Does the construction of network infrastructure reduce environmental pollution?—evidence from a quasi-natural experiment in “Broadband China”

Weiyong Zou1 · Minjie Pan1

Received: 15 March 2022 / Accepted: 19 July 2022 / Published online: 28 July 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
This paper discusses the effect of network infrastructure on environmental pollution reduction and the realization mechanism behind it. Based on the panel data of 285 cities in China from 2005 to 2019, this study regards the “Broadband China” pilot policy as a quasi-natural experiment to clarify the pollution emission reduction effect of network infrastructure construction through differences-in-differences method and other methods. The research results show the following: (1) The Broadband China pilot policy has reduced environmental pollution, that is, the construction of network infrastructure has the effect of environmental pollution reduction. The conclusion is still established after a series of robustness tests such as parallel trend test, placebo test, and instrumental variable method. Through the heterogeneity test, it is found that the pollution reduction effect of network infrastructure construction is more obvious in non-resource-based cities, first and second tier cities, and cities in the eastern region (2). The construction of network infrastructure plays a restraining role on local environmental pollution. Due to the insufficient level of regional linkage and the siphon effect of pilot cities, the spatial spillover characteristics of the pollution reduction effect are not obvious (3). The mechanism of action shows that green innovation is an important mediating effect mechanism for network infrastructure construction to reduce environmental pollution. Cities in regions with high degree of marketization and environmental regulation can strengthen the effect of network infrastructure construction on environmental pollution reduction. The research conclusions are conducive to accelerating the development of the digital economy represented by the construction of network infrastructure and provide a useful reference for promoting the level of environmental pollution reduction and achieving high-quality development.

Keywords Network infrastructure construction · Environmental pollution · Broadband China · Digital economy · Differences-in-differences method

Introduction
Over the past 40 years of reform and opening up, China has created a miracle in human economic history, but the rapid economic growth is at the expense of environment and resources (Wu et al., 2019). Environmental deterioration threatens the ecological balance and seriously restricts the sustainable development of China’s economy and society (Hou et al., 2021). According to the 2020 global environmental performance index jointly prepared by Yale University and other authoritative institutions in the USA, China ranks only 120th among the 180 countries and regions participating in the evaluation, and the ranking is still very low (Raza et al., 2021). In order to fight the tough battle of pollution prevention and control and promote the construction of ecological civilization to a new level, the Chinese government attaches great importance to the work of ecological environment. The nineteen party advocates promoting the “Internet Plus” strategy, promoting the construction of the network power and digital China, and cultivating new kinetic energy for the development of high quality. At present, the COVID-19 has led to a global economic recession. Digital economy has become a “new variable” to realize economic recovery and improve economic quality and efficiency. According to statistics from the “Global
Digital Economy White Paper—New Dawn of Recovery under the Shock of the Epidemic released by the China Academy of Information and Communications Technology, the scale of the digital economy in developed countries has reached $24.4 trillion, accounting for more than 50% of GDP. Although the digital economy scale of the developing countries is small, its growth rate is relatively faster. Among them, the digital economy scale of the United States and China is $13.6 trillion and $5.4 trillion, ranking the top 2 in the world. The digital economy scale of Germany, Japan, and the United Kingdom is $2.54 trillion, $2.48 trillion, and $1.79 trillion, ranking third to fifth respectively. The scale of the digital economy in countries around the world is still expanding, and it is necessary to integrate the digital economy into high-quality development.

What is the digital economy? According to the definition in the “Statistical Classification of Digital Economy and Its Core Industries (2021)” issued by the National Bureau of Statistics, digital economy is based on data as the key production factor, modern information network as the important carrier, and digital technology application as the main feature. Digital economy is an economic operation system based on Internet and information and communication technology. Nowadays, the relationship between the digital economy and high-quality development has attracted widespread attention from the academic community. As a more advanced economic form after agricultural economy and industrial economy, digital economy has penetrated into all fields of economy and society, but the relationship between digital economy and high-quality development remains to be explored. Most of the only research comes from the related sub topics of how the Internet promotes high-quality development such as industrial structure optimization (Su et al., 2021), technological innovation performance improvement (Li et al., 2021), human capital improvement (Grigorescu et al., 2021), and total factor productivity (Pan et al., 2022). From a microperspective, the development of the digital economy has accelerated the flow of factors and improved resource utilization and allocation efficiency, which is the best embodiment of green development. From a macroperspective, the digital economy promotes technological innovation and industrial structure upgrading, effectively improving production efficiency and enabling high-quality development (Li et al., 2022). However, the existing literature lacks a direct assessment of the environmental pollution caused by the digital economy, which provides an opportunity for further research on this topic in this paper.

In order to enhance the country’s international competitiveness, the world’s major economies have introduced digital strategies. From the US’s “Key and Emerging Technology Nation” strategy to the UK’s “National Data Strategy,” and then to the EU’s “Digital Compass 2030” plan, the construction of new digital infrastructure such as communication and network technology and big data has become the focus of various countries’ digital strategies. In order to vigorously promote the healthy development of the digital economy, China has implemented plans for the construction of digital facilities such as the Network Power Strategy. Broadband networks are an important driving force for the digital transformation of the economy and society (Wu et al., 2021). In 2013, the State Council issued the Broadband China Strategy and Implementation Plan. The Ministry of Industry and Information Technology and the National Development and Reform Commission jointly released a list of 120 Broadband China pilot cities from 2014 to 2016. The broadband China pilot policy has greatly accelerated the construction of network infrastructure and optimized network speed (Zhong et al., 2022). In 2010, there were 187 million Internet broadband access ports, and by 2020, the number of Internet access ports has reached 946 million. In 2013, the average download rate of my country’s fixed broadband network was only 3.53 M bit/s. In 2020, the average download rate has reached 43.49 M bit/s, which is 12.32 times that of the same period in 2013. Network infrastructure is a prerequisite for the realization of digital China. So, what is the relationship between the digital economy represented by the implementation of the Broadband China strategy and environmental pollution? In other words, can network infrastructure construction achieve the effect of reducing environmental pollution? If network infrastructure construction can improve environmental quality, what is the specific mechanism of action? It is of great practical significance to further explore the causal relationship and transmission mechanism between the two for accelerating digital development and promoting the construction of ecological civilization.

The existing literature lays the research logic and ideas for this study. The possible marginal contributions of this paper are as follows:

1. Research perspective. The existing literature pays more attention to the environmental related research fields of digital economy, such as industrial structure, technological innovation, human capital, and total factor productivity, while there is a lack of direct and systematic research on digital economy and environmental pollution. This paper will expand the research scope of high-quality economic development and enrich the research literature related to digital economy and ecological environment.

2. Research methods. This paper regards the Broadband China pilot policy as a quasi-natural experiment of network infrastructure construction and uses a differences-in-differences (DID) model to evaluate the impact of network infrastructure construction on pollution reduction. This study uses parallel trend test, placebo test, and other methods to examine the robustness of the original
econometric model and uses the instrumental variable method combined with the system moment estimation model to alleviate the endogeneity problem caused by the non-random selection of pilot cities. In addition, this paper examines the heterogeneity from the aspects of resource endowment, urban scale, and geographical location, which enriches the empirical evidence of this research topic.

