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The research on the effect of digital economy development on urban air quality

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Digital economy and air quality are the key issues concerned by the government and academia. The healthy and sustainable development of the digital economy and the continuous optimization of urban air quality are not only conducive to high-quality economic development but also closely related to people's livelihood. Based on the panel data of 228 cities from 2015 to 2020, using the panel regression and the mediating effect test methods, this paper verifies the impact of the digital economy development on urban air quality and then further analyzes the heterogeneity. The main results are as follows. Digital economy development can effectively improve urban air quality. The mediating effect of the urban industrial structure advancement accounts for 17.27%, and that of urban TFP accounts for 14.55%. The effect of improving air quality in cities with a high-level digital economy is more prominent, and the effect in large and medium-sized cities is more extensive. Meanwhile, in cities with a high urbanization rate, the effect of digital economy on improving air quality is more prominent.

KEYWORDS

digital economy, urbanization rate, air quality, mediating effect, threshold effect

1 Introduction

The term "digital economy" can be traced back to a report "The San Diego Union Tribune" in 1994. In recent years, as the application of digital technology has become more mature and its fields cover more extensively, the connotation of digital economy has been extended to a richer and more complex direction. According to the OECD, digital economy refers to a series of economic activities that use digital knowledge and information as key production factors, modern information network as an important carrier, and the effective use of information and communication technology as an important driving force for efficiency improvement and economic structure optimization. The digital economy has gone through a process from being characterized by digital technology to cross-border integration and innovation development. It should include all kinds of economic activities based on digital technology. With the iterative development of digital technology, the global economy is in the stage of accelerated digital transformation. China, as a developing country, is changing the traditional extensive economic development mode to vigorously develop the digital economy, gradually becoming the leader in the development of the digital economy.

The development of the digital economy and the construction of a beautiful China have an impact on China's economic development that cannot be underestimated. As an important new engine for the high-quality development of China's economy, the digital economy has greatly contributed to promoting economic growth, optimizing the industrial structure, serving enterprise development, and creating jobs. Especially during the fight against the COVID epidemic, new business forms and models derived from the digital economy have played an irreplaceable role in economic life and social production. Chinese Academy of Social Sciences calculated that the digital economy has contributed about 18.8% to China's GDP in 2020. According to the data released by the China Academy of Information and Communications Technology, the development scale of the global digital economy reached US$32.6 trillion in 2020, of which China's digital economy is worth nearly US$5.4 trillion, accounting for 16.6% of the global digital economy development scale. In terms of growth rate, the year-on-year growth rate of China's digital economy in 2020 is 9.6%, ranking first in the world. The rapid development of the digital economy has become a new driving force for economic growth, which will help China steadily get through the period of economic change, travail and policy digestion.

Of course, the development model in the new era should no longer pursue economic growth but pay attention to the requirements of the new development concept, in which green development is an important content. The implementation of the "Double Carbon" policy is the specific requirement of national green development. The embodiment of the close relationship between green development and residents lies in urban air quality. In the past, China was considered one of the countries with the most serious air pollution in the world (Liao and Shi, 2018; Chen et al., 2018). Air quality is related to people's livelihood and directly affects residents' life satisfaction (Ferreira et al., 2013). Studies have confirmed that air pollution will negatively affect economic development and residents' physical and mental health (Xu et al., 2013; Zhang et al., 2017; Hao et al., 2018). A few years ago, the PM readings were often "off the charts", indicating the severity of air pollution. But now the situation has changed, with the implementation of a series of national environmental policies, the transformation and development of industrial structure, and the continuous improvement of ecological compensation mechanisms, the air quality is getting increasingly better. According to the data released by the Ministry of Ecology of China during the 13th Five-Year Plan period, in the fourth quarter of 2020, the PM2.5 value of Beijing-Tianjin-Hebei region and its surrounding 39 cities decreased by 39%, and the number of days of heavy pollution decreased by 87% compared with the same period in 2016. The average number of good days of urban air quality has also increased significantly. So, what factors have improved urban air quality?

Many scholars have discussed the causes of urban air quality improvement in China from different fields and perspectives. Wang et al. (2021) found that social media applications can significantly improve urban air quality based on the panel data at the prefecture-level in China. Based on Beijing's environmental monitoring data from 2013 to 2019, Li et al. (2020) found that the significant decreasing in coal consumption caused by the change in energy structure is the main factor for the improvement of Beijing's air quality. Song et al. (2020) conducted research on the gradual expansion of China's air pollution joint prevention and control area in recent years, and the research confirmed that with the expansion of the number of cities in the alliance, the air quality in the region has been further improved. Meanwhile, the impact of urbanization on air quality has also aroused extensive discussion in the academic community. Lin and Zhu (2018), Wang et al. (2020) and Wang et al. (2021) also have demonstrated the relationship between urbanization and air pollution from different perspectives. What's more, some scholars have analyzed the improvement of air quality from the perspective of government policy and environmental protection inspectors (Chen et al., 2021; Tan and Mao, 2020).

In fact, the period when China's air quality changes significantly is the period when China's economic development strategy makes major adjustments. In 2015, the Chinese government officially put forward the new development concept. Digital-economy-related policies have been continuously implemented since the "National Big Data Strategy" was put forward in 2015. By the end of 2022, the scale of the digital economy will reach 7.1 trillion US dollars. So is there an inevitable relationship between the improvement of air quality and the development of digital economy? The research of Li Z. et al. (2021) believes the development of China's digital economy not only has a far-reaching impact on economic operation but also brings profound changes to the environmental system, which is mainly reflected in the fluctuating rising trend in the coupling and coordination degree between the digital economy system and the environmental system. Wen et al. (2021) found that in the process of China's industrial digital transformation, the environmental performance of manufacturing enterprises has been significantly improved. On the contrary, according to the research report "Towards Carbon Neutrality: A Road map for China's Internet Technology Industry to Achieve 100% Renewable Energy" released by Greenpeace, an international environmental protection organization, the proportion of greenhouse gas emissions of the global ICT (Information and Communications Technology) industry will increase from 1% to 1.6% in 2007 to more than 14% in 2040. This report clearly points out that the digital economy industry is becoming one of the major contributors to carbon emissions. According to the Environmental Kuznets Curve (EKC) theory, the industrial structure adjustment and technological iterative progress brought by the development of digital economy can improve the environment to a certain extent.

