frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 17 March 2023
DOI 10.3389/fenvs.2023.1120953

OPEN ACCESS

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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 10 December 2022
ACCEPTED 17 February 2023
PUBLISHED 17 March 2023

CITATION
Zhang Z, Ding Z, Geng Y, Pan L and Wang C (2023), The impact of digital economy on environmental quality: Evidence from China.
Front. Environ. Sci. 11:1120953.
doi: 10.3389/fenvs.2023.1120953

The impact of digital economy on environmental quality: Evidence from China

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With the rapid development of new generation of information technology and the continuous deterioration of ecological environment, the environmental effect of digital economy has begun to receive attention. Based on panel data from 30 provinces in China during the period of 2014–2020, this study investigates the impact and mechanisms of digital economy on environmental quality using the fixed effect model and moderating effect model. The results show that the digital economy can significantly inhibit environmental pollution. The inhibitory effect of digital economy shows obvious regional heterogeneity, which is the strongest in the west, followed by the east, and the weakest in the center. The economic development level and income distribution inequality play positive and negative roles in regulating the negative linkage between digital economy and environmental pollution, respectively. The government should implement a differentiated strategy to promote the comprehensive development of digital economy and maximize its environmental effects, accelerate the integrated development of urban and rural economies through inclusive growth, and optimize the moderating effect of economic development level and income distribution inequality.

KEYWORDS

digital economy, environmental quality, economic development level, income distribution inequality, moderating effect

1 Introduction

Since China's reform and opening up, China's economy has entered a long-term process of rapid growth. With good opportunities and abundant production factors, China has made full use of its advantages in resource endowment and demographic dividend. After decades of rapid development, China's GDP has become the second largest in the world. Since the 1980s, the rise of information and communication technology and its worldwide popularity have given birth to a new industry -- the "digital economy". New technologies, new forms of business and new products have become new growth points for the global economy as science and technology are upgraded and industrial changes continue. Digital economy plays an important role in improving economic efficiency (Yang and Jiang, 2021). For example, Industrial digitalization reduces the production scale of heavy-polluting enterprises and improves product innovation and green total factor productivity (Wen et al., 2021). And promoting regional innovation ability (Xiong and Cai, 2020), optimizing industrial structure upgrading (Li et al., 2020), and digital economy has become an important force of enabling economy in the new era. According to the White Paper on the Development and Employment of China's Digital Economy, by 2020, the scale of China's digital economy will reach 39.2 trillion yuan, accounting for 38.6% of the gross National Product, which is

sufficient to show that the development of digital economy plays an important role in economic development.

However, with the extensive development of urbanization and industrialization in China, serious environmental pollution has followed. Most of China's economic growth relies on sacrificing environmental quality, and there is a serious lack of environmental protection. For example, China's emissions of sulfur dioxide reached 19,744,300 tons in 2014, causing serious harm to China's environmental quality. According to the Bulletin on the State of China's Ecological Environment (2018), only 35.8 percent of China's 338 cities above the prefecture level had good air quality in 2018. Air quality exceeded the standard in 217 cities, accounting for 64.2 percent. The continuous deterioration of ecological environment and energy shortage are not conducive to the sustainable and healthy development of China's economy. However, according to the existing means and methods of environmental pollution control in China, the main way is to introduce relevant laws and regulations in order to achieve control results. Although the government has reduced carbon and sulfur dioxide emissions to some extent by implementing these measures to protect the environment, overall, China's environmental quality needs to be further improved. Digital economy continues to integrate and develop with other fields, greatly improving people's life quality (Fan and Duan, 2021). Then, the development of digital economy will also change the relationship between human and environmental quality through direct or indirect effects on the ecological environment. Then digital economy as one of the important factors promoting high economic growth, whether it will have an impact on environmental quality? In other words, can the development of digital economy significantly improve China's environmental quality? What is its influence mechanism and conduction path? These problems need to be studied and discussed in depth, so as to provide theoretical support for China's more efficient control of urban environmental pollution and improvement of residents' living environment, which has important policy implications for promoting the development of digital economy and environmental governance.

To sum up, previous studies mostly analyzed the impact of digital technology applications such as the Internet or big data or a certain performance of the digital economy on resource utilization efficiency and pollution emission from a starting point, and were mostly theoretical studies. Few studies analyzed the impact of the development of the digital economy on environmental pollution from both theoretical and empirical perspectives. In view of this, based on the panel data of 30 provinces in China from 2014 to 2020, this paper adopts the fixed-effect model and the moderated effect model to study the impact of digital economy on environmental quality and its mechanism. The novelty of this paper lies in the following three aspects. Firstly, the fixed effect model and the regulated effect model are used to prove that the digital economy can significantly inhibit pollution emission. It also has a positive impact on the development of environmental quality. This provides new evidence of synergies between the digital economy and green development. Secondly, the data show that the role of digital economy in promoting environmental quality has regional heterogeneity, with the strongest performance in western China, followed by eastern China and weakest in central China. Thirdly, the empirical analysis shows that the level of economic development and inequality of income distribution have positive and negative moderating effects on the environmental impact of digital economy respectively.

