive contribution to the environment. Xu et al. (2021) pointed out that technological innovation have little effect in financial development affecting CO2 emissions. Brannlund et al. (2007) proposed that technological advances may lead to the expansion of production in some companies, while the quality of the environment may decline.

In recent years, exploring the relationship between digital economy and environmental pollution has become a new topic. Li J. et al. (2021) proposed that there is an inverted U-shaped nonlinear relationship between the digital economy and carbon dioxide emissions. Martynenko and Vershinina. (2018) proposed that digitalization has accelerated the ecological modernization of production, which can not only save resources, but also promote global sustainable development. Li Y. et al. (2021) analyzed that digital economy adjusts the relationship between coal energy structure and carbon emissions. Liu et al. (2022) found that there is a positive relationship between the digital economy and green total factor productivity, but the promotion effect has obvious regional differences. Bukht and Heeks (2017) believed that the digital economy drives the greening of new business models. Zhou et al. (2021) found that digital economy can reduce haze pollution through the role of industrial structure. Li et al., 2021a suggested that digital economy reduced PM2.5. Li et al., 2021b argued that there is a moderating effect of the digital economy between energy mix and carbon emissions. Ren et al. (2021) proposed digitization contributes to the reduction of energy consumption intensity. Wen et al. (2021)found that industrial digitization reduced the production scale of heavy polluters and increased product innovation and green total factor productivity, but its effect on total factor productivity was not significant. However, the study did not conduct mediation effect and heterogeneity analysis.

Based on the summary of the existing literature, we found the research gaps in the existing research. PM2.5 pollution has become a worldwide problem, which is related to nature, physics, production process and efficiency, economic and social factors and the use of new technologies. Most studies explore the impact of economic and social development factors on PM2.5 concentration. Although some studies have discussed the relationship between digital economy and carbon dioxide emission, environmental efficiency, the existing studies lack to explore the mechanism of digital economy affecting PM2.5, which provides an expandable space for this study.

2.2 Theoretical Analysis

The digital economy uses information technology to realize the real-time monitoring of intelligent monitoring system, improve the monitoring of environmental pollution, and effectively control various pollutants and pollution sources. Especially for polluting industries and enterprises, the intelligent monitoring system urges polluting industries and enterprises to manage and dispose of the discharge of pollutants exceeding the standard, and finally achieve environmentally friendly production and reduced PM2.5 emission. The digital economy promotes the flow of production factors and resources to low pollution industries and enterprises, so as to reduce pollutant emissions (Li Z. et al., 2021).

The information technology that digital economy relies on is mainly based on the input of knowledge, technology and other factors, which has the advantages of low-cost diffusion, high marginal income and scale income. The input of new factors will help to accelerate the integration with traditional industries, optimize product structure, improve energy efficiency, promote its transformation to the direction of low energy consumption and low emission, and finally reduce PM2.5 pollution emission. In short, the digital economy can effectively reduce pollution emissions from highly polluting industries, achieve green development of industries, and reduce environmental pollution. To this end, we propose Hypothesis 1: digital economy can reduce PM2.5 emissions.

The digital economy eliminates the obstacles of information transmission, strengthens the spillover of knowledge, and improves the efficiency of innovation. The application of digital technology helps reduce carbon emissions in multiple fields (The Exponential Roadmap, 2020). The enterprises use information technology to fully grasp the supply and demand dynamics of high-tech products, and improve the input-output ratio of innovation.

The continuous integration of digital technology and various fields of economy and society provides new opportunities for green and sustainable development (Zhang B. et al., 2020). Digital economy is conducive to promoting technological innovation. Innovative technology saves resource consumption, improves energy efficiency, and produces ideal output (Liu et al., 2020). The technological innovation will promote the digital transformation of the industrial chain, break the restrictions of traditional enterprises limited by plant, equipment and transportation, effectively integrate online and offline, front-end and back-end links, build a “production-transportation-consumption -recycling” whole industrial chain, improve the energy and resource utilization efficiency, and reduce the PM2.5 emissions. To this end, we propose Hypothesis 2: The digital economy reduces PM2.5 emissions by promoting technological innovation.

