Digital Economy Development and Haze Pollution: Empirical Evidence from Chinese Cities

shuai Che (✉ jgcheshuai@163.com)

China University of Petroleum Huadong <https://orcid.org/0000-0002-3225-326X>

jun Wang

China University of Petroleum Huadong

Research Article

Keywords: Digital economy, Haze pollution, Urban heterogeneity, National big data comprehensive experimental area, Mediation effect

Posted Date: January 25th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1184709/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

The development of the digital economy radiates to national ecological protection and resource utilisation, holding the key to haze governance. Firstly, this paper examines whether the development of digital economy in China has a restraining effect on haze pollution. Secondly, the article verifies the robustness of the research results through the instrumental variable method and quasi-natural experiment. Finally, the paper examines the potential transmission channels of haze pollution affected by the digital economy. Results show the digital economy negatively affects urban haze pollution in China. Specifically, in resource-based, non-resource-based, eastern and large cities, the growth of the digital economy has an obvious repression on haze pollution. The establishment of the "national big data comprehensive experimental area" is conducive to the control of haze pollution. Finally, the results reveal that the development of the digital economy significantly reduces haze pollution through economic growth, industrial structure and foreign direct investment effects.

1. Introduction

China has created a miracle of rapid growth for more than 40 years since the reform and opening up. However, the extensive economic development model guided by GDP has led to difficulties of economic transformation, serious ecological damage and environmental quality decline (Wu et al., 2021). Especially as China's economy and urbanisation develop rapidly, haze weather frequently occurs in many places, which seriously affects the sustainable development of the economy and ecological environment and people's health. Protecting the regional environment, promoting the quality of economic growth and promoting the modernisation of governance capacity demand alleviating and effectively improving the urban environment problem mainly with haze (Liu et al., 2020a). Particularly in developing countries, governments like China, must continue to work hard to promote economic development and improve the quality of life. Therefore, achieving a win-win outcome of economic growth between climate change mitigation is widespread concern of academia and policymakers. Studying the improvement factors of haze pollution offers the necessary decision reference for addressing the dilemma of economic development and environmental pollution (Gan et al., 2021a).

2. Literature Review

The academic circles have conducted numerous research papers on haze pollution. These papers are generally mainly divided into three categories: the features of haze pollution (Xie et al., 2021), the economic and social impact and the influencing factors of haze pollution (Dong et al., 2019; Guo et al., 2020). The first category includes the chemical characteristics, temporal and spatial diffusion and migration characteristics of haze pollution. Haze pollution exhibits the typical characteristics of concentration in winter (Wang et al., 2020), big cities (Wang et al., 2021) and high economic density areas (Zhou et al., 2021). The second category focuses on the impact of haze pollution on residents' behaviour. Haze pollution can improve the willingness of residents to buy cleaning equipment, and egoism and altruism are important driving factors (Zhao et al., 2019). In addition, haze pollution will lead to long commuting time of residents and low life satisfaction of bus passengers (Wang et al., 2021). Household energy consumption will also be positively affected by haze pollution. Residents reduce outdoor activities during the haze period and then increase the consumption of household water and electricity (Agarwal et al., 2020).

The third type of investigation is rather rich, and academic discussion has focused on the influencing considerations of haze pollution. Local government competition (Zhang et al., 2020), public participation (Li et al., 2021; Qu et al., 2021), environmental regulation (Zhou et al., 2021), economic development (Feng and Yuan, 2021a; Gan et al., 2020), environmental information disclosure (Feng et al., 2021a), industrial agglomeration and structure (Li et al., 2021; Shi et al., 2020) and trade openness are often considered to be closely related to haze pollution changes (Xu et al., 2020). Notably, the development of digital technology is triggering the fourth industrial revolution in the world (Gnangnon, 2020). The development of digital technology, which is represented by cloud computing and the IoT, can improve the productivity and sustainability of the energy system, thus affecting the environment (Imbulana Arachchi and Managi, 2021).