The rest of this paper is organized as follows: Section 2 provides a detailed literature review. Section 3 presents theoretical analysis and research hypothesis. Section 4 describes the model and the data. Section 5 discusses the empirical results. Section 6 reports conclusions and recommendations.

2 Literature review

2.1 Digital economy

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 effective use of information and communication technology as an important driving force for improving efficiency and optimizing economic structure (OECD, 2014). Therefore, the research on the impact of Internet, big data, artificial intelligence and other digital economy contents on environmental pollution can provide references for this paper. For example, Moyer and Hughes (2012) found that the application of ICT can improve productivity, reduce energy intensity, and promote carbon emission reduction. Xu et al. (2019) believe that the development of big data technology can improve the ability of resource integration, scientific decision-making and environmental supervision, and provide an important means and guarantee for the green production of enterprises, the green life of residents and the beautiful ecological environment. Cao et al. (2022) examines the spatial effect of financial development and technological innovation on green growth in China using the Spatial Durbin Model (SDM) based on the 30 provinces' panel data from 2011 to 2018.

Most of the literatures related to digital economy focus on the calculation and evolution of digital economy index (Xu and Zhang, 2020; Han et al., 2021; Wang et al., 2021; Wei et al., 2022) and the impact of digital economy on total factor productivity (Yang et al., 2021a; Du and Zhang, 2021; Lu et al., 2023), High-quality Economic Development (Zhao et al., 2020; Li et al., 2021c), Innovation Performance (Hou and Song, 2021; Zhao, 2021), Green economy (Zhang et al., 2022b). At the same time, the influence of digital economy development on all aspects of society is studied from different perspectives after the measurement of digital economy index system. For example, the relationship between digital economy and high-quality urban development, and proposes that digital economy can influence high-quality urban development by stimulating mass entrepreneurship. Wen et al. (2020) calculates the digital economy indicator system through provincial panel data and finds that the digital economy can promote innovation. Yang and Jiang (2021) proposed that the development of digital economy would affect the total factor productivity, and constructed an evaluation system for the development of China's digital economy from the perspective of digital industrialization and industrial digitalization. Combined with empirical analysis, she found that digital economy would have an impact on the total factor productivity through the upgrading of human capital and

industrial structure. It is believed that the development of digital economy will help improve the total factor productivity of surrounding areas. And the development of digital economy can not only optimize the employment structure, improve workers' labor remuneration and labor protection, but also greatly improve China's overall employment environment, create a higher quality employment environment, and realize people's high-quality employment. Cong and Yu (2020) combined relevant data at the provincial level and found that the development of digital economy is conducive to improving the flow efficiency of Chinese labor force and the efficiency of resource allocation, and passed the significance test. Moreover, the accelerated development of digital economy promotes the marketization process of local labor force, which is more conducive to people looking for jobs in the local area and improving people's happiness.

2.2 Environmental quality

Environmental issues are closely related to people's lives, and scholars have been constantly studying environmental pollution related issues, and has been the focus of scholars' research. There are a lot of research results related to environmental pollution, and most of the relevant research results are exploring which factors will aggravate environmental pollution, and which factors will inhibit environmental pollution. For different influencing factors, From different perspectives, scholars use different estimated samples and research methods to explore, which mainly fall into the following categories.

(1) Technological innovation level

Scholars believe that technological innovation does have a certain impact on environmental quality, but scholars have not formed a unified view on whether technological innovation can aggravate environmental pollution or restrain environmental pollution. Some scholars believe that technological innovation can improve environmental quality and reduce the emission of environmental pollutants. Yang et al. (2022b) research on energy internet and energy misallocation is of critical relevance to achieve low-carbon sustainable development. For example, Grossman and Krueger (1991) argued that the stronger the technological innovation ability, the better the environmental quality, that is, technological innovation can improve the environmental quality by improving the efficiency of governance. Aghion and Howitt (1992) established a model based on which they believed that technological innovation would not only reduce carbon emissions, but also further indirectly reduce carbon emissions by driving economic development. However, some scholars believe that technological innovation will not necessarily reduce environmental pollution, but aggravate it in certain circumstances. For example, concluded through research that technological innovation would not only not reduce environmental pollution, but also increase it if the early technical investment resources were concentrated in the polluting sector. Bian and Bai (2017) took provincial panel data from 2000 to 2013 as sample data and found that technological innovation did not have a linear relationship with environmental pollution, but showed a trend of first increasing and then decreasing environmental pollution caused by technological innovation.

(2) The level of opening-up

Dai et al. (2015) used 2SLS method to study and conclude that trade opening can reduce the emission of some industrial pollutants, and proposed that if foreign enterprises continue to be introduced and the level of opening to the outside world is improved, the emission of environmental pollutants can be effectively reduced. Liu (2018) took the high-pollutant industry above the designated scale as the research object and pointed out that the higher the degree of external prescription, the smaller the negative environmental externality, that is, opening to the outside world can improve the environmental quality.