As an important medium for China's economic transformation and growth mode, the digital economy takes the development of digital industry as the main line, and the deep integration of digital technology and various industries as the main axis. It optimizes the efficiency of resource allocation in an all-round and multi-level manner, and promotes China's economic development to high quality. Under such an economic background, China's urban air quality generally presents a friendly rising trend. Then, with the vigorous development of the digital economy, will the digital economy make an important contribution to the improvement of air quality? Specifically, what is the degree of improvement if the digital economy can improve urban air quality? Through what mechanism or path to achieve the goal? In view of this, this paper takes the impact of digital economy development on urban air quality and path exploration as the research goals, constructs models such as panel data regression and mediating effect test, and systematically analyzes the impact of digital economy development on urban air quality.

The marginal contributions of this paper are as follows. 1) Based on systematically analyzing the changes in air quality brought about by the digital economy development, this paper conducts theoretical and empirical tests on the impact of the digital economy development on urban air quality. 2) Combined with the mediating effect test, this paper objectively analyzes the transmission path of the development of digital economy affecting urban air quality. 3) This paper analyzes the impact of the digital economy on urban air quality under different levels of digital economy development, city scales, and urbanization rates to depict the overall picture of the impact of digital economy development on urban air quality.

China is not only an important representative of developing countries but also a leader in the world's digital economy and an outstanding contributor to environmental improvement. As a role model of transiting from an extensive economic development mode to a green economy mode, China has great reference significance in the world both in terms of economy and environmental improvement. Therefore, this paper selects Chinese cities as samples to analyze the impact of digital economy on air quality. On the one hand, the purpose is to hope that the research results can provide practical reference for other developing and developed countries with immature digital economy development, offering new ideas for world carbon neutrality and air quality improvement. On the other hand, on the basis of corroborating previous research, this research is expected to enrich the theory of environmental economics and supplement the research results of digital economy and environmental effects that are relatively lacking in the current academia. Through the innovation of research data and methods, the relationship between digital economy and air quality is illustrated in a more microscopic and specific manner, and the air quality indicators are scientifically subdivided.

The remaining structure of this paper is arranged as follows. Section 2 elaborates on the theoretical analysis and research hypothesis, mainly deducing the impact path of digital economy on air quality from a qualitative perspective and proposing possible research hypotheses. Section 3 describes the variable selection, data sources, and model settings, determining the variables and data sources selected by the research and listing the general forms of models used in the research. The fourth Section conducts the empirical analysis, which gives the results of the benchmark regression and the mediating effect test, respectively. Section 5 further analyzes the heterogeneous impact of the digital economy development on urban air quality. The sixth section systematically summarizes the research conclusion.

2 Theoretical analysis and research hypothesis

The impact of digital economy development on air quality can be elaborated from two aspects. First, the digital economy takes high technology as the medium and the real economy as the carrier. While integrating the development of the real economy, it helps the real economy to transform and develop into the high-tech field. Therefore, the digital economy participates in the real economy with its technological advantages, reducing the possibility of air pollution caused by the development of the real economy, thereby directly affecting the urban air quality. Second, the development of the digital economy can accelerate the adjustment of industrial structure and improve the total factor productivity. Through the integration of the digital economy with the development of the real economy, high-tech-oriented modern industries will force cities to eliminate high-pollution and energy-intensive industries, accelerating the adjustment of urban industrial structure and thus indirectly affecting urban air quality. Similarly, the digital economy relies on its technological advantages; therefore, its technological spillovers will improve urban total factor productivity, and technological progress will improve resource utilization efficiency, indirectly affecting urban air quality.

2.1 Digital economy development and air quality

The essence of the digital economy development is to use technological progress or technological innovation to affect the production, circulation, or consumption of products, and thereby affecting the final output. Specifically, digital economy development relies on the development of the real economy, and by integrating digital technology into the real economy, it further improves the environmental pollution and urban air-quality problems of the development of the real economy. Existing literature shows that the air pollution issue is one of the environmental problems that need to be solved urgently in China (Gu and Yim, 2016), and air quality is an important indicator to measure regional environmental pollution (Liu and Lin, 2019). Based on the panel data of 30 provinces in China from 2011 to 2017 and using the extended STIRPAT model, Li Y. et al. (2021) analyzed that digital economy development had an inhibitory effect on carbon emissions. Zhou et al. (2021) empirically tested the relationship between the digital economy and haze pollution using spatial and threshold models, and they concluded that the development of the digital economy can significantly reduce haze pollution. Based on analyzing the coupling and coordination degree of the digital economy and environmental system, Li Z. et al. (2021) further investigated the relationship between the digital economy and PM2.5. The results showed that when the regional population density and urbanization rate pass a certain threshold, digital economy development will significantly inhibit PM2.5 (Li Z. et al., 2021). With the development of the digital economy, urban transformation triggered by the digital economy can significantly improve air quality (Leung and Fat, 2021; Wang et al., 2022). The digital economy that affects the environment has the scale effect, the technology effect and the structural effect, which are basically in line with the EKC theory. At the same time, other scholars have put forward opposing views, including the aforementioned research report released by the Greenpeace. Based on the EU data from 2001 to 2014, Yongmoon et al. (2018) concluded that Internet use is posing a threat to sustainable development. The empirical findings of Avom et al. (2020) also confirm that the information and communication technology significantly stimulates local CO_2 emissions. As far as current research is concerned, it is still controversial that the digital economy can improve air quality. On the one hand, most literatures show that the digital economy has an improving effect on urban air quality. On the other hand, it turns out that the air quality of Chinese cities has indeed improved in recent years, but is this improvement related to the development of China's digital economy? Has the digital economy played a role in improving air quality?