3. Research mechanism. In order to deeply explore the internal mechanism of network infrastructure construction and environmental pollution, this paper adopts the spatial DID method to investigate the spatial spillover mechanism of network infrastructure construction. This study introduces the level of green technology innovation as an intermediary variable and the level of marketization and environmental regulation as moderator variables to examine the impact channels of network infrastructure construction to achieve pollution reduction.

The rest of this paper is arranged as follows: The second part puts forward the theoretical hypothesis of network infrastructure construction and environmental pollution. The third part describes the methods of empirical analysis, including normative empirical model, estimation method, index calculation, and data source. The fourth part introduces the empirical estimation results and empirically analyzes the relationship between network infrastructure construction and environmental pollution, including robustness test, heterogeneity analysis, and endogenous test. The fifth part discusses the internal mechanism of the relationship between the two, including the mechanism of mediating effect and moderating effect. The sixth part is to summarize the research of this paper and put forward a series of policy suggestions and research prospects.

**Research hypothesis**

In order to explore the theoretical mechanism of the research topic, this paper investigates the direct influence mechanism and the indirect influence mechanism respectively and puts forward corresponding theoretical hypotheses accordingly.

**Direct impact mechanism**

The direct effect of network infrastructure construction on environmental pollution is mainly reflected in the following aspects: First, network communication technology breaks the time and space constraints based on traditional means of production such as factories and equipment. By building a digital platform for information sharing and intercommunication, it can effectively reduce the excessive consumption of physical resources and energy. The Internet is a green production mode with low energy consumption, low emission, and low pollution. It is a way to transform traditional industries based on digital technology and promote backward production capacity to withdraw from the market (Fromhold-Eisebith et al., 2021). Second, the Internet can improve the efficiency of public participation in environmental supervision. In the context of the digital economy, the development of digital media has accelerated the speed and breadth of information dissemination. The public can grasp environmental change and environmental protection knowledge in time, and strengthen social environmental supervision through online participation, which promotes the government and all sectors of society to participate in environmental governance (Yang et al., 2020). Third, the Internet advocates the concept of green consumption. Green digital consumption platforms such as online shopping and non-inductive payment are subtly leading consumers to change their consumption patterns and actively advocate and promote the development of green consumption. The increased demand for green consumption will force a green transformation of production methods and optimize the supply system for green consumption (Martin et al., 2018).

Hypothesis 1: The construction of network infrastructure can effectively reduce environmental pollution.

**Indirect impact mechanism**

**Spatial effect mechanism**

According to the central-peripheral city theory, the development of central cities will have a strong radiation driving effect on the surrounding hinterland (Kang et al., 2022). The policy pilot cities have radiation effects and demonstration effects, providing new impetus for environmental pollution reduction in surrounding cities. Policy pilot cities and surrounding cities form an open system with close economic exchanges. New industries and new business forms generated by economic activities can radiate and drive the development of surrounding cities. Incentive policies can bring talents, technology, capital, and other resources together, attracting high-tech enterprises to settle in. Enterprises in surrounding cities obtain the spillover of advantageous resources by copying and learning from policy pilot cities. With the gradual promotion of reform and innovation experience, the dividends of reform can be copied and shared. Policy pilot cities bring momentum to surrounding cities by reducing institutional costs. However, due to the scale effect and agglomeration effect generated by the incentive policies, the policy pilot cities are more attractive than the surrounding cities and will also have a “siphon effect” on the resource elements of the surrounding cities. The phenomenon of
The moderating effect mechanism of marketization.

Moderating effect mechanism

The moderating effect mechanism of marketization.

Under the condition of open economy, the higher the degree of marketization, the more conducive it is to optimize the efficiency of regional resource allocation and promote technological innovation to improve the level of pollution control. A high level of marketization means that the product market and factor market are relatively well developed. The higher the degree of development of the product market, the more sensitive the market price signal, which is conducive to the transfer of production factors between industries. A high degree of marketization can reduce production costs, which can improve the efficiency of resource utilization and allocation and finally achieve the purpose of energy conservation and emission reduction (Pan and Tang, 2021). The market mechanism can stimulate the enthusiasm of producers, and the market price can reasonably reflect the scarcity of resources and the supply and demand of products, so as to provide reasonable guidance for production allocation. An effective market is conducive to cross regional competition and cooperation, and cities with a high degree of marketization reduce repeated construction. Enterprises form economies of scale through mergers, acquisitions, and opening up new markets, which improve production efficiency and reduce environmental pollution emissions (Chen et al., 2021). Producers can improve business performance through digital innovation, and producers in the same industry “survive with innovation.” The market mechanism forces producers to leave the comfort zone and provide new capabilities and products, which is conducive to environmental pollution reduction (Albort-Morant et al., 2018).

Hypothesis 4: Areas with a high level of marketization can strengthen the environmental pollution reduction effect of network infrastructure construction.

The moderating effect mechanism of environmental regulation.

Many producers are accustomed to the extensive development model of “high consumption, high emissions, and high pollution” and believe that the cost of environmental governance is expenditure outside the production cost, so they try to avoid the main responsibility. The traditional environmental supervision mode is inefficient and backward. When facing numerous and complex environmental management objects, the effect of supervision and law enforcement is poor. In order to improve the scientific decision-making of environmental supervision and the precise and efficient governance, the government can promote the transformation of environmental supervision from traditional human sea tactics to modern information technology and traditional post-event supervision to whole-process supervision by adopting digital technology. (Li et al., 2020). On the one hand, digital technologies such as the Internet can help the government to dynamically monitor information such as the...
pollution discharge of producers and the carrying capacity of
the regional ecological environment in real time and improve
the early warning and traceability of pollution sources. On
the other hand, the government provides data support for the
formulation and implementation of environmental protection
policies through the scientific application of the integrated
digital information. The Internet will vigorously promote
the construction of the environmental governance system
and the modernization of governance capabilities (Linkov
et al, 2018).

Hypothesis 5: Areas with high intensity of environmen-
tal regulation can strengthen the environmental pollution
reduction effect of network infrastructure construction.

Research design
Measurement model construction
In order to verify whether the construction of network infra-
structure can reduce urban environmental pollution emis-
sions, this paper regards the Broadband China strategy as an
exogenous policy shock and uses a multi-period DID method
to evaluate the effect of digital emission reduction (Fang
et al. 2022). The DID model is constructed as follows:

\[
\text{Pollution}_{it} = \alpha_1 + \beta_1 \text{DID}_{it} + \delta_1 \text{Control}_{it} + \varphi_i + \lambda_t + \epsilon_{it} \tag{1}
\]

Among them, Pollution is the explained variable, indicat-
ing the degree of urban environmental pollution. DID is the
core explanatory variable, \( \text{DID} = \text{Treat} \times \text{Time} \), indicating
whether it is a pilot city of Broadband China policy. If the
value of Treat is 1, it means that city \( i \) is a policy pilot city,
and if the value of Treat is 0, it is a non-policy pilot city. If
the value of Time is 1, it means that city \( i \) implements the
policy in the current year and after, and if the value of Time
is 0, it means that city \( i \) does not implement the policy in
the current year. \( \beta_1 \) is the emission reduction effect of policy
pilot cities. \( \alpha_1 \) is the constant term, Control is the control vari-
able, which represents the relevant variables affecting envi-
ronmental pollution, and \( \delta_1 \) is the estimation coefficient of
the control variable. \( \varphi_i \) and \( \lambda_t \) are urban fixed effect and year
fixed effect respectively, and \( \epsilon_{it} \) is the random error term of
the model. Subscripts \( i \) and \( t \) are city and year respectively.