(3) Industrial structure

The study of industrial structure on environmental pollution was carried out earlier in foreign countries. Stern (2002) believed that the change of industrial structure would affect the emission of $S0_2$, that is, the change of industrial structure would have a certain impact on environmental quality. Maria Llop (2007) concluded through research that the optimization of industrial structure is conducive to improving environmental quality and residents' living environment. Han and Yu (2015) made an analysis based on VAR model and also obtained relevant results, and believed that the secondary industry has a great impact on the environment. Conducted an empirical study based on provincial panel data and found that the current industrial agglomeration is conducive to reducing the emission of environmental pollutants. However, from the overall perspective the relationship between industrial agglomeration and environmental pollution is firstly aggravated and then suppressed, that is, there is an inverted "U" -shaped relationship.

(4) Other influencing factors

In addition to studying the impact of the above factors on environmental pollution, scholars also explored the impact of economic growth, environmental regulation, population aging, fiscal decentralization and other factors on environmental pollution. Grossman and Krueger (1991) pointed out that in the early stage of economic development, there is an inverse relationship between economic growth and environmental quality, but when the economy develops continuously and exceeds a certain critical value, economic development will in turn restrain environmental pollution, that is, there is an inverted "U" shaped relationship. Furthermore, the Environmental Kuznets Curve (EKC) is proposed. Shen (2012) found that environmental regulations have different effects in different polluting industries. For example, in heavily polluting industries, environmental regulations can not only improve environmental quality, but also increase environmental pollution. Yang et al. (2022a) empirically analyzes the impact of land finance on haze pollution using a dynamic spatial Durbin model based on panel data of 269 prefecture-level cities in China from 2004 to 2017. However, in clean production industries,

environmental regulations can promote the improvement of environmental quality.

2.3 Digital economy and environmental quality

As China's economy enters the era of Industry 4.0, digital economy has become an important driving force for high-quality economic development and plays an important role in transforming the economic development pattern and promoting ecological civilization. However, there are few researches on the relationship between digital economy and environmental quality. The existing researches on the relationship between digital economy and environmental pollution are mainly divided into four categories.

The first argument is that the digital economy encourages the reduction of emissions (Zhao et al., 2022). The current state of research indicates that digital economy contributes to the improvement of environmental quality. Digital ecology can promote the formation of a green, low-carbon and recyclable environment and effectively avoid environmental damage in the process of development (Shen and Ye, 2021). The improvement of Internet coverage can significantly reduce the eco-environmental pollution index, reduce the level of ecological destruction, reduce the concentration of regional air pollution (Ozcan and Apergis, 2018), improve the efficiency of energy use, optimize the coupling degree of economic society and ecological environment, and then improve and reshape the eco-environmental governance pattern (Li et al., 2021a). The development of communication technology can significantly improve the technical level of enterprises, reduce the work demands of manufacturers on physical sites, and reduce the energy intensity of enterprises (Zhang and Wei, 2019). Using BRICS panel data, Ulucak and Khan (2020) found that the use of Internet information technology can significantly reduce carbon emissions. Relevant economic departments can help decarbonization activities by promoting technological progress. Digital economy can integrate information resources between the production and consumption ends, supply and demand ends, improve the production efficiency of enterprises, and reduce resource waste (Xu et al., 2019). The advantages of Internet platform are beneficial for enterprises to seek product innovation, develop cleaner production methods, accelerate the transformation of environmental scientific and technological achievements, and promote the economic structure adjustment of environmental protection industry (Hui and Chen, 2020). The digital economy can expand the scale of the tertiary industry economy, reduce the proportion of coal consumption, and promote green technology innovation. Consequently, the digital economy can indirectly reduce carbon dioxide emissions. Using the dual fixed effect model and spatial econometric model, Chen (2022) found that the digital economy can promote the development of clean energy through technological innovation and city bank loans. This influence effect is effective in realizing sustainable development.

The second argument is China's digital economy has a low technical level for now, imperfect hardware facilities and software environment, and the industry development space still needs to be improved, which makes it difficult to achieve energy efficiency improvement in the production field (Li, 2019). Driven by the maximization of profits, the optimization and improvement of the appearance and performance of communication technology often consumes a lot of resources, increases energy consumption and demand, and has an indirect energy predatory effect (Wang and Li, 2016). Green policy measures may not only accelerate the development of fossil fuels, but also lead to a large amount of greenhouse gas emissions. Based on the panel data of 30 provinces in China from 2012 to 2019, Zhang et al. (2022a) found that the development of digital economy is not conducive to improving energy efficiency, thereby indirectly raising carbon emissions. Industrial digitalization leads to more energy consumption and poorer environmental performance than ever before. The digital economy can be conducive to the greening of China's economy in the short term, but in the long term, it will increase energy consumption. The scale expansion of digital capital has not only failed to achieve the effective substitution of factor innovation and energy demand, but also solidified the existing energy consumption mode and intensified the energy rebound effect (Fan et al., 2021). The impact of the Internet economy on environmental quality can be seen from the dynamic environmental monitoring, the informatization of government environmental supervision The public participation in environmental protection is deepened and the environmental protection industry is intelligent (Xie et al., 2017). It was also stated by Li et al. (2020) that while the digital economy promotes technological progress, it will also force enterprises to adopt efficient production equipment during the initial stages of development. Enterprises try to increase their production by increasing resource extraction and energy consumption. However, this misconduct will increase noxious emissions.