Therefore, this paper puts forward the following hypothesis:

Hypothesis 1. Digital economy development of can effectively improve urban air quality.

2.2 The mediating effect of the industrial structure

Digital economy development has a significant impact on the industrial structure. Acemoglu et al. (2018) pointed out through research that technological innovation can promote industrial structure advancement. The digital economy just conforms to this feature. How digital economy development affects the industrial structure has been discussed in detail in academia. The technology life-cycle theory holds that a technology goes through a similar process of birth, growth, development, maturity, and then decline. The development mode of digital economy based on digital and information technology provides knowledge and data empowerment for economic development and industrial upgrading (Su et al., 2021). Digital economy development has gradually changed the industrial structure from the traditional labor, capital, and technology-intensive industries to digital-intensive industries, and the advanced industrial structure has been significantly improved (Jiang and Sun, 2020). Su et al. (2021) focused on the internal mechanism of the digital economy to promote the upgrading of the industrial structure from the micro, meso, and macro perspectives. Heo and Lee (2019) and Lee et al. (2009) also confirmed through empirical tests that digital economy can promote the upgrading of industrial structure. From the above analysis, it can be seen that the assertion that digital economy promotes industrial structure upgrading seems to have been fully and positively answered. So, can digital economy influence air quality through promoting the industrial structure advancement? According to the Environmental Kuznets Curve (EKC) theory, with the integration and development of the digital economy and the traditional economy, traditional pollution-intensive industries are transformed into green and economic industries, thereby reducing environmental pollution and improving air quality. The research of Li X. et al. (2021) supported the EKC theory, that is, there is an inverted U-shaped nonlinear relationship between carbon dioxide emissions and the digital economy. Moreover, can industrial structure affect air quality? Li and Li (2022) adopted a multi-level growth model to conduct research based on China's urban data from 2015 to 2018, and the results confirmed that industrial structure upgrading can significantly improve air quality. Studies like Zheng et al. (2020) and Chang (2015) have confirmed that the adjustment of industrial structure is one of the main factors for improving air quality. Therefore, this paper proposes the following hypothesis by drawing on the existing research conclusions and ideas:

Hypothesis 2. Digital economy development can affect the urban industrial structure, thereby affecting the urban air quality.

2.3 The mediating effect of the total factor productivity

Digital economy is the product of scientific and technological innovation (Wen et al., 2022). Thompson et al. (2013) found through research that digital economy can provide innovation resources for enterprises. Thus, digital economy can affect urban total factor productivity (TFP) through innovation. From a micro perspective, Chen and Jiang (2021) analyzed the data of A-share listed companies and believed that the development of digital finance can effectively improve enterprise TFP. Pan et al. (2022) analyzed the impact of China's digital economy on the TFP from a macro perspective and concluded that digital economy is the innovative driving force of the TFP growth. Based on quasi-natural experiments, Qiu and Zhou (2021) held that digital economy development has a positive effect on improving regional TFP, and the effects vary among different regions. Of course, some scholars choose other samples to discuss the impact of digital economy on TFP. For example, Liang and Chen (2021) selected the TFP of China's service industry, and Tian and Liu (2021) chose the TFP of China's listed digital enterprises. Their research results confirm that digital economy can improve the TFP. However, the relationship between TFP and air quality has not yet reached a unanimous conclusion. The digital economy development is inseparable from technological progress, and the governance of air quality also requires cutting-edge technology. As a proxy variable of technological progress, TFP is not only related to the digital economy development but also with a pollution control effect, which can effectively reduce environmental pollution and improve urban air quality. Therefore, this paper uses the TFP as a mediating variable and puts forward the following hypothesis:

Hypothesis 3. Digital economy development can affect urban air quality by influencing urban total factor productivity.

2.4 Heterogeneity of the impact of digital economy development on urban air quality

The heterogeneity of the impact of digital economy development on urban air quality should also be considered. Different scales of digital economic development may have differential impacts on air quality. A high-level digital economy development scale will allow the real economy to absorb more technological elements, which may have a more significant impact on urban air quality; a low-level digital economy will have a weaker impact on urban air quality, because it cannot integrate more scientific and technological elements. Li Y. et al. (2021) also demonstrated this problem in their research. Meanwhile, the impact of the digital economy development on urban air quality may also be related to the size of urban population. The digital economy development under different urban scales may have different impacts on urban air quality. When Li Z. et al. (2021) studied the relationship between digital economy and PM2.5 emissions, they found that urbanization, population density and economic development all have threshold effects. The Environmental Kuznets Curve shows that there is a nonlinear relationship between economic development and environmental pollution. As a significant indicator of the urban economic development level, the urbanization level should have a significant impact on the urban air quality. When the level of urbanization is under a certain state, coupled with the automatic restoration function of the environment, the air quality will not be significantly affected. However, when the urbanization level reaches or even exceeds a certain level threshold, the environment cannot be repaired automatically, and the air quality will suffer an irreversible impact. So, what role does urbanization play in the relationship betwen digital economy and urban air quality? It is worth digging deeply. At the same time, since the process of urbanization can affect urban air quality, it is worth exploring what role urbanization plays in the impact of digital economy on urban air quality. From this point of view, this paper proposes a heterogeneity impact hypothesis:

Hypothesis 4. The impact of digital economy development on urban air quality is heterogeneous; that is, the impact of digital economy on urban air quality varies with the level of digital economy, city size, or urbanization.