As a result, our study explain the relationship between digital economy and PM2.5 pollution. We further explain the impact of technological innovation on the relationship between the digital economy and PM pollution, and explore regional heterogeneity. **Figure 1** depicts the research framework.

3 EMPIRICAL MODEL, VARIABLE DESCRIPTION, AND DATA

This section includes model construction, variable calculation, and data sources.

3.1 Variable Description

This section includes measurements of the digital economy, PM2.5 pollution, and technological innovation.

3.1.1 Digital Economy

Referring to the method by Zhao et al. (2020), Sun et al. (2021) and Liu et al. (2022), this study established an evaluation system for urban digital economy. The evaluation index system of digital economy includes the Internet penetration rate, Internet relevant employees, Internet related outputs, mobile phone penetration and digital inclusive finance. The Internet penetration rate reflects the popularity of digtal infrastructure. The Internet relevant employees represents the penetration of digital economy in the job market. The Internet related outputs reflects the output or performance of digital economy. The mobile phone penetration reports the penetration of digital economy into people’s life and work. The digital inclusive finance indicates the impact of digital technology on financial development. We use principal component analysis to calculate the digital economy development index. Firstly, the data of the five indicators are standardized; secondly, the digital economy development index is obtained by dimensionality reduction. Based on the principal

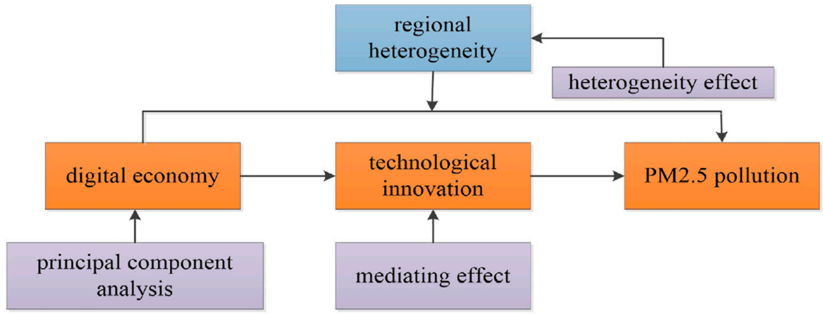

FIGURE 1 | Research framework of digital economy affecting PM2.5 pollution.

component score coefficient matrix, we obtained linear expressions for the two principal components as follows:

$$Y_1 = 0.54X_1 + 0.53X_2 + 0.54X_3 - 0.14X_4 + 0.32X_5 \quad (1)$$

$$Y_2 = 0.08X_1 + 0.23X_2 + 0.24X_3 + 0.73X_4 - 0.59X_5 \quad (2)$$

We divide the variance contribution rates of the two principal components by the sum of the variance contribution rates of the two principal components respectively to obtain their weights. The digital economy development index is calculated by the following formula:

$$\text{digital} = 0.656Y_1 + 0.344Y_2 \quad (3)$$

The original data can be obtained from the "China Urban Statistical Yearbook". The data on the development of digital finance comes from China's digital inclusive finance index.

3.1.2 PM2.5 Pollution

This study calculates the annual average data of PM2.5 concentration bases on the data masked in ArcGIS in prefecture level cities in China according to the Chinese map (Bereitschaft and Debbage, 2013). PM2.5 pollution is from 2011 to 2016 of accessible pulmonary particulate matter data of Columbia University, which is released by the Social Economic Data and Application Center (SEDAC) of Columbia University International Earth Science Information Network Center (CIESIN). The PM2.5 data calculated from satellite observations is scientific and accurate. Compared with ground monitoring data, this method can measure air pollution on a large scale, and can provide air pollution estimation in areas lacking ground monitoring network (Zhang B. et al., 2020).

3.1.3 Technological Innovation

Based on the method of Sun et al. (2020), our study uses the urban innovation index to measure technological innovation (innovation). The innovation index comes from the report on China's urban and industrial innovation power of Fudan University. Based on micro patent big data and new enterprise registration data, the city's innovation index focuses on innovation output and patent value, avoids the disadvantages of only considering the innovation investment and patent quantity in the past, and more accurately reflects the urban innovation.