The third argument is Through further research and empirical analysis, many scholars have begun to believe that there is a non-linear feature between digital economy and environmental pollution. Li et al. (2021a) performed fixed effect regression on global panel data for 190 countries and found that there is an inverted U-shaped non-linear relationship between carbon dioxide emissions and digital economy. Li et al. (2021b) believed that the digital economy has a threshold effect on environmental quality through urbanization and population density. When the urbanization rate and population density exceed a certain threshold, the digital economy has a significant inhibitory effect on PM2.5. Based on space and threshold models, Zhou et al. (2021) empirically tested that the digital economy can reduce haze pollution through the optimization and upgrading of industrial structures and such an effect shows a non-linear feature.

The fourth argument that there is no definitive link between CO_2 emissions and the digital economy (Park et al., 2018). The rationale could be that numerous constraints limit the connection between carbon emissions and the digital economy and that these factors cooperate to produce a negligible relationship between the two.

In summary, there is no consensus on the impact of digital economy on environmental pollution, and it is necessary to further explore the relationship between the two to clarify the reasons for this mixed result. When it comes to the digital economy, the majority of researchers still focus on its meaning and measuring techniques, small number researchers also look at its influencing aspects. Some academics have researched the connotation, calculation, and influencing elements of the environmental quality. Current research focuses on how the digital economy

affects regional industrial upgrading or urban innovation, both of which are linked to the city's green economy. Meanwhile, due to historical, natural, geographical and other factors, there are significant differences between various regions in China. It is meaningful to explore whether the impact of digital economy on environmental quality shows regional heterogeneity.

3 Theoretical analysis and research hypotheses

3.1 Influence effect analysis

The digital economy can promote urban pollution reduction through the urban green innovation effect, industrial structure optimization effect, and financial development effect. On the one hand, relevant departments can leverage big data technology and digital integrated platforms to collect data on energy conservation and emission reduction more efficiently and conveniently. These data will help the departments achieve real-time dynamic monitoring of ecological environmental quality indicators and improve environmental supervision efficiency. On the other hand, relevant enterprises can integrate all kinds of production information resources and analyze and plan product data based on digital technology, thus effectively reducing resource waste and improving production efficiency. In addition, with the continuous upgrading of network infrastructure, information technologies such as the Internet, cloud computing, blockchain and the Internet of Things will be constantly updated and iterated. This development has promoted the transformation of the industrial economy to an intelligent economy, spawned a novel economic form based on network platforms, and B2C business models such as shared bicycles and shared electric vehicles have also emerged as the time required. Such technological innovation can not only optimize the allocation of social resources and improve production efficiency, but also alleviate traffic congestion, reduce road wear, and achieve green and low-carbon travel. Accordingly, this paper proposes the following hypotheses:

Hypothesis 1: The digital economy has a positive effect on environmental quality.

3.2 Influence mechanism analysis

The traditional view holds that economic development is inseparable from industrial production, However, industrial production cannot avoid energy consumption and environmental pollution. Grossman and Krueger (1995) first explored the relationship between economic growth and ecological environment and proposed the environmental Kuznets curve. They argue that there is an inverted U-shaped relationship between economic growth and environmental pollution. Some scholars have verified the existence of this curve through a series of theoretical and empirical studies. Income distribution is an inevitable factor in the process of economic development. Its impact on environmental quality is a key point in the extension of the environmental Kuznets curve. Income distribution inequality may affect the public's time preference for environmental use, leading to deviation in environmental policies, and thus causing degradation of environmental quality. As the main economic form after agricultural and industrial economies, the digital economy has brought new ideas for maintaining sustainable and healthy economic development and narrowing the income inequality between urban and rural residents. On the one hand, by integrating with traditional real economies, the digital economy can promote high-quality economic development by facilitating industrial structural transformation and upgrading as well as technological innovation. On the other hand, the digital economy, such as internet information technology, blockchain technology, and digital Pratt and Whitney Finance, can be deeply integrated into life and production through its own shared and universal utility characteristics. This role can alleviate the problem of unbalanced development between urban and rural areas to a certain extent. Accordingly, this paper proposes the following hypotheses:

Hypothesis 2: The economic development level and income distribution inequality positively and negatively regulate the promoting effect of digital economy on environmental quality, respectively.