3 Variable selection, data sources and model settings

3.1 Variable selection and data sources

Firstly, the explained variable in this research is the urban air quality (U-AIRQuality). There are three ways to measure air quality, namely the comprehensive index, the emission index and the concentration index. After comparative analysis, this paper composes the Air Quality Index (AQI) to measure the comprehensive situation of urban air quality. Urban Sulfur dioxide emission (SO2) is chosen to represent the emission of urban air quality pollutants. PM2.5 and PM10 are selected to represent the pollutants concentration of urban air quality. According to the original datas, which come from the China Air Quality Online Monitoring and Analysis Platform, the larger their values are, the worse the air quality is. This paper organizes the annual data on urban air quality as needed. To eliminate the heteroscedasticity effect, all research variables are processed logarithmically.

Secondly, the core explanatory variable is the development level of digital economy (Digital), which is mostly measured by provincial data, such as China's Digital Economy Development Index released by CCID and Deyang, Sichuan and the Urban Digital Economy Industry Development Index released by Beijing Big Data Research Institute using enterprise-level data. Considering the research purpose, operability and existing literature, this paper follows the research of Huang et al. (2019) and Zhao et al. (2020), which have been adopted by many studies, to consider the development of urban digital economy from the perspective of the Internet development level and digital financial inclusion (Guo et al., 2020). The Internet development level includes four parts: the Internet penetration rate, the number of Internet-related employees, the Internet-related output, and the number of mobile Internet users. As for digital financial inclusion, this paper adopts the Peking University Digital Financial Inclusion Index, which includes three categories: breadth of coverage, depth of use, and level of digitization. Using the principal component analysis method to extract principal components, the Internet development level and the digital financial inclusion are integrated into the development level of the urban digital economy (Digital).

Thirdly, by referring to Zhou et al. (2021), who selected industrial structure advancement as the mediating variable to empirically analyze the impact of digital economy on smog pollution, this paper chose industrial structure advancement (IND) as the mediating variable. The ratio of the added value of the tertiary industry to the added value of the secondary industry is employed to calculate the IND. This paper also sets the second mediating variable, city total factor productivity (CITY-TFP), which refers to the level of TFP in different cities. The main reason for selecting urban TFP as the mediating variable is to consider the high-tech effect of digital economic development, which can improve the existing production process and production links, and then transform the production mode of some enterprises with high energy consumption, high pollution and low output, thereby improving the efficiency of resource utilization and achieving the goal of improving air quality. Therefore, in this process, the technological effect of the digital economy development can further affect the urban air quality by improving the urban TFP. According to Huang et al. (2019), this paper calculate the urban TFP using the stochastic frontier analysis and the data envelopment analysis methods.

Finally, combined with the existing research literature, this paper holds that the pollution emissions brought about by economic growth will inevitably have an impact on the environment. Generally speaking, the level of foreign direct investment will impact environmental issues. In the case of investing in high-tech industries, the air quality will be improved; if FDI goes into high-emission industries, air pollution may increase. The level of social consumption is also closely related to air quality. Social consumption is often the main source of air pollutants, so paying attention to the level of social consumption means paying attention to urban air quality. Due to the lack of data on fiscal expenditures of environmental protection in some cities, the proportion of local government fiscal expenditures in GDP is used to indicate the possible financial strength that the city may be used to control air pollution. According to data from China's seventh census, population density is inversely proportional to air quality. Based on the above considerations, this paper selects five control variables, namely the logarithm of GDP per capita (LNPGDP), the logarithm of foreign direct investment (LNFDI), social consumption (SALES), fiscal level (Fin), population density (LNPde) (Zhao et al., 2019; Li Y. et al., 2021; Deng and Zhang 2022). The specific calculation methods are as follows. LNPGDP is measured by taking the logarithm of a city's per capita GDP. LNFDI is calculated by taking the logarithm of the value of foreign direct investment in a city. SALES refers to the ratio of the total retail sales of consumer goods in a city to the city's GDP. Fin is measured by the proportion of the fiscal expenditure in GDP. LNPde is calculated by taking the logarithm of the number of people per unit area of a city.

In view of the serious lack of data in some remote areas, this paper selects the data of 228 cities from 2015 to 2020 as the panel data to conduct the research. Among them, the basic data collection relies on China Urban Statistical Yearbooks, China Statistical Yearbooks, Peking University Digital Financial Inclusion Index, and the statistical yearbooks of various provinces over the years. The mean value replacement interpolation method is used to fill in a small number of missing data. If there is a missing value of a variable in a city, the average of the remaining years of the variable is used to fill in the missing value. Table 1 presents the descriptive statistics of research variables.

3.2 Model setting

According to the research purpose and the above research hypotheses, the following econometric models are constructed to empirically test the impact of digital economy development on urban air quality. The first one is the direct effect model to explore the impact of digital economy development on urban air quality. The second one is the mediating effect model that tests whether digital economy development affects urban air quality by affecting the industrial structure advancement or urban TFP.