Digital economy indicates an array of economic activities with the use of digital knowledge and information as an important production considerations, modern information network as the key carrier, and the effective use of information and communication technology as a key driver to improve efficiency and optimize the economic structure (Calvano and Polo, 2021; Sareen and Haarstad, 2021). According to the white paper on the development of Chinese digital economy issued by China Information and Communication Research Institute, Chinese digital economy scale will amount to 39.2 trillion yuan in 2020, making up 38.6% of GDP, thereby effectively supporting epidemic prevention and socio-economic developments. The growth of the digital economy has become a new engine of economic growth and a new path of industrial upgrading. Data can be employed directly or indirectly for guiding resources and accelerating the integration with all walks of life (Olena-Ivanna et al., 2021). The continuous growth of the digital economy has produced many digital low-carbon, energy and environmental protection technologies. The application of these technologies helps reduce the output and emissions of various kinds of wastes in daily production activities, thus minimising haze pollution (Yang et al., 2021). The growth of the digital economy can also encourage manufacturers to take the initiative to adopt electronic clean technology, high-end energy storage and pollution treatment remote sensing

machines, innovate the traditional mode of product and service creation and value profit model, shape a new mode of resource-saving and green economic development and finally improve the living and development environment of Chinese people (Yang et al., 2021).

However, the current academic investigation on the effect of the digital economy mainly focuses on the industrial structure and energy efficiency (Ren et al., 2021). A significant negative correlation exists between Internet technology and energy consumption intensity. Internet development can accelerate energy reduction and upgrade industrial structure through economic growth, R & D investment and other factors. The development of digital technology has become a key driving force for the intelligent development of environmental governance in China, which can significantly improve its green total factor energy efficiency (Wu et al., 2021). Overall, the empirical evidence on the role of the digital economy in haze pollution in China is still quite lacking. In particular, three questions have not been answered in previous literature. Firstly, can the growth of the digital economy effectively restrain the haze pollution in Chinese cities? Rather than the growth of Chinese digital economy, existing investigations majorly focus on how technological progress affects haze pollution (Yi et al., 2020). Secondly, is significant heterogeneity observed in how digital economy development affects haze pollution in different cities in China? Many types of cities are found in China, and the economic characteristics of different types of cities are quite different, which leads to the various link between economic growth and haze pollution (Feng and Yuan, 2021b). Finally, what are the transmission channels of haze pollution affected by the growth of the digital economy? The existing investigation focuses on how the digital economy affects industrial change, economic growth and resource consumption (Ben Youssef et al., 2021; Pouri, 2021) but did not build a link between the growth of the digital economy and the environment field.

Therefore, the current study investigates how digital economy development affects haze pollution in China and provides some reference for promoting air pollution control in developing countries. This paper mainly answers the unsolved problems from the following three aspects. Firstly, this paper provides new evidence of how digital economy growth affects urban haze pollution. Secondly, in terms of urban heterogeneity, this paper gives priority to the inhibitory effect consistency of digital economy development on urban haze pollution. Finally, the potential transmission channels of how digital economy development affects haze pollution are determined, and the countermeasures and suggestions to promote urban haze governance through the growth of the digital economy are introduced. The rest of this article is arranged below. The literature review was introduced by Section 2. The method and data were presented by Section 3 comprehensively. Benchmark empirical was reported and discussed by Section 4. Further analysis of baseline regression results was reported in Section 5. The conclusion and corresponding policy recommendations were provided by Section 6. To sum up, the research flow chart of this paper is as follows:

3. Approaches And Data

3.1. Econometric model

Firstly, the following benchmark econometric models are considered for studying how digital economy growth affects haze pollution.

$$Hp_{it} = \alpha + \beta Dgc_{it} + \varphi X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

where Hp_{it} represents the haze pollution of city i in t period; Dgc_{it} represents the growth level of digital economy of city i in t period; X_{it} indicates a set of control variables, encompassing economic growth, industrial structure, innovation and entrepreneurship level, government intervention, foreign direct investment, labour force, science and education support; α represents the intercept term; β represents the core estimation parameter; μ_i represents the individual fixed effect of city i , which does not change with time; δ_t represents the time fixed effect; ε_{it} represents the stochastic disturbance term.