4 Methodology and data

4.1 Proposed model

To verify whether the digital economy has a promoting effect on environmental quality, this paper constructs the following model:

$$EQ_{it} = \alpha_0 + \alpha_1 DE_{it} + \alpha_2 Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

In Eq. 1, EQit EP_{it} represents the environmental quality index of province i in year t; DEit represents the digital economy development level of province i in year t; Zit represents the relevant control variables affecting environmental quality, including urbanization level, population density, industrial structure, and open level; μ_i represents the province fixed effect; λ_t represents the year fixed effect; ε_{it} represents the random error term.

To further verify whether economic development level and income distribution inequality play a moderating role in the digital economy promoting environmental quality improvement, this paper adds economic development level and its interaction term with digital economy, income distribution inequality and its interaction term in Eq. 1. The specific model is as follows:

$$EQ_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 EDL_{it} + \beta_3 IDI_{it} + \beta_4 (DE_{it} \times EDL_{it}) + \beta_5 (DE_{it} \times IDI_{it}) + \beta_6 Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1a)$$

4.2 Variable selection

4.2.1 Dependent variable

The dependent variable in this paper is environmental quality (EQ). Based on the reference of Zhou and Li (2020), and considering the validity and availability of data, this paper selects three indicators

TABLE 1 Digital economy comprehensive development level indicator system.

First-level indicator	Secondary indicators	Unit
Information development	Optical cable line length	Kilometer
	Software business revenue	Billion
	Number of mobile phone base stations	Ten thousand
Internet development	Number of Internet Broadband Access Ports	Ten thousand
	Internet penetration	%
	Mobile phone penetration	%
Digital transaction development	Ecommerce sales	Billion
	Number of companies with e-commerce transactions	—

of chemical oxygen demand, sulfur dioxide emissions, and nitrogen oxide emissions in wastewater to construct a comprehensive environmental quality index. The entropy method can determine the corresponding weight according to the different degree of each index value. It is a relatively objective method of weighting, which reduces deviations due to human factors and improves the rationality and accuracy of the index system. Therefore, this paper adopts the entropy method to measure.

4.2.2 Independent variable

The independent variable in this paper is digital economy (DE). Currently, there is little relevant literature related to the measurement of digital economy. This paper draws on the research of Chen et al. (2020) to construct an indicator system for the comprehensive development level of digital economy from the three dimensions of the development of informatization, the development of the Internet, and the development of digital transactions (Table 1). The development of informatization specifically includes the length of optical cable lines, software business income, and the number of mobile phone base stations; the development of the Internet specifically includes: the number of Internet broadband access ports, the Internet penetration rate, and the penetration rate of mobile phones; the development of digital transactions specifically includes: ecommerce sales, the number of companies with ecommerce transaction activities. Similar to the environmental quality index, this paper uses the entropy method to measure the comprehensive development level of digital economy.

4.2.3 Moderating variable

Moderating variables include economic development level (EDL) and income distribution inequality (IDI). The economic development level is closely related to environmental pollution, and digital economy can contribute to optimizing the regional economic structure according to the environmental Kuznets curve theory. Referring to the existing literature, economic development level is measured by the provincial GDP *per capita*. Whether the income distribution is fair or not will affect people's attention to environmental issues, and public participation will help improve environmental quality. Compared with the income ratio of urban and rural residents, the Theil index can accurately measure China's income distribution because it considers the population factor. Therefore, this paper uses the Theil index to measure the income distribution inequality between urban and rural residents.

4.2.4 Control variables

Referring to the research of Zhou and Li (2020), this paper selects the following control variables: Urbanization rate (UR): the higher the level of urbanization, the more serious the degree of environmental pollution. This paper uses the population urbanization rate of each province to express the urbanization level. Population Density (PD): When the regional population continues to increase, it is necessary to increase production to meet people's material needs. However, if the production growth rate exceeds the natural purification rate of the environment, environmental pollution will be aggravated. This paper uses population per square kilometer to measure population density. Industrial Structure (IS): In the process of development, industry consumes a lot of energy and emits pollutants, which in turn causes a series of environmental problems. In this paper, the proportion of secondary industry in GDP is employed to represent the industrial structure. Openness level (OL): According to existing literature, trade openness is likely to increase the emission of pollutants and harm the environment. Therefore, this paper introduces openness level as a control variable and uses the proportion of total import and export trade to GDP to indicate it. Green technological innovation refers to the variable selection of Zhou and Wang (2022), selects the number of green patents authorizations of each province as the technological innovation (GTI).

4.3 Data sources

Due to the serious lack of data in Tibet, Hong Kong, Macau, Taiwan, and other regions, this paper selects 30 provinces, municipalities, and autonomous regions in China as research objects. Around 2014, a series of documents issued by the Chinese government began to mention the application of emerging technologies such as the Internet of Things, the Internet, cloud computing, and big data to the construction of infrastructure projects and encouraged the promotion of the

TABLE 2 Descriptive statistics for key variables.