Variable setting and data description

1. Explained variable (Pollution). Industrial “Three
Wastes” indicators are widely used in environmental
research. Based on the availability of environmental pol-
ution data at the city level, this paper uses the emissions
of industrial wastewater, industrial soot, and industrial
sulfur dioxide, combined with the entropy method to
calculate the comprehensive pollution index to measure
urban environmental pollution (Dong et al. 2020). In
addition, this study also uses sulfur dioxide and haze as
robustness indicators. Among them, the haze emission
concentration comes from the PM2.5 satellite remote
sensing data released by the Atmospheric Composition
Analysis Group of Dalhousie University. The above two
indicators have good representation as proxy variables
of environmental pollution (Chen et al, 2018a, b).

In this study, ArcGIS 10.5 software was used to draw
the spatial distribution map of the environmental pollu-
tion index in 2019 (left of Fig. 1), and it was divided intoive levels according to the natural discontinuity method.
It can be seen from the results that the environmental

Fig. 1 Temporal and spatial distribution characteristics of entropy value of industrial three wastes
pollution index in the eastern region is higher. Compared with the central and western regions, the eastern region has a faster economic development and a more developed industrial system. Although the proportion of industrial pollutants in the eastern region of the country is declining, it is still more than that in the central and western regions. A broken line diagram is used to show the time evolution of the environmental pollution index (right of Fig. 1). It can be seen from the results that the environmental pollution index shows signs of improvement and generally shows a fluctuating downward trend. Among them, the pollution index decreased significantly in 2015, which is the second year of the implementation of the pilot policy of Broadband China.

2. Core explanatory variable (DID). Broadband China policy is the core explanatory variable, and the virtual variable is assigned as: \( \text{DID} = \text{Treat} \times \text{Time} \). When the city is a pilot city of Broadband China policy, the value of \( \text{Treat} \) is 1; otherwise, it is 0. When the city implements Broadband China in the current year and after, the value of \( \text{Time} \) is 1; otherwise, it is 0. The intersection term of \( \text{Treat} \) and \( \text{Time} \) is the policy variable of Broadband China. The spatial distribution of pilot cities is shown in Fig. 2:

3. Mechanism variables. This paper selects green technology innovation as the intermediary variable and the level of marketization and environmental regulation as the regulating variables. Green technology innovation (\( \text{Pgtech} \)): Based on the “International Green Patent Classification List” issued by the World Intellectual Property Organization in 2010, the patent classification number IPC information of the State Intellectual Property Office is matched, identified and calculated, and sorted into sample data at each city level (Jiao et al, 2020). Market level (\( \text{Market} \)): Based on the research of Fan Gang’s marketization index, the index measures the marketization level of Chinese cities from five dimensions: the relationship between

---

Footnote 1: According to the United Nations Framework Convention on climate change, the search entry divides green patents into seven categories: energy conservation, alternative energy production, transportation, waste management, administrative supervision and design, nuclear power, and agriculture and forestry.
the government and the market, the development of non-state-owned economy, the development of product market, the development of factor market, the development of market intermediary organizations, and the legal environment (Mei et al. 2021). Environmental regulation (Reg): Learn from Chen et al. (2018a, b), select the frequency of Environmental Related words in the work reports of local municipal governments as the proxy variable of environmental regulation, and use Python technology for data mining and manual sorting. The search term frequency of this article includes ecology, environmental protection, environmental protection, emission reduction, sewage discharge, air, green, carbon dioxide, pollution, energy consumption, low carbon, chemical oxygen demand, sulfur dioxide, and PM2.5. PM10.

4. Control variables. In order to more accurately evaluate the pollution reduction effect of network infrastructure construction, it is necessary to control the factors affecting environmental pollution. Among them, Internet penetration (Net): measured by the number of Internet broadband access users. Industrial structure (Ind): measured by the proportion of the added value of the secondary industry to GDP. Fiscal R&D Expenditure (Pte): measured by per capita fiscal expenditure on science and technology. Financial development (Fin): expressed by the ratio of various loan balances of financial institutions to GDP. Level of openness (Fdi): measured by foreign direct investment as a percentage of GDP. Enterprise scale (Comp): measured by the number of industrial enterprises above designated size, and the logarithm is used for processing. Economic development level (GDP): measured by per capita GDP and processed by logarithm. According to the “EKC” curve hypothesis, there is an inverted U-shaped curve relationship between economic development level and environmental pollution. In this paper, lnGDP and ln(GDP)² are included in the analysis model at the same time.

5. Data sources

In view of the lack of many data values in some cities such as Turpan and Nyingchi, the sample was excluded. This paper selects 4275 sample data from 285 cities in China from 2005 to 2019. Relevant data comes from China Urban Statistical Yearbook, urban statistical yearbooks of local cities, CSMAR database, EPS database, SRTM database, CNRDS database, State Intellectual Property Office, Dalhousie University’s satellite grid data, work reports of local municipal governments, etc. The missing phenomenon of individual data is filled by interpolation method.

Empirical results and analysis

Benchmark regression

Taking Broadband China as a quasi-natural experiment, this paper adopts a multi-period DID method to identify the relationship between the digital economy represented by network infrastructure construction and urban environmental pollution reduction. Table 1 shows the estimation results of the benchmark regression model, and columns (1) and (2) show the empirical results of excluding and including control variables respectively. The results show that the estimation coefficient of policy variables is significantly negative (β = −0.00919, p < 0.01, model 1; β = −0.00709, p < 0.01, model 2). This shows that the Broadband China pilot policy can significantly curb urban environmental pollution emissions, that is, promoting the development of digital economy represented by network infrastructure construction can improve environmental pollution. The research conclusion verifies hypothesis 1. It is worth noting that since the 18th National Congress of the Communist Party of China, the construction of ecological civilization has been incorporated into an important strategic position in state governance. A series of environmental protection policies have been introduced to improve China’s environmental pollution problems. These policies partially overlap with the Broadband China pilot policy. In order to exclude the interference of relevant environmental protection policies on the empirical results, this paper refers the research results of Li and Zhou (2021) for further processing. In the measurement equation, two policy dummy variables of “Central Environmental Protection Inspector” and “Smart City” are added to column (3) and column (4) respectively, and these two policies are included in the model at the same time in column (5). The results show that the estimated coefficients of the policy variables of the Broadband China pilot are still significantly negative (β = −0.00716, p < 0.01, model 3; β = −0.00705, p < 0.01, model 4; β = −0.00711, p < 0.01, model 5). This further shows that excluding the influence of other environmental policies, the construction of network infrastructure still has a significant effect of reducing environmental pollution.