Benchmark regression model

$$U-AIRQuality_{it}=\beta_0+\beta_1 Digital_{it}+\beta_c Z_{it}+\mu_i+\theta_t+\varepsilon_{it}$$

Mediating effect model of industrial structure advancement:

$$IND-Structure_{it}=\alpha_0+\alpha_1 Digital_{it}+\alpha_c Z_{it}+\mu_i+\theta_t+\varepsilon_{it}$$

$$U-AIRQuality_{it}=\eta_0+\eta_1 Digital_{it}+\eta_2 IND_{it}+\eta_c Z_{it}+\mu_i+\theta_t+\varepsilon_{it}$$

Mediating effect model of urban TFP:

$$CITY-TFP_{it}=\delta_0+\delta_1 Digital_{it}+\delta_c Z_{it}+\mu_i+\theta_t+\varepsilon_{it}$$

$$U-AIRQuality_{it}=\omega_0+\omega_1 Digital_{it}+\omega_2 CITY-TFP_{it}+\omega_c Z_{it}+\mu_i+\theta_t+\varepsilon_{it}$$

The explained variable U-AIRQuality has four expressions, namely LNAQI, LNSO2, LNPM2.5, and LNPM10; β_0, β_1, and β_c represent the intercept term, the coefficient of the core

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TABLE 1 Descriptive statistics of research variables.

Variable		Symbol	Obs	Mean	Std. Dev	Min	Max
Explained variable	Urban air quality level	LNAQI	1368	4.279	0.371	1.098	5.799
		LNSO2	1368	2.617	0.719	0.000	6.182
		LNPM2.5	1368	3.590	0.592	0.693	6.236
		LNPM10	1368	4.191	0.529	2.079	7.284
Explanatory variable	Urban digital economy level	Digital	1368	5.742	0.576	2.916	8.875
Mediating variable	Industrial structure advancement	IND	1368	0.904	0.475	0.126	4.335
	Urban total factor productivity	CITY-TFP	1368	1.076	0.145	0.731	1.348
Control variable	Per capita GDP	LNPGDP	1368	10.945	0.612	8.994	16.112
	Foreign direct investment	LNFDI	1368	11.916	1.922	3.126	17.012
	Social consumption	SALES	1368	0.442	0.416	0.108	0.624
	Fiscal level	Fin	1368	0.225	0.186	0.092	0.685
	Population density	LNPde	1368	5.882	1.026	1.715	7.986

Mean value, standard deviation, minimum value and maximum value of explained variable (LNAQI, LNSO2, LNPM2.5, LNPM10), explanatory variable (Digital), Mediating variable (IND, CITY-TFP) and control variable (LNPGDP, LNFDI, SALES, Fin, LNPde).

explanatory variable and the coefficient of the control variable, respectively; μ_i represents the fixed effect of city i that does not change with time; θ_t represents the time fixed effect; ε_{it} represents the random error term, and others are also coefficient variables. The mediating effect will be further determined according to the significance level of the coefficient.

4 Empirical analysis

4.1 Benchmark regression analysis

According to the research scheme, this paper first analyzes the overall situation of the impact of digital economy development on urban air quality. Before conducting the model benchmark regression, authors first carry out stationarity, endogeneity, and Hausman tests on research variables. This paper adopts LLC and ADF-Fisher, respectively, to test the stationarity of all variable sequences, and the results show that all variables pass the tests at the 5% significance level. This paper chooses the DWH test method for the endogeneity test, and the test p-value is 0.1256, which doesn't reject the null hypothesis, indicating that the model has no endogeneity problem. The Hausman test results show that the test p-value is 0.000, and the null hypothesis is rejected, so the model should adopt a fixed-effect estimation.

Table 2 presents the benchmark regression results of the model. Among them, the explained variables are listed from three types of cases, and control variables are added. Both the individual and time effects are fixed. The specific analysis results are as follows. First, the impact coefficients of the digital economy on urban air quality all pass the test at the 5% significance level, and all the coefficient values are negative. The result indicates that urban digital economy development can effectively reduce the value of AQI, SO_2 pollution emissions, and the concentrations of PM2.5 and PM10 in the air, thereby improving urban air quality. Hypothesis 1 is verified. Second, the impacts of per capita GDP and social consumption variables on urban air quality show a pollution effect. The positive

TABLE 2 Benchmark regression model results.

Variable	Urban air quality			
	LNAQI	LNSO2	LNPM2.5	LNPM10
Digital	−0.022***	−0.008***	−0.015**	−0.025***
	(−3.85)	(−2.96)	(−2.24)	(−3.68)
LNPGDP	0.151***	0.016***	0.156***	0.162***
	(4.35)	(5.56)	(5.80)	(6.26)
LNFDI	−0.016***	−0.142	−0.052***	−0.058
	(−3.64)	(−1.62)	(−3.54)	(−1.08)
SALES	0.114**	0.095**	0.092**	0.108***
	(2.28)	(2.43)	(2.50)	(3.69)
Fin	−0.012**	−0.020	−0.006	−0.008
	(−2.42)	(−0.42)	(−0.36)	(−0.26)
LNPde	0.036	0.055	0.036	0.044
	(1.05)	(0.80)	(1.15)	(0.96)
City effects	Fixed	Fixed	Fixed	Fixed
Time effects	Fixed	Fixed	Fixed	Fixed
_Cons	3.529***	2.012***	4.102***	4.320***
	(38.26)	(12.66)	(14.85)	(15.24)
N	1368	1368	1368	1368
Adj-R2	0.425	0.550	0.520	0.486

***, **, and * indicate passing the test at the significance level of 1%, 5%, and 10%; t values are in brackets.The panel data adopts double fixed effect regression results, in which the explained variable in column 1 is (LNAQI), column 2 is (LNSO2) and column 3 is (LNPM2.5), and column 4 is (LNPM10).

coefficient value means that the AQI value, SO_2 emission, and PM2.5 and PM10 concentrations can be increased, and the coefficient has also passed the test at the significance level of 1% or 5%. This means that both per capita GDP and social consumption have deteriorated urban air quality. Third, there are differences in the impacts of FDI, fiscal level, and population density on urban air quality. The impacts of FDI and fiscal level on urban air quality are uncertain, while the impact of population density on urban air quality is not significant. Fourth, the overall fitting of the model is good. It can be seen from the four regression models that the value R^2 of the model is high.