The two-stage least square approach (2SLS) is employed for estimating how digital economy development affects haze pollution for alleviating the potential endogenous problems. The regression equations below are employed for parameter estimates:

$$Dgc_{it} = \alpha' + \lambda' Iv_{it} + \varphi' X_{it} + \mu_i' + \delta_t' + \varepsilon_{it}' \quad (2)$$

$$Hp_{it} = \alpha'' + \beta'' dgc_{it}' + \varphi'' X_{it} + \mu_i'' + \delta_t'' + \varepsilon_{it}'' \quad (3)$$

The first- and second-stage regressions are shown in Equations (2) and (3), separately. Iv_{it} is the instrumental variable of the urban annual digital economy, including the lag term of the digital economy and the average value of the provincial digital economy. dgc' is the fitting value obtained from the first-stage regression. Combining Equations (2) and (3), how the digital economy affects urban haze pollution can be further determined. The expression of other variables is the same as Equation (1).

The mediating effect is how explanatory variables directly affect explained variables (Mackinnon et al., 2000). The standard method of mediation effect analyses is divided into the following: (i) a set of steps to evaluate the statistical significance of slope estimation in regression, or (ii) product of slope coefficient along causal path and significance test of the product (Kosuke et al., 2010). The main practical limitation of the existing approaches is that it's unable to conduct sensitivity analysis on the sequential negligible hypothesis, an important component of

causal analyses. The ‘medeff’ command of Hicks provides an approach of analyzing sensitivity, which is an important identification hypothesis needed to explain the results of mediating effect (Hicks and Tingley, 2011). Therefore, this command is used to analyse the causal mediating impact of the digital economy on haze pollution based on the following model:

$$M_{it} = \theta_0 + \theta_1 Dgc_{it} + \theta_2 Y_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (4)$$

$$Hp_{it} = \theta'_0 + \theta'_1 Dgc_{it} + \theta'_2 M_{it} + \theta'_3 Y_{it} + \mu'_i + \nu'_t + \varepsilon'_{it} \quad (5)$$

where M_{it} is the mediation variable. In addition to intermediary variables, the variable Y_{it} is a portfolio of control variables. variables μ_i and μ'_i represent the fixed impact of the city of formulas (4) and (5), respectively. ν_t and ν'_t separately indicate the time fixed impact of formulas (4) and (5). ε_{it} and ε'_{it} represent the random disturbance term of Equations (4) and (5), respectively.

3.2. Explanation of the variables

The investigation collected the balanced panel data from China’s 275 cities from 2011 to 2018. The variable structure is below.

3.2.1. Dependent variable

The dependent variable of the investigation is haze pollution (Hp), whilst PM10 and PM2.5 are indexes for measuring haze pollution. PM2.5 is selected as the determination index of haze pollution in the article due to the following two causes. For starters, the World Health Organisation gives considerable priority to environmental pollution, and its report on air pollution generally takes PM2.5 as an important index. Second, the annual mean concentration of PM2.5 acquired by optical remote sensing satellite is the most reliable and sustainable urban air pollution data in China. Therefore, the explained variable of this study is expressed by PM2.5, which comes from the satellite monitoring data released by the Socio-economic Data and Applications Center of Columbia University, and can objectively and fairly represent the environmental pollution situation of the city.

3.2.2. Independent variable

An important independent variable of the investigation is digital economy (Dgc), and the current research mostly uses the provincial-level digital economy development index for measuring the digital economy growth level. This study comprehensively evaluates the digital economy index of city-level from two aspects of Internet development (Dgc2) and digital inclusive finance (Dgc2). The indicators of the Internet development level are constructed from the following four aspects: internet-related industry output (total telecom business per capita), internet-related industry employees (the proportion of computer service and software industry employees in urban unit employees), internet-related industry employees (the proportion of computer service and software industry employees in urban unit employees) and internet penetration (number of per 100 people broadband Internet users) and mobile phone penetration (quantity of per 100 people mobile phone users). Digital inclusive finance is represented by the Digital finance research center of Peking University and Ant Financial Services Group, which mainly includes coverage, use depth and digital level. Four indicators of Internet development level and indicators of digital inclusive finance are respectively standardised in this study through principal component analyses and dimension reduction for obtaining the growth level of China’s urban digital economy.