Variable	Illustrate	Mean	S.D.	Min	Max
EQ	Environmental quality	0.752	0.195	0.000	0.995
DE	Digital economy	0.765	0.163	0.102	0.962
EDL	Economic development level	6.003	2.756	2.617	16.422
IDI	Income distribution inequality	0.087	0.037	0.020	0.211
UR	Urbanization rate	58.374	12.113	25.750	89.600
PD	Population density	493.476	758.850	8.103	4186.207
IS	Industrial structure	40.725	7.987	15.800	54.140
OL	Openness level	23.932	25.323	0.763	121.557
GTI	Green technology innovation	10.885	0.398	10.172	11.851

TABLE 3 Benchmark regression results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
DE	−1.064 (0.154)	−0.417*** (0.131)	−0.305*** (0.123)	−0.385*** (0.165)	−0.398*** (0.115)	−0.452*** (0.135)
UR	—	3.360*** (0.378)	3.577*** (0.377)	2.734*** (0.480)	2.694*** (0.437)	2.694*** (0.477)
PD	—	—	0.003*** (0.001)	0.003*** (0.001)	0.003*** (0.001)	0.003*** (0.001)
IS	—	—	—	−0.009*** (0.003)	−0.008*** (0.003)	−0.008*** (0.003)
OL	—	—	—	—	−0.000 (0.000)	−0.000 (0.000)
GTI	—	—	—	—	—	0.00107
						(0.0272)
_cons	1.546*** (0.080)	−0.975*** (0.288)	−2.596*** (0.644)	−1.914*** (0.677)	−1.739** (0.678)	−1.692** (0.689)
Province fixed	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes
N	210	210	210	210	210	210
R^2	0.414	0.617	0.638	0.654	0.663	0.663

Note: Standard error is in parentheses. *, **, and *** represent significant at the 10%, 5%, and 1% levels, respectively.

"Internet +" action. Thus, the digital economy has entered a new round of development stage. This paper selects 2014-2020 as the research period. The data are all from China Statistical Yearbook, China Urban Statistical Yearbook, and China Environmental Statistical Yearbook. The descriptive statistics of the main variables are shown in Table 2.

5 Empirical results

5.1 Benchmark regression analysis

According to the results of the Hausman test, the fixed effect model was used for regression analysis in this paper, and the estimated results are shown in Table 3. Column (1) only considers the independent variables. The results of this column show that the estimated coefficient of digital economy is significantly negative at the 1% level, indicating that digital economy can help curb pollution emissions and improve environmental quality. Columns (2)-(5) sequentially add control variables such as urbanization rate, population density, industrial structure, and openness level. The results of these columns show that the estimated coefficient of digital economy is still significantly negative. Specifically, in column (5), the estimated coefficient of digital economy is −0.452. This coefficient has passed the 1% significance test, indicating that the digital economy can significantly reduce pollutant emissions. This finding is consistent with Yu et al. (2022) who find that digital economy has a positive effect on environmental quality. Therefore, Hypothesis 1 is validated.

From the perspective of control variables, the coefficient of urbanization level is significantly positive. This coefficient indicates that urbanization will increase environmental pollution, which is consistent with the conclusion of Chen

TABLE 4 Heterogeneous regression results.

Variable	Eastern region	Central region	Western region
DE	−0.174*** (0.053)	−0.025* (0.028)	−0.491*** (0.137)
UR	3.331*** (0.887)	4.578*** (1.135)	2.756*** (0.816)
PD	0.002*** (0.001)	0.015*** (0.006)	0.000 (0.004)
IS	−0.010** (0.005)	−0.009 (0.006)	0.003 (0.005)
OL	−0.000 (0.000)	−0.000*** (0.000)	−0.000 (0.000)
GTI	−0.0102 (0.00859)	−0.0122 (0.0244)	−0.0084 (0.00932)
_cons	−3.677*** (1.306)	−6.327*** (1.932)	−0.360 (0.760)
Province fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
N	84	63	63
R^2	0.674	0.769	0.728

Note: Standard error is in parentheses. *, **, and *** represent significant at the 10%, 5%, and 1% levels, respectively.

et al. (2020). Urbanization construction will lead to several problems, such as the occupation of cultivated lands, the accumulation of construction waste, and the development of landfills, leading to serious soil and water pollution. The coefficient of population density is significantly positive, indicating that high population density is not conducive to maintaining good environmental quality. With the continuous growth of the population, the scale of human production also expands. The expansion of production will lead to an increase in industrial activities, resulting in the rapid growth of energy consumption and the reduction of resource utilization rate. Finally, it will produce a large amount of polluting waste and aggravate environmental pollution. The industrial structure coefficient is significantly negative, indicating that optimization and upgrading of industrial structures can effectively mitigate environmental pollution. The digital economy has transformed the industrial structure from traditional labor, capital, and technology-intensive industries to digital-intensive industries. With digital and information as the main production factors, the digital economy also drives traditional industries to intelligent and digital transformation and effectively improves industrial energy utilization rate. Meanwhile, the use of digital platforms to monitor and control relevant environmental pollution emission indicators will also help reduce ecological load and alleviate environmental pollution problems. The coefficient of openness level is negative, but it fails to pass the robustness test. The results show that import and export trade is not the main factor causing environmental pollution at the current stage and also does not play a significant role in improving environmental quality.