TABLE 3 Test results of the mediating effect of the industrial structure advancement.

Variable	Model (1)	Model (2)	Model (3)
	LNAQI	IND	LNAQI
Digital	−0.022***	0.214***	−0.014**
	(−3.85)	(3.35)	(−2.64)
IND			−0.018**
			(−2.28)
Control variable	Yes	Yes	Yes
City effects	fixed	fixed	fixed
Time effects	fixed	fixed	fixed
_cons	3.529***	0.786***	3.820***
	(38.26)	(10.58)	(14.23)
Mediating effect value	−0.0038 (−0.018*0.214)		
Mediating effect	17.27% (−0.0038/−0.022)		

***, **, and * indicate passing the test at the significance level of 1%, 5%, and 10%; t values are in brackets.In Models (1)–(3), there is mediating effect analysis result of the explained variable LNAQI.

4.2 Mediating effect analysis

This paper selects two mediating variables, namely, the industrial structure advancement and the urban TFP. Authors choose the stepwise regression method to test the mediating effect. The first step is the regression of digital economy development and urban air quality; the second step is the regression between digital economy and mediating variables; the last step is the regression of digital economy, mediating variables and urban air quality. According to the idea of step-by-step regression, this paper conducts the mediating effect tests of the industrial structure advancement and the urban TFP. The results are shown in Table 3 and Table 4. For the operability and convenience of the mediating effect research, this paper selects the AQI to represent urban air quality in this process.

From the regression results in Table 3, it can be seen that in Model (2), digital economy development has a significant positive impact on industrial structure advancement, indicating that digital economy development can effectively improve the degree of industrial structure advancement. In Model (3), industrial structure advancement has a significant improving effect on urban air quality. Since the model's coefficients all passed the test at the significance level of 5% or above, this indicates that a mediating effect exists; that is, digital economy development can affect the urban air quality by influencing the industrial structure advancement of a city. The mediating effect ratio of the industrial structure advancement is 17.27%. To sum up, hypothesis 2 is verified.

Table 4 shows the test results of urban TFP as a mediating variable. Model 2) in Table 4 shows that the impact of urban digital economy on urban TFP is positive, indicating that digital economy development can improve urban TFP. In Model (3), the impact of urban TFP on urban air quality is negative, indicating

TABLE 4 Test results of the mediating effect of the CITY-TFP.

Variable	Model (1)	Model (2)	Model (3)
	LNAQI	CITY-TFP	LNAQI
Digital	−0.022***	0.265**	−0.018***
	(−3.85)	(2.15)	(−3.69)
CITY-TFP			−0.012***
			(−4.22)
Control variable	Yes	Yes	Yes
City effects	Fixed	fixed	fixed
Time effects	Fixed	fixed	fixed
_cons	3.529***	1.288***	3.415***
	(38.26)	(12.21)	(18.68)
Mediating effect value	−0.0032 (−0.012*0.265)		
Mediating effect	14.55% (−0.0032/−0.022)		

***, **, and * indicate passing the test at the significance level of 1%, 5%, and 10%; t values are in brackets.In columns 1–3, there is mediating effect analysis result of the explained variable LNAQI.

that urban TFP can effectively improve urban air quality. According to the analysis of the results, urban TFP plays a mediating role in the impact of digital economy on urban air quality, of which the mediating effect accounts for 14.55%. Thus, hypothesis 3 is verified.

4.3 Robust test

Through the above benchmark regression and mediating effect tests, it can be seen that digital economy can significantly improve urban air quality. In order to ensure the research results are robust, the robust regression analysis is carried out below. Based on previous experience, the method of changing sample size is selected to carry out the robust test: one is to eliminate the provincial capital cities in the sample, and the other is to reduce the tail of the sample by 1%. The test results show that when provincial capitals in the sample are removed, or the sample tail is reduced by 1%. The values of the core explanatory variable coefficients are between -0.007 and -0.024 and they pass the test at the significance level of 5%, indicating that the result that urban digital economy can improve urban air quality is robust.

The robust test of the mediating effect adopts the idea of replacing the explained variables, using LNSO2, LNPM2.5, and LNPM10 to replace LNAQI. The test results show that both the industrial structure advancement and the urban TFP have significant mediating effects. By calculating the values, the mediating effect is about 18%.

Based on the above research results, it can be concluded that digital economy has a significant positive effect on air governance, which is the same as the research results of Li Y. et al. (2021), Zhou et al. (2021) and Li Z. et al. (2021). The difference is that this paper analyzes and confirms the indirect impact and specific transmission path of the digital economy on the improvement of air quality by introducing two mediating variables: the urban industrial structure advancement and the urban total factor productivity. From the economic point of view, the digital economy development has certain environmental performance while generating considerable economic benefits. It can also bring about the upgrading of the industrial structure and the improvement of the urban TFP, thereby improving the urban air quality.

5 Heterogeneity analysis

5.1 Heterogeneity analysis under different levels of digital economy development

Considering that the impact of digital economy development on urban air quality may be heterogeneous, this paper makes an objective analysis of the possible heterogeneity, specifically involving three categories: first, the impact of digital economy development on urban air quality may be different under different levels of digital economy development; second, the impact of digital economy development on urban air quality may be different in different scales of cities; third, there is a threshold variable that makes the impact of digital economy on urban air quality different. In this paper, the development level of urban digital economy is ranked from high to low and then divided into a high-level city cluster, a medium-level city cluster, and a low level city cluster in equal proportions[1]. At the same time, according to the "Notice on Adjusting the Criteria for Urban Size Classification" issued by the State Council, cities are divided into five categories and seven grades. However, in order to ensure the reliability of the research results, the data of four municipalities directly under the central government are excluded from the sample, and cities are divided into four types according to the permanent population, namely, mega cities, large cities, medium-sized cities, and small cities. According to different classifications, the impact of urban digital economy on urban air quality under different grouping types is investigated. The specific estimation results are shown in Table 5 and Table 6.