3.2 Empirical Method

This section discusses the empirical analysis method of the impact of digital economy on PM2.5 pollution. We use the system generalized method of moments (GMM), which solve the endogeneity and the dynamic deviation of model (Stephen, 1982). The core of GMM is to minimize the square sum of all sample moments, and its estimator is obtained based on the minimization of the weighted square sum of sample moments. The System GMM estimation method combines the difference GMM and the horizontal GMM method, and takes the lag term of the first-order difference of the dependent variable as the instrumental variable. Compared with differential GMM estimation, this method can obtain smaller deviation in limited samples and greatly reduce the small sample error.

The purpose of this study is to establish a dynamic model considering the first lag of PM2.5 pollution. First, PM2.5 pollution emission has dynamic characteristics. Second, the lag of PM2.5 pollution corrects the bias of the analysis results. Third, adding lagged terms of PM2.5 pollution as independent variables in the model improves the robustness of the empirical results.

Based on the Sun et al. (2020), this study constructs the following regression test model:

$$pm2.5_{i,t} = \lambda_0 + \lambda_1 pm2.5_{i,t-1} + \lambda_2 digtal_{i,t} + X_{it}T + \varepsilon_{it} \quad (4)$$

where i denotes city and t denotes year; measures the PM2.5 pollution; measures the digital economy; X denotes the control variables; εit is a random term. The coefficient λ_2 indicates the impact of digital economy on PM2.5 pollution.

Our study constructs an mediating model to test the influencing mechanism of technological innovation. In other words, digital economy promotes technological innovation, which reduces PM2.5 emissions. Based on the Sun et al. (2020), the mediating model is as follows:

$$innovation_{i,t} = \theta_0 + \theta_1 innovation_{i,t-1} + \theta_2 digtal_{i,t} + X_{it}T + \varepsilon_{it} \quad (5)$$

$$pm2.5_{i,t} = \eta_0 + \eta_1 pm2.5_{i,t-1} + \eta_2 digtal_{i,t} + \eta_3 innovation_{i,t} + X_{it}T + \varepsilon_{it} \quad (6)$$

where $innovation_{i,t}$ measures the technological innovation. θ_1 denotes the time response; the coefficient θ_2 indicates the

TABLE 1 | Statistical descriptions of the variables.

	Obs	Mean	Std Dev	Min	Max
Pm2.5	1,686	3.4421	0.5329	0.9287	4.4599
digtal	1,686	−0.0795	1.1663	−1.3800	12.6400
pgdp	1,686	10.5939	0.5746	8.7729	13.0556
S_pgdp	1,686	112.5609	12.2669	76.9641	170.4510
population	1,686	5.8597	0.6730	2.9704	7.2435
industrial	1,686	0.4939	0.1014	0.1495	0.8934
expenditure	1,686	0.1918	0.1052	0.0153	1.5751
hum	1,686	1.8177	2.5604	0.0182	35.0218

relationship between the digital economy and technological innovation; Eq. (Xie et al., 2019) examines the effect of technological innovation in digital economy affecting PM2.5 pollution. X is the control variable vector, which is consistent with model 5.

3.3 Data Source and Descriptive Statistics

This study conducts an empirical test using panel data of 281 prefecture-level cities in China from 2011 to 2016. The variable data are obtained from the China Urban Statistical Yearbook (2012-2017). According to the previous research on the factors affecting PM2.5 (Li et al., 2016; Zhang et al., 2019; Sun et al., 2021), this study selects the economic development, population, industrial development, fiscal expenditure and human capital as the control variables. The economic development is measured using the logarithm of GDP per capita (pgdp). Based on the environmental Kuznets curve (EKC) hypothesis, this study also added the square of the logarithm of per capita GDP (S_pgdp). The population is calculated by the logarithm of total population density (population). Industrial development is measured by ratio of the added value of secondary industry to GDP (industrial). The fiscal expenditure is calculated by the ratio of fiscal expenditure to GDP (expenditure). The ratio of the number of college students to the population is used to calculate human capital (hum). **Table 1** lists the statistical descriptions of variables from 2011 to 2016, revealing the characteristics of data distribution.