5.2 Heterogeneous feature analysis

Considering the different levels of industrialization and economic development in different regions of China, the impact of digital economy development on environmental quality may have regional heterogeneity. Therefore, according to the classification standards of the National Bureau of Statistics, the data are divided into three parts: eastern, central, and western. Regression analysis was carried out for each region. The regression results are shown in Table 4.

According to the regression results in Table 4, the digital economy index coefficients in the three regions are all significantly negative, indicating that the digital economy has an inhibitory effect on environmental pollution in different regions. Among the three regions, the inhibitory effect on pollutants in the western region is the largest, followed by the eastern region and the smallest in the central region. Considering the late economic development and inadequate digital economic infrastructure in western China, there is still much room for improvement in the development of digital economy. Meanwhile, the western region is vast in territory, rich in ecological resources, less developed, and relatively healthy in ecological environment. Moreover, the national government attaches great importance to the ecological environment of the western region and has introduced many relevant policies to better protect the already high-quality ecological environment. Therefore, the digital economy can assist the western region in protecting the environment more effectively, improving environmental quality while maintaining the existing good environmental conditions. The industrial level in eastern China is relatively high, and environmental pollution problems appear earlier and more frequently. Although the digital economy development level is higher than that in the central and western regions, the growth space of the dividend effect of digital economy in the eastern region is limited. Hence, the promotion effect of the eastern region on environmental quality is not as pronounced in the West. For the central region, the development of digital economy and the quality of environment is in a relatively balanced state. Therefore, the positive effect of digital economy on the environment is rather weak.

TABLE 5 Moderating effect results.

Variable	(1)	(2)
DE	−0.264*** (0.217)	−0.245*** (0.272)
UR	3.589*** (0.677)	3.179*** (0.615)
PD	0.054*** (0.008)	0.036*** (0.007)
IS	−0.013** (0.010)	−0.009** (0.009)
OL	0.008 (0.002)	0.007 (0.001)
GTI	0.0039 (0.0317)	−0.0286 (0.0464)
EDL	0.026*** (0.010)	—
IDI	—	−0.009 (0.021)
DE*EDL	−0.051*** (0.032)	—
DE*IDI	—	0.013*** (0.021)
_cons	−2.951*** (0.887)	−2.596*** (0.870)
Province fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	210	210
R^2	0.678	0.673

Note: Standard error is in parentheses. *, **, and *** represent significant at the 10%, 5%, and 1% levels, respectively.

5.3 Moderating effect analysis

To further clarify the mechanism by which digital economy affects environmental quality, this paper conducts regression analysis according to Eq. (2). The results are shown in Table 5. The coefficient of interaction term between digital economy and economic development level in column (1) is significantly negative, indicating that economic development level is conducive to the inhibitory effect of digital economy on environmental pollution. China's economic development mode has shifted from focusing on speed and large scale to focusing on efficiency and quality. The economic structure has been adjusted from increasing the quantity and expanding production capacity to revitalizing the stock and achieving both excellent and incremental development. The driving force of development has shifted from mainly relying on resources and low-cost labor and other factors to innovation-driven. Green and steady development has become the most important goal of China's economic development. These measures have guided the green transformation of relevant key industries and infrastructure to a certain extent. In addition, they have increased the constraints of enterprises on environmental pollution, which is conducive to reducing pollution and promoting green production.

The coefficient of the interaction term between digital economy and income distribution inequality in column (2) is significantly positive, indicating that the excessive income distribution inequality is not conducive to the inhibitory effect of digital economy on environmental pollution. The problem of unbalanced and insufficient development accompanied by high-speed economic growth will further lead to unequal income distribution. Existing literature shows that income inequality harms environmental policies, and has a positive effect on pollutant emissions. When the income gap is too large, residents usually pay more attention to economic development and income level linked to their interests and are easy to ignore the ecological environment. However, when the income gap narrows, residents will also focus on the external environment and pursue a higher-quality living environment while feeling satisfied with the material level. And they will not only actively cooperate with environmental governance policies but also actively participate in environmental protection work. Based on the above analysis, Hypothesis 2 has been verified.

5.4 Robustness check

This paper use the instrumental variable method to examine the robustness in order to guarantee the validity and reliability of the aforementioned empirical conclusions. The lag period of digital economic development is used as an instrumental variable to test. Table 6 presents the outcomes. In the test results with the lag period of the digital economy development index as the tool variable, the impact effect of the digital economy on the environmental quality is still valid, the coefficient is significant at the level of 1%, and the LM statistic p value of kleibergen PAAP rk is 0.000, indicating that the original assumption "insufficient identification of tool variables" is rejected; The Wald F statistic of kleibergen PAAP rk is greater than the critical value of the weak identification test at the level of 10%, which shows that it is reasonable to select the lagging term of the digital economic development index as the instrumental variable.

TABLE 6 Robustness test results.