Robustness test

1. Parallel trend test. The premise of multi period DID method is to meet the hypothesis of parallel trend. That is, before the implementation of the Broadband China policy, the treatment group and the control group have the same change trend under the control of a series of
factors. This paper refers to the time event research method of Beck et al. (2010) for testing, and sets the following model:

\[ \text{Pollution}_t = \alpha + \sum_{i=9}^{5} \gamma \text{DID}_i \times \text{Year}_t + \delta \text{Control}_t + \varphi_i + \lambda_t + \epsilon_t \]  

In the formula, \( \text{DID}_i \times \text{Year}_t \) represents the dummy variable for implementing the Broadband China policy at different time points. Specifically, it refers to the interaction item between the pilot city and the event impact time. If the value range of \( s \) is \(-9 \leq s \leq 5\). If the value of \( s \) is 0, it means that the pilot city is in the current implementation period. If the estimated coefficient \( \gamma \) fluctuates around 0 before the implementation of the policy and does not pass the significance test, it means that it passes the parallel trend test. The results are shown in Fig. 3.

The left and right figures of Fig. 3 are the parallel trend charts with no control variables and with control variables respectively. The vertical axis is the estimated coefficient of environmental pollution emission from the implementation of the pilot policy at different time points, and the horizontal axis is the relative time before and after the implementation of the pilot policy. 0 is the initial period of the pilot policy, and the dotted lines above and below the hollow circle represent the 90% confidence interval. The results show that before the implementation of Broadband China pilot policy, the policy variables have no significant impact on environmental pollution, and the \( \gamma \) value fluctuates up and down at 0, indicating that it has passed the parallel trend test.

### Table 1 Benchmark regression

| Variables            | (1)          | (2)          | (3)          | (4)          | (5)          |
|----------------------|--------------|--------------|--------------|--------------|--------------|
| \( \text{DID} \)     | -0.00919***  | -0.00709***  | -0.00716***  | -0.00705***  | -0.00711***  |
|                      | (0.00151)    | (0.00152)    | (0.00153)    | (0.00152)    | (0.00152)    |
| \( \text{Net} \)     | -0.00004**   | -0.00004**   | -0.0004*     | -0.0004*     | -0.0004*     |
|                      | (0.00002)    | (0.00002)    | (0.00002)    | (0.00002)    | (0.00002)    |
| \( \text{Ind} \)     | 0.00017**    | 0.00017**    | 0.00017**    | 0.00017**    | 0.00017**    |
|                      | (0.00008)    | (0.00008)    | (0.00008)    | (0.00008)    | (0.00008)    |
| \( \text{Pte} \)     | -3.64e-06*   | -3.58e-06*   | -3.64e-06*   | -3.58e-06*   | -3.58e-06*   |
|                      | (1.27e-06)   | (2.17e-06)   | (2.17e-06)   | (2.17e-06)   | (2.17e-06)   |
| \( \text{Fin} \)     | 0.00004***   | 0.00004***   | 0.00004***   | 0.00004***   | 0.00004***   |
|                      | (0.00001)    | (6.77e-06)   | (6.80e-06)   | (6.81e-06)   | (6.81e-06)   |
| \( \text{Fdi} \)     | -0.0004*     | -0.00040*    | -0.00040*    | -0.00040*    | -0.00040*    |
|                      | (0.00024)    | (0.00024)    | (0.00024)    | (0.00024)    | (0.00024)    |
| \( \text{Comp} \)    | 0.00668***   | 0.00679***   | 0.00665***   | 0.00676***   |
|                      | (0.00134)    | (0.00134)    | (0.00134)    | (0.00134)    | (0.00134)    |
| \( \text{GDP} \)     | 0.03048**    | 0.03055**    | 0.03054**    | 0.03060**    |
|                      | (0.01516)    | (0.01518)    | (0.01511)    | (0.01513)    | (0.01513)    |
| \( \text{GDP}^2 \)   | -0.00157*    | -0.00157*    | -0.00157*    | -0.00157*    |
|                      | (0.00090)    | (0.00091)    | (0.00091)    | (0.00091)    | (0.00091)    |
| \( \text{Environmental Inspectors} \) | -0.00334 | -0.00328 |
|                      | (0.00247)    | (0.00247)    | (0.00247)    | (0.00247)    | (0.00247)    |
| \( \text{Smart city} \) | -0.0019** | -0.0019** |
|                      | (0.00087)    | (0.00087)    | (0.00087)    | (0.00087)    | (0.00087)    |
| \( \_\text{Cons} \) | 0.0458***    | -0.15125**   | -0.15165**   | -0.15144**   | -0.15183**   |
|                      | (0.0004)     | (0.0671)     | (0.06721)    | (0.06699)    | (0.06708)    |
| Urban fixed          | YES          | YES          | YES          | YES          | YES          |
| Year fixed           | YES          | YES          | YES          | YES          | YES          |
| Observations         | 4275         | 4275         | 4275         | 4275         | 4275         |
| \( N \)              | 285          | 285          | 285          | 285          | 285          |
| \( R^2 \)            | 0.7714       | 0.7796       | 0.7797       | 0.7797       | 0.7798       |

Numbers in parentheses denote the standard error of the respective coefficients.

*"" Significance at the 1% level; ** significance at the 5% level; *significance at the 10% level
In addition, the pilot policy has a certain lag in the emission reduction effect of environmental pollution. The possible reason is that the construction of broadband network has not reached the corresponding scale in the short term, which is not enough to support the pilot of Broadband China to give full play to the emission reduction effect. Policy pilot cities need a certain period of time to play a role in emission reduction.

2. Placebo test. The above analysis excludes the interference of other environmental policies on the research results. At the same time, the parallel trend test shows that the research samples meet the premise hypothesis of multi-stage DID. But the potential threat is that the policy pilot cities themselves have a stronger tendency to reduce pollution. Therefore, this paper uses the placebo test to investigate the random allocation of pilot cities to the sample. One hundred eight cities were randomly selected from 285 cities as the treatment group, and the unselected cities were used as the control group (Chen and Lin, 2021). If the estimated coefficient of policy variables is still significant at this time, it indicates that the research results are caused by other unobserved factors. On the contrary, it shows that the emission reduction effect of the pilot policy really exists, and the construction of network infrastructure is conducive to promoting environmental pollution reduction. In this study, random sampling was repeated 500 times, and the regression was performed according to column (2) of Table 1 to obtain the density distribution of policy variable $t$ value (Fig. 4). The area enclosed by the blue solid line is the estimated kernel density curve obtained by randomly selecting the policy intervention group, and the dotted line is the estimated coefficient of policy intervention. The results show that the nuclear density curves are symmetrically distributed on both sides at 0, indicating that the density curve is normally distributed. The actual estimated policy variable coefficient in column (2) of Table 1 is $-0.00709$, that is, there is a significant difference between the estimated coefficient of the intervention group of Broadband China pilot real policy and
random sampling policy. The research results show that the effect of promoting environmental pollution reduction through network infrastructure construction is not derived from unobservable factors, and the research results are robust.