3.2.3. Control variables

(1) Economic development (Pgdp). Some investigations have suggested economic development is a key determinant of haze pollution (Feng and Yuan, 2021c). The acceleration of economic growth will aggravate the degree of haze pollution (Liu et al., 2020b). However, the relationship between them is significantly different in various regions, and the green transformation of China’s economy will reduce the degree of haze pollution (Gan et al., 2021b). The study employs per capita GDP for measuring economic growth.

(2) Industrial structure (Isu). Upgrading the industrial structure measures the deepening ‘service’ process of economic structure and reflects the transformation of industrial structure from low to high level. This conversion can enhance energy efficiency and lessen environmental pollution (Yu et al., 2017). The secondary industry is generally more polluted than the primary and tertiary industries (Chen et al., 2019). Therefore, the industrial structure is characterized by the ratio of the added value of the tertiary industry in GDP and that of the added value of the secondary industry in GDP.

(3) Innovation and Entrepreneurship (Riei). The digital economy growth will activate the innovation and entrepreneurship atmosphere of the society, thus producing many high-tech industries, the key to achieving sustainable economic growth and improving environmental quality (Wang et al., 2020). The investigation employs per capita regional innovation and entrepreneurship index to measure innovation and entrepreneurship, respectively. The index is calculated by the following seven sub-dimensions: new enterprise entry, number of foreign investment, number of vcpe investment, number of invention patent authorisation, number of utility model patent disclosure, number of

appearance patent disclosure and number of trademark authorisation. The index can also comprehensively investigate the actual output of innovation and entrepreneurship of enterprises in the city, thus forming an objective and realistic evaluation of innovation and entrepreneurship.

(4) Government intervention (Gov). Appropriate government intervention can play a positive role in environmental protection (Chen et al., 2018). However, a high degree of government intervention may result in rent-seeking and corruption, resulting in waste of resources and environmental pollution (Shao and Yang, 2014). The investigation employs public expenditure ratio in GDP as an indicator of government intervention.

(5) Fdi. The environmental effects of FDI present two views. The first is the ‘polluted port hypothesis’, where FDI increases the environmental pollution of host countries (Cole et al., 2010). The second view is that high-quality FDI contributes to technology spillover effect, thus reducing environmental pollution (Xu et al., 2021a). The investigation uses the amount of FDI to express variables.

(6) Labour force (Emp). On one hand, production and living activities are frequent in labor-intensive areas, which greatly affects environmental pollution (Li et al., 2019). Looking from another aspect, areas with high labour reserves may have a high human capital level, which helps reduce environmental pollution (Zhang et al., 2021). The number of employees in urban units at the end of the period is used in this study to represent the labour force.

(7) Social consumption (Soc). On the one hand, traditional social consumption will aggravate the resource and environmental crises (Noda and Kano, 2021). On the other hand, ecological consumption is constrained by the ecosystem, which helps promote clean production, thus lessening haze pollution (Song et al., 2019). This study uses the ratio of retail sales of social product consumption to GDP to represent social consumption.

(8) Science and education support (Tec). In the era of the digital economy, science and education expenditures are important reserves to improve environmental pollution. The increase of science and education support can promote the improvement of science and technology levels, thus reducing technology haze (Feng et al., 2021b). Science and education support are respectively expressed in this study by science and education expenditures of each city.

3.2.4. Data sources

The original data for calculating the digital economy index were obtained in 2011. Thus, from 2011 to 2018, the study focused on 275 cities above the prefecture level in China. The data employed in this study were all from the China Urban Statistical Yearbook, and the missing data were supplemented by the annual statistical reports of some prefecture-level cities, guotai’an database and provincial statistical yearbooks. Therefore, the descriptive statistical results of the major research variables are exhibited (Table 1). The results reveal considerable differences in economic growth quality amongst different cities, aligning with the basic national conditions of China’s unbalanced development.

Table 1.

Summary statistics of variables.