4 RESULTS AND DISCUSSION

4.1 Basic Regression Analysis

Our study uses the system GMM method to test the impact of digital economy on PM2.5 pollution. The empirical results are reported in **Table 2**. Prior to the regression test, we performed the sargan test, AR (1) and AR (2) tests. The results indicate that there is no second-order serial correlation.

We present the empirical regression results by incrementally adding a control variable. Without adding control variables, the regression coefficient of digital economy is significantly −0.1052 in column (Liu et al., 2019). This preliminarily indicates that the digital economy reduces the PM2.5 emission. In colunm (Zhou et al., 2019), adding the control variable of economic development, the coefficient of digital economy (digtal) is significantly negative. In column (Zhang M. et al., 2020), the square term of economic development is gradually added, and the coefficient of digital economy is still negative, which is at the statistical significance of 1%. Subsequently, we gradually added variables such as population, industrial development, fiscal expenditure and human capital. The results show that the regression coefficient of digital economy is still negative. This study takes column (Du et al., 2018) with all control variables added as the benchmark result. We find that the digital economy reduces PM2.5 pollution. Therefore, digital economy is conducive to reducing PM2.5 pollution and improving environmental quality.

According to the estimated value of the pgdp and S_pgdp, we can find that the relationship between urban PM2.5 emissions and economic growth in China shows a "U-shaped" curve, i.e., with economic growth, urban PM2.5 emissions show a trend of first decline and then increase. In other words, the cities have not achieved the "inverted U-shaped" environmental Kuznets curve development, and in high-income cities, with further economic growth, urban air pollution has a tendency to continue to deteriorate in the current stage of China.

4.2 Result of Influence Mechanism Test

According to the benchmark regression results, there is a negative correlation between digital economy and PM2.5 pollution. The digital economy has an important impact on green sustainable environment and environmental quality through technological innovation. To this end, our study uses the mediating model to analyze the influencing mechanism of technological innovation.

Table 3 presents the results of the mediating model effect. The results indicates that the coefficient of digital economy is positive in column (Liu et al., 2019). That is, the digital economy promotes technological innovation.

The digital economy is a collection of digital technologies that trigger the digital transformation of economy and society. The digital economy realizes the reengineering of production mode and the improvement of efficiency through digital technology, and realizes the digital transformation of economy and society. The digital economy brings new production factors such as information and data to economic development. Through industrial integration, the digital economy promotes the optimal allocation of traditional production factors, produces scale effect and competitive effect, promotes the formation of new industries, new formats and technological innovation.

The results in column (Zhou et al., 2019) of **Table 3** show that the digital economy has a positive effect on reducing PM2.5 pollution, and technological innovation is also conducive to reducing PM2.5 pollution. These findings amply illustrate that the digital economy promotes technological innovation, which in turn reduces pm2.5 emissions, which is largely in line with expectations.

4.3 Result of Heterogeneity Test

China has an uneven development between regions, with significant differences in the natural conditions, economic foundation and structure of the eastern, central and western regions. We discuss the heterogeneous impact of digital economy on PM2.5 pollution across regions. According to the national

TABLE 2 | Regression of digital economy on PM2.5 pollution.