3. Other robustness analysis

Eliminate macro factors. Generally speaking, cities with a higher level of economic development will give priority to the development of network infrastructure and have the “first mover advantage” of digital economy. By controlling the province effect and the interaction effect between provinces and years, this paper aims to alleviate the impact of macro systematic environmental change on digital economy. As shown in Table 2, the results of column (1) (2) show that after considering the systematic changes of macro factors, the estimation coefficient of policy variables is still significantly negative (\(\beta = -0.00709, p < 0.01\), model 1; \(\beta = -0.00546, p < 0.01\), model 2). It shows that the research results are robust.

Replace the interpreted variable. \(\text{SO}_2\) emission and \(\text{PM2.5}\) annual average concentration are often used as proxy variables of environmental pollution in production and life (Guo et al., 2021; Thind et al., 2022). Columns (3) and (4) are regression models with \(\text{SO}_2\) emission and \(\text{PM2.5}\) annual average concentration as explained variables respectively. The results show that the estimated coefficient of policy variables is still significantly negative (\(\beta = -0.07927, p < 0.05\), model 3; \(\beta = -0.95265, p < 0.01\), model 4). It shows that the research results are robust.

Table 2 Robustness test

| Variables          | Eliminate macro factors | Replace interpreted variable | Replacement model |
|--------------------|-------------------------|-------------------------------|------------------|
|                    | (1) (2)                 | (3) (4)                       | (5) (6)          |
| \(\text{DID} \)    | \(-0.00709***\)         | \(-0.07927**\)              | \(-0.00658***\)  |
|                    | (0.00152)               | (0.03352)                    | (0.00166)        |
| Cons               | YES                     | YES                           | YES              |
| Control variable   | YES                     | YES                           | YES              |
| Province fixed     | YES                     | NO                            | NO               |
| Province \(\times\) Year | NO                   | NO                            | NO               |
| Urban fixed        | YES                     | YES                           | YES              |
| Year fixed         | YES                     | YES                           | YES              |
| Obs                | 4,275                   | 4,275                         | 4,275            |
| N                  | 285                     | 285                           | 285              |
| \(R^2\)            | 0.7796                  | 0.7729                        | 0.8403           |

Numbers in parentheses denote the standard error of the respective coefficients

** **significance at the 1% level; ** **significance at the 5% level; *significance at the 10% level

Endogenous analysis

Because the Broadband China pilot policy is not set up randomly, it is disturbed by factors such as urban economic development and resource endowment, resulting in endogenous problems in the model. Generalized method of moments (GMM) is commonly used to solve the endogenous problem of models. It is divided into differential GMM (DIF-GMM) and System GMM (SYS-GMM). Since the SYS-GMM combines the DIF-GMM model and the
horizontal GMM model, the estimation efficiency can be improved compared with the DIF-GMM estimation (Liu and He, 2019). In this paper, the SYS-GMM method is used for further regression to solve the endogenous problem.

Digital technology originated from the promotion of fixed line telephone. Cities with high penetration of fixed line telephone in history generally have a high level of digital economic development. At the same time, before the popularization of fixed telephone, people used the post office system as the main way of information communication. The post office system is also the executive department of fixed telephone, which affects the construction of fixed telephone, Internet access, and other facilities to a certain extent; affects the development of digital economy; and meets the relevance. In addition, the impact of traditional telecommunications tools such as fixed line telephone and post office on current economic development is gradually reduced to meet exclusivity. Based on this, this paper looks for the appropriate tool variables of policy variables from the perspective of traditional telecommunications tools. Referring to the method of Huang et al. (2019), this study uses the number of fixed-line telephones per 100 people and the number of post offices per million people in 1984 as instrumental variables for policy variables. The original data of instrumental variables are in the form of cross-section and cannot be directly used for panel data for quantitative analysis. Referring to Nunn and Qian (2014), this study introduces the dummy variable of each year as an interactive item with the section tool variable to construct the panel tool variable.

In addition to including the explained variables with a lag of one period, columns (1) and (2) included the fixed telephone and post office in 1984 as instrumental variables respectively. Table 3 shows the SYS-GMM regression results. The results show that the estimated coefficients of the policy variables of Broadband China are still significantly negative ($\beta = -0.03767, p < 0.01, \text{model 1}; \beta = -0.04524, p < 0.01, \text{model 2}$). The sequence correlation test rejects the original hypothesis that there is no first-order autocorrelation in each estimated residual sequence, but the test does not reject the original hypothesis of second-order autocorrelation. It can be seen from the Hansen test that the model setting is reasonable and the selection of instrumental variables is effective.

### Heterogeneity analysis

Due to the great differences in resource endowments, urban scale, and geographical location between Chinese cities, there are differences in the regional emission reduction effects of the implementation of the Broadband China pilot policy. Therefore, this paper analyzes the heterogeneity from three aspects: resource endowment, urban scale, and geographical location. According to the “National Sustainable Development Plan for Resource-Based Cities (2013–2020)” issued by the State Council, this paper divides the sample into 115 resource-based cities and 170 non-resource-based cities. According to the division basis of the “City Business Charm Ranking” released by the New First-tier Cities Research Institute, the sample is divided into first and second tier cities and third, fourth, and fifth tier cities. According to the criteria of the National Bureau of Statistics for the division of China’s three major regions, the sample is divided into eastern cities and central and western cities.

Table 4 shows the results of the heterogeneity analysis. The results show that the Broadband China pilot policy has significant emission reduction effects in both resource-based and non-resource-based cities ($\beta = -0.00384, p < 0.10, \text{model 1}; \beta = -0.00833, p < 0.01, \text{model 2}$). However, compared with resource-based cities, the pollution reduction effect of non-resource-based cities is more obvious. Resource-based cities with long-term mining and processing of local minerals, forests, and other natural resources as their leading industries need to strengthen the construction of network infrastructure (Li and Zou, 2018). The Broadband China pilot policy has significantly reduced environmental pollution in first and second tier cities and eastern cities ($\beta = -0.01088, p < 0.01, \text{model 3}; \beta = -0.01269, p < 0.01, \text{model 5}$). The pollution reduction effect of the Broadband China pilot policy is relatively small in third, fourth, and fifth tier cities, and the emission reduction effect in the central and western regions is not obvious ($\beta = -0.00297, p < 0.05, \text{model 4}; \beta = -0.00197, p > 0.10, \text{model 6}$). The

| Variables (1) | (2) |
|---------------|-----|
| L_\_Pollution | 0.62848*** | 0.61275*** |
| (0.02410)     | (0.02796)  |
| DID           | -0.03767*** | -0.04524*** |
| (0.00801)     | (0.00820)  |
| _Cons         | YES    | YES      |
| Control variable | YES   | YES      |
| Urban fixed   | YES    | YES      |
| Year fixed    | YES    | YES      |
| AR(1)         | -2.76*** | -2.76*** |
| [0.006]       | [0.006]  |
| AR(2)         | 0.63    | 0.73     |
| [0.525]       | [0.464]  |
| Hansen test   | 0.312   | 0.131    |
| Obs           | 3,990   | 3,990    |
| N             | 285     | 285      |

Numbers in parentheses denote the standard error of the respective coefficients

*Significance at the 1% level/**significance at the 5% level/***significance at the 10% level [ ] is a p value
possible reason for this difference is that compared with the third, fourth, and fifth tier cities and cities in the central and western regions, the first and second tier cities and eastern cities play a “leading role” in pollution reduction. These cities have advantages in capital, technology, talents, and industrial foundation, which create superior conditions for the construction of network infrastructure (Zhou et al., 2021).