Variable	Obs.	Mean	Std. Dev	Min	Max
Hp	2200	3.628	0.480	1.419	4.702
Dgc	2200	5.556	0.606	2.817	8.760
Pgdp	2200	1.706	0.574	-0.883	6.465
Isu	2200	0.908	0.443	0.114	4.244
Riei	2200	3.681	0.872	-1.073	4.605
Gov	2200	0.249	0.278	0.044	5.500
Fdi	2200	9.985	1.815	2.708	14.150
Emp	2200	3.619	0.779	1.739	6.419
Soc	2200	0.474	0.392	0.000	5.671
Tec	2200	1.085	1.273	-2.586	6.319

4. Outcomes And Discussion

4.1. Baseline estimation outcomes

Firstly, how digital economy growth affects urban haze pollution in China is investigated from the overall sample level. The benchmark regression results using the two-way fixed-effect model are exhibited (Table 2). Columns (1) to (9) are the regression outcomes of adding control variables during the sample period. The coefficient of the core explanatory variable digital economic index is obviously negative at the level of 1% despite the presence or absence of the control variable. The following conclusions can be drawn from column (9) (Table 2). The digital economy growth can inhibit haze pollution. However, if the relevant variables remain uncontrolled, then the haze reduction effect of digital economy will be underestimated to varying degrees. The internal reason for this phenomenon is as follows. On the one hand, the core production factor of the digital economy is digital knowledge and information, and digital technology can enhance the efficiency of energy and resources and promote the development and utilisation of renewable energy (Ren et al., 2021). Looking from another aspect, digital economy promotes the production, sales and consumption efficiency of products and services in the entire society, reduce the demand for energy and raw materials through the dematerialisation of human activities and exchanges and then reduce environmental pollution (Andersen et al., 2021) (Yang et al., 2021).

Economic growth, industrial structure and government intervention can effectively reduce haze pollution considering the regression results of control variables. With the growth notion of 'lucid waters and lush mountains are invaluable assets', the green attribute of per capita GDP is gradually increasing considering economic growth (Lin and Zhu, 2020). Considering industrial structure, the rising ratio of the tertiary industry optimises the original pollution-intensive and energy-intensive industrial structure, thus achieving a significant haze reduction effect (Hao et al., 2020). The emphasis of the Chinese government on environmental protection and investment in recent years has effectively controlled haze pollution considering government intervention (Zhou et al., 2019). In addition, the current level of innovation and entrepreneurship in China does not have a substantial repression on haze pollution, which proves the atmosphere of innovation and entrepreneurship in China must still be improved. Foreign direct investment, labour force, social consumption, science and education support are not conducive to the haze pollution control of China. Moreover, still as the largest developing country, China plays the role of 'pollution haven' in the process of international trade considering foreign investment (Xu et al., 2021b). Considering labour force, the labour market of China is in a state of 'quantity but no quality'. The backward labour quality hinders the economic transformation and upgrading. Similarly, the role of social consumption in promoting haze precisely reflects that the green transformation of consumption remains to be a key problem for the government to solve. Science and education support aggravates the haze pollution, which proves that the technology derived from science and education support in China is still production-oriented, and high technology has not been effectively applied and implemented.

Table 2.

Baseline regression outcomes.