TABLE 5 Impact heterogeneity test under different levels of digital economy development.

Variable	Model (1)	Model (2)	Model (3)
	High-level	Medium-level	Low-level
LNAQI	−0.038***	−0.020***	−0.010
	(−4.16)	(−3.96)	(−0.25)
LNSO2	−0.012**	−0.009**	−0.002
	(−2.08)	(−2.15)	(−1.05)
LNPM2.5	−0.020**	−0.012***	−0.008**
	(−2.10)	(−4.98)	(−2.28)
LNPM10	−0.035***	−0.020**	−0.016**
	(−3.26)	(−2.25)	(−2.14)
Control variable	Yes	Yes	Yes
City effects	Fixed	fixed	Fixed
Time effects	fixed	fixed	Fixed
N	456	456	456

***, **, and * indicate passing the test at the significance level of 1%, 5%, and 10%; t values are in brackets.Model (1) indicates the regression results of the city sample group with a high level of digital economy.Model (2) indicates the regression results of the city sample group with a medium level of digital economy.Model (3) indicates the regression results of the city sample group with a low level of digital economy.

1 The development level of urban digital economy is ranked from high to low, and the cities in the top 1/3 are defined as high-level digital economy city cluster; the cities in the top 1/3–2/3 are defined as medium level digital economy city cluster; the cities in the bottom 1/3 are defined as low-level digital economy city cluster.

TABLE 6 Impact heterogeneity test under different city sizes.

Variable	Model (1)	Model (2)	Model (3)	Model (4)
	Mega city	Large city	Medium city	Small city
LNAQI	−0.030***	−0.026**	−0.015**	−0.011
	(−5.62)	(−2.32)	(−2.35)	(−0.95)
LNSO2	−0.015*	−0.010***	−0.007**	−0.002
	(−2.02)	(−6.75)	(−2.21)	(−0.34)
LNPM2.5	−0.015	−0.018**	−0.009*	−0.008*
	(−1.60)	(−2.52)	(−1.98)	(−2.08)
LNPM10	−0.032	−0.028**	−0.020***	−0.013
	(0.82)	(−2.40)	(−6.35)	(−0.68)
Control variable	Yes	Yes	Yes	Yes
City effects	fixed	fixed	fixed	Fixed
Time effects	fixed	fixed	fixed	fixed
N	66	702	426	174

***, **, and * indicate passing the test at the significance level of 1%, 5%, and 10%; t values are in brackets.Model (1) shows the regression results of mega city sample cities.Model (2) shows the regression results of large city sample cities.Model (3) shows the regression results of medium city sample cities.Model (4) shows the regression results of small city sample cities.

Table 5 shows the impact of digital economy development of different city clusters on urban air quality under different levels of digital economy development. The left side of the Table is the evaluation variables of urban air quality, namely the comprehensive index, the emission index, and the concentration index. The coefficients show the impact of digital economy on urban air quality. It can be seen from Table 5 that in the high-level digital economy city cluster, all coefficients passed the test, and their impact on urban air quality is also significantly higher than that of the medium and low-level digital economy city clusters. In the low-level digital economy city cluster, the impacts of digital economy on air quality indexes in different cities are different, and the impacts on the comprehensive and emission indexes are not significant. Based on the above analysis, this paper concludes that in the high-level digital economy city cluster, the role of digital economy development in improving urban air quality is more prominent. Digital economy development can also improve urban air quality in the medium and low-level digital economy city clusters, but the improvement effect is poor. Hypothesis 4, that the impact of digital economy on urban air quality varies with the level of digital economy, is verified.

5.2 Heterogeneity analysis of impacts under different city sizes

Table 6 presents the heterogeneity test of the impact of digital economy on urban air quality under different city scales. According to the analysis results, the sample regression results of large and medium cities are more significant, and the sample regression results of mega cities and small cities fail to pass the significance test for some variables, which may be due to the number of small sample, of which the sample size of mega cities is 66, and the sample size of small cities is 174. In the mega city samples, the digital economy development has the greatest impact on the AQI. In the samples of large and medium cities, the digital economy development has the greatest impact on PM10. In the sample of small cities, the digital economy development has the greatest impact on PM2.5. To sum up, under different city scales, digital economy development can improve urban air quality, and the improvement effect of large and medium-sized cities is more significant; in mega cities and small cities, although the digital economy development can also improve urban air quality, the effect is not obvious. Hypothesis 4, that the impact of digital economy on urban air quality varies with the city size, is verified.

5.3 Impact heterogeneity analysis based on threshold regression

The above analysis shows that the relationship between digital economy and urban air quality is different among cities divided according to different population. This paper speculates that there may be a threshold variable that results in different degrees of impact. Next, this paper draws on the idea of Hansen (1999) to conduct a panel threshold regression analysis on the sample data. The existence of the threshold effect should be tested before conducting panel threshold regression. Considering that the impact of digital economy on urban air quality may be related to the threshold variable urbanization rate (Urban-rate), a panel threshold regression model with urbanization rate as the threshold variable is constructed.

TABLE 7 Threshold effect existence test with Urban-rate as the threshold variable.

Threshold number	Threshold variable	F Statistics	10%	5%	1%	*p*-value
Single threshold	Urban-rate	38.500	18.544	21.423	27.833	0.000
Double threshold		17.990	15.163	20.004	32.316	0.067
Triple threshold		3.470	28.345	36.061	51.874	0.840

Threshold effect existence test.

TABLE 8 Threshold effect regression and robust test of the impact of digital economy on urban air quality.