Further analysis

Spatial effect analysis

The original intention of the Broadband China pilot policy is to have a positive effect on the surrounding areas through the “Institutional Highland,” but can pilot cities really realize the spillover effect of policy dividends? The spatial model used in this study can well examine the spatial spillover mechanism of the model. The spatial Dubin model considers not only the correlation of independent variables, but also the correlation between independent variables and dependent variables in adjacent areas. Therefore, it is general to choose a spatial Dubin model to analyze this topic. Before establishing a spatial model, it is necessary to perform a spatial autocorrelation test on the core indicators. Table 5 shows the global Moran index test. It can be seen from the results that the global Moran index of environmental pollution has passed the 1% significance level test. It shows that the overall spatial correlation degree of environmental pollution is relatively high, and the spatial model can be used for further analysis. Considering the heterogeneity of cities, this study chose a temporal and spatial double fixed effect model. This study selects the geographical distance matrix to represent the spatial relationship between cities. The long-term spatial effect is considered through the spatial dynamic model of the explained variables with a lag of one period. The regression coefficient of the spatial Dubin model cannot accurately explain the influence of the explained variables and the spatial spillover, so its decomposition model is the focus of the analysis (LeSage and Pace, 2009).

Table 6 shows the regression results of the dynamic space Dubin model. The model is further decomposed into short-term direct and indirect effects and long-term direct and indirect effects. The results show that the effect coefficient of the Broadband China pilot policy on local environmental pollution is significantly negative in both short term and long term, and the effect coefficient of the long-term effect is greater than that of the short term ($\beta = -0.00228, p < 0.10, \text{model 3}; \beta = -0.00584, p < 0.10, \text{model 5}$). It shows that the construction of network infrastructure not only inhibits local environmental pollution, but also has a more sustainable long-term impact on environmental pollution reduction. The indirect effect of the Broadband China pilot policy on the environmental pollution index is positive in both the short and long term, but it has not passed the significance test ($\beta = 0.00243, p > 0.10, \text{model 4}; \beta = 0.00650, p > 0.10, \text{model 6}$). It shows that the network infrastructure construction has little effect on the reduction of environmental pollution in the surrounding cities. There are two possible reasons: First, due to the insufficient level of regional linkage between Broadband China pilot cities and surrounding cities, the pilot emission reduction effect is still limited to the local. Second, the pilot cities expand the coverage of broadband networks and improve the quality of information network services. However, for non-pilot cities, this phenomenon has caused the consequences of resource plundering and the siphon effect of crowding out, aggravating the “lowland effect” of...
policy implementation (Yang et al., 2021). The conclusion of the study verifies hypothesis 2B.

Analysis of mediating effect mechanism

The above research results show that the Broadband China pilot policy significantly promotes the reduction of environmental pollution, that is, the construction of network infrastructure has the effect of reducing environmental pollution. Combined with the previous theoretical analysis, this paper examines the mediating effect mechanism from the perspective of green technology innovation and examines the moderating effect mechanism from the perspectives of marketization and environmental regulation. Referring to the research ideas of Peng et al. (2021), the models are constructed as follows:

\[ \text{Pollution}_{it} = \alpha_1 + \beta_1 \text{DID}_{it} + \delta_1 \text{Control}_{it} + \varphi_i + \lambda_t + \epsilon_{it} \]  

(3)

\[ M_{it} = \alpha_2 + \beta_2 \text{DID}_{it} + \delta_2 \text{Control}_{it} + \varphi_i + \lambda_t + \epsilon_{it} \]  

(4)

\[ \text{Pollution}_{it} = \alpha_3 + \beta_3 \text{DID}_{it} + \delta_3 \text{Control}_{it} + \varphi_i + \lambda_t + \epsilon_{it} \]  

(5)

\[ \text{Pollution}_{it} = \alpha_4 + \beta_4 \text{DID}_{it} + \psi \text{Adj}_{it} + \delta_4 \text{Control}_{it} + \varphi_i + \lambda_t + \epsilon_{it} \]  

(6)

\[ \text{Pollution}_{it} = \alpha_5 + \beta_5 \text{DID}_{it} + \psi \text{Adj}_{it} + \omega \text{DID}_{it} \times \text{Adj}_{it} + \delta_5 \text{Control}_{it} + \varphi_i + \lambda_t + \epsilon_{it} \]  

(7)

Equations (3) to (5) are the test steps of mediating effect mechanism, and Eqs. (6) and (7) are the test steps of moderating effect mechanism. \( M_i \) represents the mediate variable, \( \text{Adj}_{it} \) represents the moderate variable, and the other formula variables are consistent with the benchmark model mentioned above. Among them, the judgment rules of mediating effect mechanism are as follows: If \( \beta_1, \beta_2, \) and \( \beta_3 \) are significant, and \( \beta_1 \) is smaller or significantly lower than \( \beta_3 \), it

### Table 5 Global Moran index test of environmental pollution

| Year | Moran’s I | Z value | P value | Year | Moran’s I | Z value | P value |
|------|-----------|---------|---------|------|-----------|---------|---------|
| 2005 | 0.146     | 5.418   | 0.00    | 2013 | 0.130     | 4.903   | 0.00    |
| 2006 | 0.157     | 5.877   | 0.00    | 2014 | 0.168     | 6.111   | 0.00    |
| 2007 | 0.142     | 5.247   | 0.00    | 2015 | 0.144     | 5.270   | 0.00    |
| 2008 | 0.139     | 5.142   | 0.00    | 2016 | 0.202     | 7.281   | 0.00    |
| 2009 | 0.150     | 5.561   | 0.00    | 2017 | 0.261     | 9.390   | 0.00    |
| 2010 | 0.190     | 6.984   | 0.00    | 2018 | 0.177     | 6.835   | 0.00    |
| 2011 | 0.112     | 4.189   | 0.00    | 2019 | 0.179     | 6.983   | 0.00    |
| 2012 | 0.172     | 6.240   | 0.00    |      |           |         |         |