	(1)
	EQ
DE	0.324**
—	(0.091)
UR	−0.003
—	(0.0542)
PD	0.343*
—	(0.166)
IS	0.130*
—	(0.097)
OL	−0.613***
—	(0.178)
GTI	−0.0119
—	(0.0285)
Individual fixed effect	control
Time fixed effect	control
Kleibergen-Paap rk LM	16.918
	(0.000)
Kleibergen-Paap rk Wald F	123.256
	{16.48}
N	180
R^2	0.636

Note: ***, **, and * denote statistical significance at 1%, 5%, and 10%.

6 Conclusions and implications

Based on panel data of 30 provinces from 2014 to 2020, this paper empirically tests the impact and mechanisms of digital economy development on environmental quality by using the fixed effect model and moderating effect model. The main conclusions are as follows: First, the digital economy can effectively restrain environmental pollution and positively promote environmental quality. Second, there is regional heterogeneity concerning the effects of digital economy on environmental quality, with the strongest effects in the west, the second strongest in the east, and the weakest in the center. Third, economic development level and income distribution inequality play positive and negative roles in regulating the negative linkage between digital economy and environmental pollution, respectively.

Based on the above conclusions, this paper provides the following suggestions: Firstly, China should vigorously develop digital economy and maximize its role in curbing environmental pollution. Currently, digital transformation has become the key to achieving the goal of "double carbon". To improve the infrastructure construction of digital economy, the Chinese government should take into account the needs and development of the industry, and accelerate the pace of scientific planning and construction. First, China should take advantage of the characteristics of digital economy platforms and sharing to accelerate the integration of information technology and various industries, and transform and upgrade its industrial structure. Through these methods, we can reduce the energy consumption of the industry and achieve the goal of energy conservation, emission reduction, and green development. Second, we should attach importance to the technological advantages of digital economy, actively promote the deep integration of the digital economy and technological innovation, and deeply empower the digital and low-carbon transformation of traditional industries to help Chinese enterprises develop sustainably and low-carbon. Third, relevant departments should vigorously develop the natural, green, and inclusive nature of digital finance, and realize the interconnection of resources, market, technology, and capital through digital service platforms, to expand the financing scale of the supply chain and help green transformation enterprises better integrate into the capital chain, value chain, and industrial chain.

Secondly, we should implement the differentiated digital economy development strategy according to local conditions. The impact of digital economy on environmental quality is heterogeneous. While strengthening the development of digital economy in eastern China, we should also make up for the shortcomings of digital economy in central and western China. We will foster a novel pattern of development in the western region, accelerate the rise of the central region, and encourage modernization in the eastern region. In the western region, we should strengthen the construction of basic economic facilities, expand the economic scale, and promote the multi-level and in-depth development of the industrial structure. In the central region, space should be optimized. A new pattern of coordinated development between regions should be established. Reform and innovation should be accelerated, and industrial transformation and upgrading should be further optimized and enhanced to achieve comprehensive and balanced development. The eastern region should make full use of its economic, political and environmental advantages. The government should vigorously promote technological innovation, improve the integration of digital economy and technological innovation, and realize a better situation of green and innovative development.

Finally, China should insist on the concept of inclusive development and balance the relationship between economic growth and income distribution inequality. The economic growth due to population expansion is the main reason for improving economic quality. The government should give full play to the positive externalities of population concentration to improve the quality of the population and the awareness of environmental protection, change the mode of economic development by making rational use of foreign direct investment, and promote industrial transformation and upgrading. Meanwhile, the widening income gap indirectly caused by population expansion will exacerbate pollution emissions. Enterprise managers should increase employees' wages and establish paid input-output analysis to alleviate the harm caused by the excessive income gap to the environment. In the formulation and implementation of policies and guidelines, the government should, while promoting economic development and narrowing the income gap, give full consideration to the environmental effect of policies, give full play to the effect of

pollution control and emission reduction of smart cities, and take urban construction of a win-win situation of economy and environment as the ultimate goal.

Although this study supplements the relevant studies on the impact and mechanisms of digital economy on environmental quality and provides some theoretical basis for environmental governance through digital economy, it still has certain limitations. First of all, the research data in this paper are mainly concentrated at the provincial level with a limited sample size, which can be more detailed and micro in the future. Secondly, this paper measures the development of digital economy from three dimensions: informatization development, Internet development and digital transaction development. Based on the existing data, there may be some measurement deviation. The selection of indicators also needs to be further improved. The mechanical part is only analyzed from the perspective of economic development level and income distribution inequality. There should be further research and analysis on the impact of different mechanisms on the environmental impact of digital economy in the future. Finally, the development of an economy is cyclical. China's digital economy is in the process of dynamic development. Future studies should further explore the dynamic factors affecting the impact of digital economy on the environment.

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

ZZ: software, writing original draft, and conceptualization. LP: software, methodology, writing original draft. ZD: data curation and searching literature. YG: investigation, supervision, and writing—review and editing. CW: conceptualization, and project administration.

Funding

This study was support by the Social Science Foundation of Nantong (No. 2022CNT041).

Conflict of interest

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

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