Variable	Model (1)	Model (2)	Model (3)	Model (4)
	LNAQI	LNSO2	LNPM2.5	LNPM10
Urban-rate (low)	0.010	0.002**	−0.003*	−0.005
	(1.15)	(2.26)	(−1.96)	(−1.46)
Urban-rate (high)	−0.032***	−0.010***	−0.012***	−0.020***
	(−4.55)	(−4.23)	(−6.18)	(−8.42)
Control variable	Yes	Yes	Yes	Yes
City effects	fixed	Fixed	Fixed	fixed
Time effects	fixed	Fixed	fixed	fixed
N	1368	1368	1368	1368
Adj-R2	0.416	0.542	0.498	0.477

Model (1) is threshold regression.Models (2)–(4) is threshold regression result robust test.

It can be known from Table 7 that the *p*-value of the single threshold test is 0.000, and the F statistic is 38.5, which means that there is a single threshold value in the model. However, the test results of double and triple thresholds show the *p* values are 0.067 and 0.840, which could not reject the null hypothesis, so the model only has a single threshold effect at the significance level of 1%. The model is set as follows:

$$LNAQI_{it} = \alpha_1 Digital - economy_{it} \cdot I\left(Urban - rate \le \gamma_1\right) + \alpha_2 Digital - economy_{it} \cdot I\left(Urban - rate > \gamma_1\right) + \theta Z_{it} + \mu_i + \varepsilon_{it}$$

The threshold value is estimated by minimizing the residual sum of squares. It is estimated that the threshold value is 0.470; the lower limit of the 95% confidence interval is 0.4594, and the upper limit is 0.4806. Then the panel threshold model is estimated. In order to obtain a robust estimator, this paper uses the method of replacing the explained variable LNAQI with LNSO2, LNPM2.5, and LNPM10 respectively to test the robustness of the model. The specific regression results are shown in Table 8, in which Model 1) is the panel threshold regression results, and Models 2)–4) are the robustness test results.

Table 8 shows the threshold effect regression and robustness test results of the impact of digital economy on urban air quality. It can be seen from the model estimation results that the urbanization rate has a significant threshold effect. When the urbanization rate exceeds 0.470, digital economy has the most significant effect on the improvement of urban air quality. Model 1) and Model 2) show that digital economy development has a pollution effect on urban air quality in cities with low urbanization rate. The reason may be that in the process of urbanization, the development of industrial structure is unbalanced, which leads to increasing pollution. Although the development of digital economy depends on scientific and technological progress and it has the engine function of green development, it is difficult to effectively improve air quality. On the contrary, in cities with high urbanization rate, the development of various industries seems to be attached to digital economy, so the digital economy has a significant improvement effect on urban air quality. In the robust regression analysis, it can be seen that even if some explanatory variables are significant, on the whole, the impact of the digital economy on air quality under the low urbanization rate is poor, even exacerbating air pollution to a certain extent. In contrast, in cities with high urbanization rate, the impact of digital economy on air quality has an improvement effect, which has passed the test at the significance level of 1%. Hypothesis 4, that the impact of digital economy on urban air quality is different under different urbanization rates, is verified.

6 Research conclusion

Based on the data of digital economy and urban air quality of 228 prefecture-level cities in China, this paper conducts a series of analysis and obtains the following research conclusions.

First, digital economy development can effectively improve urban air quality no matter from the perspective of the comprehensive air quality index, the emission index, or the concentration index. Therefore, the integration and development of digital technology and the traditional economy should be promoted, and attention should be paid to the role of digital economy in environmental governance.

Second, through the mediating effect tests, it is found that digital economy development can affect urban air quality by influencing the urban industrial structure advancement and the total factor productivity. In the path analysis of the impact of digital economy development on urban air quality, the mediating effect of the urban industrial structure advancement accounts for 17.27%, and the mediating effect of urban TFP accounts for 14.55%. Therefore, the proportion of the tertiary industry should be increased, and the investment in innovation should be enhanced to improve urban TFP.

Third, through exploring the heterogeneity in the research samples, it is found that in cities of different digital economy levels, digital economy development affects urban air quality to different degrees; under different city scales, the impact of digital economy development on urban air quality also varies. Among them, in the sample city cluster with a high digital economy level, digital economy has a stronger effect on air quality improvement; in the samples of large and medium-sized cities, the development of the digital economy has a significant impact on air quality, while in mega cities, digital economy development can only affect AQI and SO2 emissions. In small cities, it can only affect PM2.5.

Fourth, by constructing a panel threshold regression model with the urbanization rate as the threshold variable, we found that digital economy has a more obvious effect on air quality improvement in cities with a high urbanization rate. Therefore, the government should accelerate urbanization while being alert to the risks of the digital divide.

This paper analyzes the relationship between the development of digital economy and urban air quality, elaborating its internal mechanism through the mediating and threshold effect analysis. On the one hand, our findings contribute to the enrichment of environmental economic theories. As an emerging economic development mode, there is a significant relationship between the development of digital economy and the improvement of air quality. On the other hand, the conclusion of the research provides some implications for policy formulation. 1) At the present stage, the development of digital economy in China can indeed improve urban air quality, and the government should promote the high-quality integration of digital economy and various industries. 2) The digital economy can further promote the improvement of urban air quality through industrial structure upgrading and total factor productivity. Policies should guide the adjustment of industrial structure and enhance urban innovation capabilities. 3) Since the environmental effects of the digital economy vary with the development scale of the digital economy, the city scale and the urbanization rate of different cities, local governments need to consider their development levels while guiding the digital economy development to avoid the ecological environment gap (Wang and Jia, 2021).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BS and MW contributed to all aspects of this work; HS and RG mainly completed data collection and manuscript writing. All authors reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

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

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