Dependent variable: Hp									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dgc	-0.1290***	-0.1904***	-0.1168***	-0.1446***	-0.1465***	-0.1938***	-0.2309***	-0.2306***	-0.2280***
	(-8.28)	(-9.51)	(-6.07)	(-6.96)	(-6.90)	(-9.42)	(-10.67)	(-10.91)	(-10.89)
Pgdp		0.1241***	0.0526**	0.0184	-0.0172	-0.1091***	-0.1160***	-0.1051***	-0.1166***
		(5.56)	(2.42)	(0.80)	(-0.70)	(-4.22)	(-4.49)	(-4.16)	(-4.58)
Isu			-0.2672***	-0.2661***	-0.2458***	-0.2521***	-0.2615***	-0.2593***	-0.2540***
			(-11.09)	(-11.04)	(-10.04)	(-10.70)	(-10.59)	(-10.47)	(-10.34)
Riei				0.0555***	0.0470***	0.0010	0.0129	0.0119	-0.0018
				(4.79)	(4.05)	(0.10)	(1.26)	(1.19)	(-0.18)
Gov					-0.3044***	-0.2410***	-0.2196***	-0.3922***	-0.4268***
					(-4.62)	(-4.53)	(-4.33)	(-4.80)	(-4.73)
Fdi						0.1169***	0.0725***	0.0716***	0.0600***
						(19.34)	(9.26)	(9.30)	(7.39)
Emp							0.1567***	0.1411***	0.0865***
							(10.52)	(9.45)	(4.85)
Soc								0.2039***	0.2277***
								(5.23)	(5.52)
Tec									0.0625***
									(5.35)
constant	4.5624***	4.6934***	4.6172***	4.6058***	4.7254***	4.1077***	4.1526***	4.1543***	4.4593***
	(50.34)	(48.56)	(51.50)	(51.20)	(50.09)	(44.05)	(44.20)	(44.47)	(39.17)
Time fixed impact	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City fixed impact	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R ²	0.1314	0.1455	0.1911	0.1968	0.2145	0.3228	0.3516	0.3601	0.3672
N	2200	2200	2200	2200	2200	2200	2200	2200	2200
F	36.2535	35.2886	44.7061	45.1250	41.9011	78.1208	83.9995	80.2923	78.3256
Notes: t statistics in parentheses; ***, ** and * indicate statistic significance at the 1%, 5% and 10% levels, separately.									

4.2. Heterogeneity analysis

The impact of digital economy development on haze pollution in different cities is further studied considering the heterogeneity of social and economic environment in different cities. Table 3 exhibits the outcomes of heterogeneity analyses. Firstly, according to the *Sustainable Development Plan of China's Resource-Based Cities (2013–2020)*, 275 cities are classified into 111 resource-based and 164 non-resource-based cities. Columns (1) and (2) (Table 3) show the test outcomes of resource-based and non-resource-based cities, respectively. These results reveal that the Dgc coefficient is significant at the level of 1% in resource- and non-resource-based cities. That is to say, the negative impact of digital economy development on haze pollution is obvious in resource- and non-resource-based cities. The coefficient of non-resource-based cities is -0.2321, slightly exceeding that of resource-based cities (-0.2120). This finding may result from the strong dependence of resource-based cities on oil, coal, metals, and other fossil energy during the long-term economic development process, and big data, cloud computing and other digital technologies, are difficult to break through the conventional resource- and energy-intensive economy. On the contrary, the resistance to the popularisation of digital technology in resource-based cities exceeds that in non-resource-based cities. Thus, the haze reduction effect is improved.

Secondly, 275 cities are classified into 56 western, 111 eastern, and 108 central cities. Columns (3), (4) and (5) (Table 3) separately show the test outcomes of eastern, central and western cities. The digital economy growth in eastern, central and western cities generally negatively affects smog pollution. Specifically, the economic growth level of eastern cities exceeds that of western and central cities, and the technology spillover impact of the digital economy is observed. Therefore, the smog reduction impact of digital technology is more prominent than that of western and central cities. The infrastructure of western cities is weaker, and the digital economy started late. Thus, the repression of digital economy development on smog pollution is weaker than that of eastern and central cities.

Finally, according to the notice of the State Council on *adjusting the classification standard of urban scale* issued in 2014, cities and towns are classified into five categories and seven levels on basis of the demographic standard of urban residents to further verify the above conclusions: small towns, first-class small towns, second-class small towns, medium-sized cities, big cities, first-class cities, second-class cities, megacities. To ensure the comparability and characteristics of the samples, the cities directly under the central government are canceled and the five types of cities are divided into four types: small cities (less than 500,000), medium cities (over 500,000 but below 1 million), big cities (over 1 million but below 5 million) and megacities (over 5 million and less than 10 million). The results of the empirical analysis of small, medium, big and mega cities are represented in Columns (6) to (9) in Table 3. Specifically, the effect of the digital economy on haze reduction will become increasingly significant with the size of cities. The internal logic is that the development of the digital economy needs some initial factors, such as technology, capital and talents. Small cities can use the digital economy to reduce smog pollution by improving urban infrastructure and building Internet platforms. Therefore, medium and large cities are the important potential areas for the digital economy growth in the future for improving the environment.

Table 3.
Heterogeneity analyses outcomes.