	Liu et al., (2019)	Zhou et al., (2019)	Zhang et al., (2020b)	Li et al., (2021d)	Zhang et al., (2019)	Xie et al., (2019)	Du et al., (2018)
digtal	−0.1052*** (0.018)	−0.0870*** (0.017)	−0.0827*** (0.018)	−0.0886*** (0.019)	−0.0905*** (0.019)	−0.0857*** (0.019)	−0.0691*** (0.017)
pgdp		−0.2813*** (0.028)	−2.9341*** (0.408)	−2.9190*** (0.414)	−2.4991*** (0.435)	−2.6037*** (0.436)	−2.6625*** (0.425)
S_pgdp			0.1263*** (0.019)	0.1256*** (0.019)	0.1091*** (0.020)	0.1134*** (0.020)	0.1169*** (0.019)
population				−0.1061 (0.097)	−0.0975 (0.097)	−0.0756 (0.097)	−0.1199 (0.106)
industrial					0.4438*** (0.151)	0.3173** (0.156)	0.3226** (0.163)
expenditure						−0.2851*** (0.078)	−0.3069*** (0.069)
hum							−0.0108 (0.022)
PM2.5t-1	0.2998*** (0.044)	0.4297*** (0.048)	0.3895*** (0.048)	0.3835*** (0.049)	0.3746*** (0.048)	0.3641*** (0.048)	0.3132*** (0.051)
constant	2.4101*** (0.154)	4.9391*** (0.284)	18.9719*** (2.194)	19.5311*** (2.245)	16.7007*** (2.421)	17.3500*** (2.390)	18.0533*** (2.336)
N	1,405	1,405	1,405	1,405	1,405	1,405	1,405
AR (2)	0.308	0.294	0.270	0.256	0.252	0.239	0.231

**Indicates significance at the 10% level.*
***Indicates significance at the 5% level.*
****Indicates significance at the 1% level; standard error of robustness is reported in parentheses.*

TABLE 3 | Results of the mediating model.

	Liu et al., (2019)	Zhou et al, (2019)
	innovation	**PM2.5**
digtal	0.0398* (0.020)	−0.0624*** (0.016)
innovation	/	−0.0740*** (0.021)
pgdp	0.8271 (1.241)	−1.9508*** (0.440)
Sq_pgdp	−0.0341 (0.055)	0.0880*** (0.020)
population	0.0356 (0.027)	0.0975 (0.124)
industrial	0.7060 (0.853)	−0.1484 (0.215)
expenditure	−0.0613 (0.187)	−0.2051*** (0.072)
hum	0.0049 (0.008)	−0.0021 (0.021)
innovationt-1	0.1494*** (0.023)	
PM2.5t-1		0.3066*** (0.052)
constant	10.5426*** (2.350)	12.7570*** (2.622)
N	1,405	1,405
AR (2)	0.405	0.356

**Indicates significance at the 10% level.*
***Indicates significance at the 5% level.*
****Indicates significance at the 1% level; standard error of robustness is reported in parentheses.*

classification standards, we divided the whole sample into three groups: the eastern region, the central region and the western region.

This study observes the difference of regression coefficient of digital economy in different regions. The empirical results are shown in **Table 4**. The regression results reflect that the reduction of pm2.5 emissions by the digital economy is still significant in the eastern region. The inhibitory effect of digital economy on PM2.5 pollution is still significant in the central region in column (Zhou et al., 2019). There is no significant correlation between digital economy and PM2.5 pollution in column (Zhang M. et al., 2020) in the western region. This result shows that digital economy has no significant inhibitory effect on PM2.5 pollution in the western region.

4.4 Result of Robustness Test

To improve the reliability of empirical results, some robustness tests are conducted in the study. First, the impact of digital economy on PM2.5 pollution may be different in cities at different administrative levels. The provincial capital cities have advantages in resource allocation, public resource management, financial investment and resource redistribution. Therefore, this study focuses on the non capital cities. The robustness test results are reported in columns (Liu et al., 2019)—(Zhou et al., 2019) in **Table 5**. We find that the regression coefficients of digital economy are also significantly negative. In other words, the impact of digital economy on PM2.5 pollution is negative, which shows that digital economy is conducive to reducing PM2.5 pollution. The robust results are consistent with the benchmark regression results.

Second, our study uses the ratio of Internet users to population as a proxy for the digital economy and tests it empirically. The robustness test results are reported in columns (Zhang M. et al., 2020) - (Li Y. et al. (2021)) in **Table 5**. The coefficient of digital economy is also significantly negative, indicating that digital economy reduces PM2.5 pollution. In other words, the above conclusions confirm that the digital economy has a significantly negative impact on PM pollution, which is in line with expectations.