### Table 6 Spatial DID analysis

| Variables | Dynamic spatial Dublin model | Dynamic space Dublin model decomposition model |
|-----------|-------------------------------|-----------------------------------------------|
|           | (1)                           | (2) | (3) | (4) | (5) | (6) |
|           | Main                          | Wx  | SR_Direct | SR_Indirect | LR_Direct | LR_Indirect |
| L. Pollution | 0.62121*** (0.01353) | 0.08686** (0.03618) |
| DID     | -0.00243** (0.00120) | 0.00263 (0.00318) | -0.00228* (0.00114) |
| rho     | 0.10499*** (0.02868) | 0.00033*** (6.88e-06) |
| sigma2_e | 0.00033*** (6.88e-06) | 0.00033*** (6.88e-06) |
| Control variable | YES | YES | YES | YES | YES | YES |
| Urban fixed | 3.990 | 4.476 | 285 | 285 | 285 | 285 |
| Year fixed | 3.990 | 4.476 | 285 | 285 | 285 | 285 |
| Obs     | 307 | 307 | 307 | 307 | 307 | 307 |

Numbers in parentheses denote the standard error of the respective coefficients

***Significance at the 1% level; ** significance at the 5% level; *significance at the 10% level.
indicates that there is a partial mediating effect. If $\beta_1$ and $\beta_2$ are significant and $\beta_3$ is not significant, it indicates that there is a complete mediating effect. If at least one of $\beta_2$ and $\beta$ is not significant, bootstrap shall be used for further inspection.

Table 7 reports the regression results of green innovation as a mediating variable. In order to improve the reliability of mediating effect results, this paper carries out bootstrap test, and the sampling times are set to 500. BS_1 stands for indirect effect. The confidence interval for the bias correction of indirect effects is $[-0.00312, -0.0080]$, and the interval does not contain 0, indicating that the mediating effect exists. It can be seen from the results that the Broadband China pilot policy has a significant negative impact on the environmental pollution index ($\beta = -0.00709, p < 0.01, \text{model 1}$). For every one unit increase in the network infrastructure construction level, green technology innovation will be promoted by 0.49566 units, and environmental pollution will be reduced by 0.00473 units ($\beta = 0.49566, p < 0.01, \text{model 2}; \beta = -0.00473, p < 0.01, \text{model 3}$). The mediating effect of this action path accounts for 33.06730% of the total effect, and the estimated coefficient of the policy variable in column (3) is lower than that in column (1). This shows that green technology innovation plays a partial mediating effect in the promotion of environmental pollution reduction. The results verify hypothesis 3.

**Moderating effect mechanism**

Table 8 reports the regression results of the moderating effects of marketization and environmental regulation. The results show that column (1) is a model included in the marketization index, and marketization has a negative impact on environmental pollution ($\beta = -0.00138, p < 0.05, \text{model 1}$). Column (2) is a model that introduces the multiplication term ($DID \times Market$) of the policy variables of Broadband China and marketization, and the coefficient of the interaction term is significantly negative ($\beta = -0.00212, p < 0.01, \text{model 2}$). This shows that marketization has a significant positive adjustment effect on the Broadband China pilot policy. Cities in areas with a high degree of marketization strengthen the effect of network infrastructure construction on environmental pollution reduction. On the contrary, it weakens the effect of network infrastructure construction on environmental pollution reduction. The research conclusion verifies hypothesis 4. Column (3) is the model incorporated into environmental regulation. Environmental regulation has a negative impact on environmental pollution, but the coefficient is not significant ($\beta = -0.00003, p > 0.10, \text{model 3}$). Column (4) is the model that introduces the multiplication term ($DID \times Reg$) of the policy variables of Broadband China and environmental regulation, and the coefficient of the interaction term is significantly negative ($\beta = -0.00017, p < 0.10, \text{model 4}$). It shows that environmental regulation has a significant regulating effect on the Broadband China pilot policy. Cities in areas with a high degree of environmental regulation strengthen the role of network infrastructure construction in reducing environmental pollution. On the contrary, it weakens the effect of network infrastructure construction on the reduction of environmental pollution. The results of the study confirm hypothesis 5.

### Table 7 Analysis of mediating effect mechanism

| Variables | (1) Pollution | (2) Pgtech | (3) Pollution |
|-----------|--------------|------------|--------------|
| DID       | $-0.00709^{***}$ | $0.49566^{***}$ | $-0.00475^{***}$ |
|           | (0.00152)    | (0.06136)  | (0.00147)    |
| $Pgtech$  |              |            |              |
| _BS_1     | $-0.00196^{***}$ |           |              |
|           | [-0.00312, -0.00080] |        |              |
| _Cons     | YES          | YES        | YES          |
| Control variable | YES       | YES        | YES          |
| Urban fixed     | YES        | YES        | YES          |
| Year fixed     | YES        | YES        | YES          |
| Obs         | 4,275       | 4,275      | 4,275        |
| $R^2$       | 0.7796      | 0.8747     | 0.7838       |

Number in parentheses denote the standard error of the respective coefficients

"***" Significance at the 1% level; "**" significance at the 5% level; "*" significance at the 10% level; [] is the confidence interval for the Bootstrap test
Conclusion and Enlightenment

The construction of network infrastructure has important theoretical and practical significance for promoting environmental pollution control. Based on the panel data of 285 cities in China from 2005 to 2019, this paper regards the Broadband China pilot policy as a quasi-natural experiment and uses methods such as DID models to clarify the basic logic of network infrastructure reducing environmental pollution. The results show that (1) the Broadband China pilot policy has significantly reduced environmental pollution, that is, the construction of network infrastructure is conducive to reducing environmental pollution. After the robustness tests such as parallel trend test, placebo test, and endogenous test, the research results are still valid. Through the heterogeneity test, it is found that promoting the construction of network infrastructure has an asymmetric impact on the improvement of environmental pollution. In non-resource-based cities, first and second tier cities and cities in the eastern region, the environmental pollution reduction effect of network infrastructure construction is more obvious. (2) The construction of network infrastructure has an inhibitory effect on local environmental pollution, and the emission reduction effect has a more sustainable long-term impact. However, the effect of network infrastructure construction on environmental pollution reduction of surrounding cities is not obvious. On the one hand, it may be the insufficient level of regional linkage. On the other hand, the pilot cities may plunder and occupy the key resources of network infrastructure construction in non-pilot cities, resulting in siphon effect. (3) The mediating effect and moderating effect models are used to analyze the internal mechanism of research topics. The study found that the construction of network infrastructure significantly promotes green technology innovation and thus achieves the effect of environmental pollution reduction, and green technology innovation has a partial mediating effect. Cities in regions with high degree of marketization and environmental regulation can strengthen the effect of network infrastructure construction on environmental pollution reduction. Marketization and environmental regulation have a positive moderating effect on the pollution reduction effect of network infrastructure construction.