Dependent variable: Hp									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dgc	-0.2120*** (-4.30)	-0.2321*** (-9.59)	-0.3008*** (-12.21)	-0.1509*** (-3.20)	-0.1114** (-2.41)	0.0304 (0.37)	-0.1481*** (-3.61)	-0.2751*** (-9.95)	-0.3322*** (-5.36)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed impact	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City fixed impact	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R ²	0.3900	0.4025	0.3842	0.4141	0.3963	0.1822	0.3783	0.4180	0.6733
N	888	1312	888	864	448	280	688	1128	104
F	34.7035	56.9960	51.0372	35.2750	16.3093	3.5549	33.2179	52.4969	12.5851

5. Further Analysis

5.1. Haze reduction effect of Internet development and Inclusive Finance

An array of robustness tests are conducted for further verifying the reliability of the conclusion. Firstly, Equation (1) is re-estimated by replacing the explanatory variables. Columns (1) and (3) (Table 4) are the test outcomes of using internet development and digital inclusive finance as the explanatory variables, respectively, under the uncontrolled time and regional effects. Columns (2) and (4) are the estimated results using internet development and digital inclusive finance as explanatory variables, respectively, under the control of time and regional effects. The test results all passed the 1% significance level test, proving the digital economy sub-index can still reduce haze pollution.

Secondly, Equation (1) is re-estimated after the sample of provincial capital cities is removed for avoiding the resulting bias resulting from the particularity of provincial capital cities. China's provincial capitals are directly managed by local governments, with large construction areas and permanent residents, holding the key to national economic and political life. Therefore, how the digital economy affects haze pollution in provincial capital cities may be not the same as that in other cities. The outcomes in column (5) (Table 4) exhibit the Dgc coefficient is estimated to be -0.2295 at 1% significance level. The finding shows that the digital economy reduces the haze pollution of prefecture-level cities but excludes the result deviation caused by the particularity of cities. Finally, all variables are ranked by 1% to re-estimate Equation (1) to eliminate

the influence of extreme value. The outcomes in column (6) (Table 4) exhibit that the Dgc coefficient is estimated to be -0.2430 at 1% significance level, also aligning with the benchmark estimation. Overall, these robust outcomes show the credibility of the main conclusions.

Table 4.

Robustness check outcomes.

Dependent variable: Hp						
	(1)	(2)	(3)	(4)	(5)	(6)
Dgc					-0.2295^{***}	-0.2430^{***}
					(-10.57)	(-11.51)
Dgc2	-0.2006^{***}	-0.2001^{***}				
	(-10.62)	(-10.56)				
Dgc3			-0.1758^{***}	-0.3537^{***}		
			(-7.51)	(-3.55)		
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed impact	No	Yes	No	Yes	Yes	Yes
City fixed impact	No	Yes	No	Yes	Yes	Yes
R ²	0.3415	0.3669	0.3238	0.3330	0.3557	0.3891
N	2200	2200	2200	2200	2200	2200
F	120.5545	77.3233	116.8203	65.1797	65.1816	87.9147

5.2. Instrumental variable regression outcomes

A main challenge of the investigation is to determine the causal impact of the digital economy on smoke pollution, which has reverse causality and missing variables. The auxiliary variable method is used to alleviate the potential endogenous problems and solve this problem. Firstly, the article chooses the first lag term of the digital economy for constructing the first instrumental variable. Secondly, the average value of the digital economy in each province is calculated, and the value is introduced into the regression model as the second instrumental variable. Columns (1) and (3) (Table 5) report the estimated outcomes of the first-stage regression on basis of formula (2). As expected, instrumental variables above positively affect the digital economy at a significant level of 1%. In addition, when the F statistic of the first-stage regression exceeds 10, the instrumental variable is effective. The F statistical data of columns (1) and (3) in Table 5 are larger than 10, proving the rationality of tool variable choice. How the digital economy affects smog pollution based on the first-stage regression results can be further identified through the second-stage regression. Columns (2) and (4) in Table 5 show the estimated outcomes of 2SLS second-stage regression on basis of Equation (3). The outcomes indicate the digital economy can effectively reduce smog pollution and identify the robustness of the benchmark estimation results. Table 6 exhibits the verification testing outcomes of the tool variables. These outcomes reveal insufficient variable identification and weak tool variables can be eliminated. Therefore, the 2SLS result is credible.