4.5 Discussion of the Empirical Results

Based on theoretical analysis and empirical tests, we conclude that the digital economy is conducive to reducing PM2.5 pollution. It is worth noting that there are regional differences in the effect of this reduction in pollution emissions. Liu et al. (2022) found that the digital economy is conducive to the improvement of GTFP. Zhou et al. (2021) found that digital economy can reduce haze pollution through the role of industrial structure. Li et al., 2021a suggested that the digital economy improve environmental quality. These conclusions are similar to this study. The development of the digital economy relies on the new generation of information technology industries with the Internet of Things, big data, mobile Internet and cloud computing as the core. These industries are technology-intensive and low-pollution industries. The development of these industries will have a push-back effect on traditional polluting industries and enterprises, which can promote the flow of intelligent factors to polluting industries and enterprises, eliminate backward production capacity of

TABLE 4 | Results of heterogeneity test.

	Liu et al., (2019)	Zhou et al., (2019)	Zhang et al., (2020b)
	East	Central	West
digtal	−0.1148*** (0.041)	−0.0762*** (0.028)	0.0272 (0.029)
pgdp	−1.5983 (1.421)	−3.6340** (1.446)	−0.3944 (0.718)
S_pgdp	0.0715 (0.060)	0.1721** (0.070)	−0.0031 (0.034)
population	0.9010 (0.665)	−0.0110 (0.201)	0.2012 (0.130)
industrial	0.3544 (0.500)	0.0395 (0.338)	0.5555*** (0.197)
expenditure	−1.5231 (1.225)	−0.0940 (0.452)	−0.2368*** (0.026)
hum	−0.0575* (0.031)	−0.0046 (0.045)	−0.0165 (0.028)
PM2.5t-1	0.3472** (0.136)	−0.2715*** (0.042)	0.2100*** (0.068)
constant	6.0787 (7.146)	23.5378*** (7.581)	5.5611 (3.759)
N	490	500	415
AR (2)	0.267	0.211	0.183

**Indicates significance at the 10% level.*
***Indicates significance at the 5% level.*
****Indicates significance at the 1% level; standard error of robustness is reported in parentheses.*

TABLE 5 | Robustness test.

	Liu et al., (2019)	Zhou et al., (2019)	Zhang et al., (2020b)	Li et al., (2021d)
digtal	−0.0941*** (0.017)	−0.0624*** (0.017)		
A.digtal			−0.0751*** (0.010)	−0.0244* (0.013)
pgdp		−2.2383*** (0.342)		−2.0422*** (0.374)
S_pgdp		0.0996*** (0.015)		0.0919*** (0.017)
population		−0.3806*** (0.138)		−0.1963 (0.121)
industrial		0.1175 (0.138)		0.2128 (0.162)
expenditure		−0.5408*** (0.121)		−0.6517*** (0.158)
hum		−0.0789** (0.031)		−0.0106 (0.024)
watert-1	0.2595*** (0.047)	0.2817*** (0.055)	0.3111*** (0.043)	−0.0840** (0.035)
constant	2.5453*** (0.165)	18.7897*** (2.012)	3.6285*** (0.116)	16.2781*** (2.153)
N	1,405	1,405	1,405	1,405
AR (2)	0.336	0.312	0.295	0.266

**Indicates significance at the 10% level.*
***Indicates significance at the 5% level.*
****Indicates significance at the 1% level; standard error of robustness is reported in parentheses.*

polluting industries and enterprises, and improve the efficiency of enterprise resource allocation and reduce pollution emissions.

We propose that digital economy facilitates technological innovation and thus reduces PM2.5 emissions. This finding is similar to that of Feng et al. (2021), which means that green technology innovation has a suppressive effect on the haze pollution. At the same time, technological innovation plays an important role in green development (Sun et al., 2021). Aldieri and Vinci (2020) analyzed the positive role of knowledge spillovers in the field of clean production and energy. They all suggest that the development of technology contributes to improved environmental performance and green sustainability.

However, there are some differences. Zhou et al. (2021) proposed that the digital economy is the most significant in reducing haze pollution in eastern China. The digital economy reduces haze pollution through the industrial structure. Liu et al. (2022) found that the digital economy improves the green total factor productivity through the industrial structure upgrading. These studies do not consider the role of technological innovation. Li et al., 2021b took PM2.5 as a proxy variable representing environmental quality, found that the digital economy reduced PM2.5, improved environmental quality, and considered the threshold effect of urbanization and population. The present study ignores the mediating mechanism of the effect of digital economy on PM2.5 pollution, and our study precisely fills this gap.