The conclusions of this paper have the following policy implications: Actively implement the Digital China strategy to help the digital transformation of cities. Local governments should speed up the in-depth implementation of the “5G + industrial Internet” 512 project and consolidate the foundation for industrial digital development. Production departments should accelerate the deep integration of the Internet, big data, and green low-carbon industries, which will enhance the collaborative transformation and development of digital and green resources and environment. The development of the digital economy needs to adapt to local conditions, and each city needs to consider its own resource type characteristics, city scale, and geographical location characteristics to improve the efficiency of digital emission reduction. At the same time, the government should speed up the digital infrastructure construction and industrial digital transformation of resource-based cities and underdeveloped cities, which is conducive to improving the effectiveness of digital emission reduction. Build a digital economy

### Table 8 Analysis of moderating effect mechanism

| Variables       | (1)         | (2)         | (3)         | (4)         |
|-----------------|-------------|-------------|-------------|-------------|
| **DID**         | −0.00700*** | −0.00186    | −0.00711*** | −0.00531*** |
|                 | (0.00153)   | (0.00209)   | (0.00153)   | (0.00162)   |
| **Market**      | −0.00138**  | −0.00132**  | −0.00212*** | −0.00003    |
|                 | (0.00067)   | (0.00067)   | (0.00075)   | (0.0003)    |
| **DID × Market**| −0.00212*** | −0.00003    | −0.00002    | −0.00017*   |
|                 | (0.00075)   | (0.0003)    | (0.00003)   | (0.00009)   |
| **Reg**         |             | −0.00003    | −0.00002    | −0.00017*   |
|                 |             | (0.0003)    | (0.0003)    | (0.00009)   |
| **DID × Reg**   |             |             |             | −0.00017*   |
|                 |             |             |             | (0.00009)   |

Cons YES YES YES YES
Control variable YES YES YES YES
Urban fixed YES YES YES YES
Year fixed YES YES YES YES
Obs 4,275 4,275 4,275 4,275
R² 0.7798 0.7803 0.7796 0.7799

Numbers in parentheses denote the standard error of the respective coefficients
*** Significance at the 1% level; ** significance at the 5% level; *significance at the 10% level
industry collaboration mechanism between cities, promote exchanges in the digital field of cities, share digital resources, and give full play to the spatial spillover effect of digital emission reduction. The government should improve the system and mechanism of market-based allocation of factors and cultivate new industries, new formats, and new models of the digital economy. Local governments should promote the construction of a digital government, build a digital environmental monitoring system, and promote digital environmental governance.

However, there are still some deficiencies in this paper. Firstly, the empirical sample data needs to be expanded. This paper focuses on Chinese cities. The future research objects can go deep into the fields of enterprises or industries at the micro level, county-level cities, and international levels at the macro level, so as to improve the effectiveness of the study. Secondly, the measurement of digital economy remains to be explored. This study takes the construction of network infrastructure as the representative of digital economy. Since the connotation of digital economy is very broad, future research should explore a sound digital economy index system, look for digital economy pilot policies with exogenous shocks, and explore ways to solve the endogenous problems of the model. Finally, the internal mechanism remains to be enriched. This study discusses the influence channels of research topics from the aspects of technological innovation, marketization, and environmental regulation, but there may be other unrecognized mechanism variables. Future research can explore the impact of institutional variables such as human environment, industrial agglomeration, and fiscal decentralization, so as to enrich the theoretical framework of the mechanism.

Author contribution Weiyong Zou: conceptualization, methodology, writing–original draft, data collection and data curation, software, formal analysis, visualization; validation; funding acquisition. Minjie Pan: data curation, data collection and data curation, resources, supervision.

Funding This work was financially sponsored by National Office for Philosophy and Social Sciences Project (No. 19BJY079).

Data availability The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable. We strictly abide by ethical standards. No animal or human parts were used in this study.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Albort-Morant G, Leal-Rodriguez AL, De Marchi V (2018) Absorptive capacity and relationship learning mechanisms as complementary drivers of green innovation performance. J Knowl Manag 22(2):432–452. https://doi.org/10.1108/JKM-07-2017-0310
Beck T, Levine R, Levkov A (2010) Big bad banks? The winners and losers from bank deregulation in the United States. J Financ 65(5):1637–1667. https://doi.org/10.1111/j.1540-6261.2010.01589.x
Benzidia S, Makaoui N, Bentahar O (2021) The impact of big data analytics and artificial intelligence on green supply chain process integration and hospital environmental performance. Technol Forecast Soc Chang 165:120557. https://doi.org/10.1016/j.techfore.2020.120557
Chen C, Cai J, Wang C, Shi J, Chen R, Yang C, … Kan H (2018a) Estimation of personal PM2.5 and BC exposure by a modeling approach–results of a panel study in Shanghai, China. Environment International 118:194–202. https://doi.org/10.1016/j.envint.2018.05.050
Chen J, Wang L, Li Y (2020) Natural resources, urbanization and regional innovation capabilities. Resour Policy 66:101643. https://doi.org/10.1016/j.resourpol.2020.101643
Chen X, Lin B (2021) Towards carbon neutrality by implementing carbon emissions trading scheme: policy evaluation in China. Energy Policy 157:112510. https://doi.org/10.1016/j.enpol.2021.112510
Chen X, Li H, Qin Q, Peng Y (2021) Market-oriented reforms and China’s green economic development: an empirical study based on stochastic frontier analysis. Emerg Mark Financ Trade 57(4):949–971. https://doi.org/10.1080/1540496X.2019.1694885
Chen Z, Kahn ME, Liu Y, Wang Z (2018b) The consequences of spatially differentiated water pollution regulation in China. J Environ Econ Manag 88:468–485. https://doi.org/10.1016/j.jeem.2018.01.010
Dong F, Wang Y, Zheng L, Li J, Xie S (2020) Can industrial agglomeration promote pollution agglomeration? Evidence from China. J Clean Prod 246:118960. https://doi.org/10.1016/j.jclepro.2019.118960
El-Kassar AN, Singh SK (2019) Green innovation and organizational performance: the influence of big data and the moderating role of management commitment and HR practices. Technol Forecast Soc Chang 144:483–498. https://doi.org/10.1016/j.techfore.2017.12.016
Fang Z, Razzaq A, Mohsin M, Irfan M (2022) Spatial spillovers and threshold effects of internet development and entrepreneurship on green innovation efficiency in China. Technol Soc 68:101844. https://doi.org/10.1016/j.technsoc.2021.101844
Fromhold-Eisebith M, Marshall P, Peters R, Thrones P (2021) Torn between digitized future and context dependent past–How implementing ‘Industry 4.0’ production technologies could transform the German textile industry. Technol Forecast Soc Chang 166:120620. https://doi.org/10.1016/j.techfore.2021.120620
Grigorescu A, Pelinescu E, Ion AE, Dutcas MF (2021) Human capital in digital economy: an empirical analysis of central and eastern European countries from the European Union. Sustainability 13(4):2020. https://doi.org/10.3390/su13042020
Guo Z, Chen SS, Yao S, Mkuembo AC (2021) Does foreign direct investment affect SO2 emissions in the Yangtze River Delta? A spatial econometric analysis. Chin Geogr Sci 31(3):400–412. https://doi.org/10.1007/s11769-021-1197-5
Heckman, J. J. (1979). Sample selection bias as a specification error. Econometrica 153–161. https://doi.org/10.2307/1912352
Hou C, Chen H, Long R (2021) Coupling and coordination of China’s economy, ecological environment and health from a green