5 CONCLUSIONS AND POLICY RECOMMENDATIONS

Our study explores the effect of digital economy on PM2.5 pollution for a panel of Chinese prefecture-level cities. The regression results demonstrate that digital economy reduces the PM2.5 pollution, and the conclusion is still robust after changing the regression sample and measurement of independent variable. The results also show that digital economy reduces PM2.5 pollution emissions through technological innovation. We find further evidence that the inhibitory effect of digital economy on PM2.5 pollution is more significant in the eastern and central regions. Unfortunately, the effect of digital economy on reducing PM2.5 pollution emission is not significant in the western region. Our findings provide a new pathway to achieving the "carbon peaking and carbon neutrality goals".

Our conclusion provides enlightenment for follow-up research. The important finding of this study is that the digital economy, as a new form of economy, reduces PM2.5 pollution. Further future research should focus on improving environmental quality from the perspective of innovative economic form. In addition, we also provide practical enlightenment to bridge the gap between theory and practice. On the one hand, the government should vigorously develop innovative economy and promote the application of technological innovation; On the other hand, the research conclusions inspire the technological progress to reduce environmental pollution. Our empirical results show that the digital economy reduces pollution emissions. Based on the empirical findings obtained from the above study, we can put forward some policy implications.

The digital economy is an important driving force to reduce pollution emissions and improve environmental quality. However, the development of digital economy in cities across the country is not balanced, and there are significant differences in digital infrastructure construction. Therefore, all regions should increase capital investment and policy support, promote the infrastructure construction related to the information technology, and accelerate the development of digital economy. On this basis, the government promotes the green transformation of industries and enterprises by promoting the promotion of digital technology. The government should accelerate the application of a new generation of mobile information technology, strengthen Internet access capacity and provide strong support for the digital economy. At the same time, the bottleneck of developing digital economy in backward areas is the lack of high-quality talents, which leads to the lag of digital application and digital industry reform. The government should carry out national digital literacy education, which can not only cultivate high-end talents of digital technology, but also improve the national digital application ability. We need to strengthen regional environmental protection cooperation and bring into play the spatial radiation of the green effect of the digital economy. We should strengthen the interconnection and coordination of regional environmental protection policies, vigorously promote regional joint prevention and control, establish a unified cross-regional joint early warning and pollution data sharing platform, and create a low-carbon living circle of the digital economy in the process of pollution prevention.

Technological innovation is the influencing mechanisms of digital economy affecting PM2.5 pollution. Technological innovation is the key factor affecting environmental quality. The government should stimulate the energy saving and new energy technology innovation, and give full play to the important role of energy-saving technology transformation in promoting the optimization and upgrading of energy-saving industries and promoting energy efficiency in enterprises to reduce pollution emissions. The government should build an innovation system to promote the development of the digital economy, improve the ability to promote and apply new knowledge and technology, promote the deep penetration and integration of traditional industries with modern information technology, and achieve the overall development of the digital economy. Industries and enterprises should actively introduce advanced energy-saving and emission reduction and other green technologies to improve the efficiency of resource utilization, reduce the waste of resources in the production process, and reduce PM2.5 pollution emissions.

This study has some limitations. Firstly, we use the panel urban data from 2011 to 2016 for empirical test, which is limited by the data. If the global data can be used to test the research conclusion, the robustness of the conclusion can be increased. Secondly, the threshold effect should be added in the future research. Threshold variables may change the linear relationship between digital economy and PM2.5.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XS was involved in the development of research idea, methodology, original draft and writing. ZC was involved in conceptualization and writing. XS and LL analyze the data and complete the final manuscript.

FUNDING

This work is supported by the Natural Science Foundation of Fujian (2021J011036), General project of educational research project for young and middle-aged teachers (SOCIAL SCIENCES) of Fujian Provincial Department of Education (JAS21259); School level scientific research project of Minjiang University (MYS21005).

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