Table 5.

Instrumental variable regression results.

	Dgc	Hp	Dgc	Hp
	(1)	(2)	(3)	(4)
Dgc		-0.2761^{***}		-0.3977^{***}
		(-4.59)		(-11.66)
L.Dgc	0.3422^{***}			
	(5.71)			
ADgc			1.0223^{***}	
			(18.66)	
Control variables	Yes	Yes	Yes	Yes
Time fixed impact	Yes	Yes	Yes	Yes
City fixed impact	Yes	Yes	Yes	Yes
N	1925	1925	2200	2200
F	32.61	94.6630	348.25	151.7583

Table 6.

Verification testing outcomes of tool variables.

Tool variable	Under-identification test	Weak tool variable test	
	Kleibergen-Paap rk LM statistic	Cragg-Donald Wald F statistic	Stock-Yogo deviation threshold
L.Dgc	43.24	219.14	16.38 (10%)
ADgc	153.85	608.26	16.38 (10%)

5.3. Further inspection based on national big data comprehensive test area

The previous paper has made robust research conclusions by changing explanatory variables, eliminating special cities and instrumental variables. In this section, based on the quasi natural experiment of the national big data comprehensive test area, this paper provides a new perspective for evaluating the impact of digital economy development on haze pollution on the basis of overcoming potential endogenous problems. From February to October 2016, the national development and Reform Commission, the Ministry of industry and information technology and the central network information office sent letters to approve the eight national big data comprehensive test areas, including the first big data comprehensive test area (Guizhou), two cross regional comprehensive test areas (Beijing, Tianjin, Hebei and the Pearl River Delta), and four regional demonstration comprehensive test areas (Shanghai, Henan, Chongqing Shenyang) and a comprehensive test area for the overall development of big data infrastructure (Inner Mongolia).

Table 7 reports the impact of the establishment of national big data comprehensive test area on Urban Haze pollution. Based on the test of ordinary DID model, Column (2) reports the estimation results of propensity score matching double difference method (PSM-DID) to enhance the credibility of the assessment. It can be seen that the estimation results of the two methods show that the establishment of national big data comprehensive test area can effectively reduce urban haze pollution, which is consistent with the research conclusions of this paper. Furthermore, China's vast territory leads to an objective development gap between cities, and the urban level is also an important influencing factor of haze pollution. Therefore, in order to further accurately estimate the impact of digital economy development level on haze pollution, the city level is added as the reference group for triple difference (DDD) test, and the test results are shown in Column (3). DDD test results show that after controlling the difference of urban level, the policy effect is more accurate, and the development of digital economy can still significantly reduce haze pollution. The rationality of the test results of the double difference method is based on a series of assumptions, one of which is to meet the parallel trend hypothesis. Therefore, this study uses the event analysis method to study the impact of the establishment of national big data comprehensive experimental area on Urban Haze pollution. It can be seen from the estimation results in the Column (4) that the estimation coefficients are not significant before the implementation of the policy, but pass the significance level test after the implementation of the policy. The above research results effectively support the research conclusions of this paper from the new perspective of policy evaluation.

Table 7.

Analysis results of national big data comprehensive test area.

	(1)	(2)	(3)	(4)
	DID	PSM-DID	DDD	Parallel trend test
did	-0.1069**	-0.0982**		
	(-2.28)	(-2.10)		
ddd			-0.0310**	
			(-2.15)	
Pre_2				-0.0536
				(-1.21)
Pre_1				-0.0568
				(-0.71)
Current				-0.0237**
				(-2.49)
Post_1				-0.0433***
				(-2.76)
Post_2				-0.2504***
				(-2.99)
Control variables	Yes	Yes	Yes	Yes
Time fixed impact	Yes	Yes	Yes	Yes
City fixed impact	Yes	Yes	Yes	Yes
R ²	0.2349	0.2210	0.2351	0.2378
N	2168	2117	2168	2168
F	35.4492	32.7914	35.4262	29.7033

5.4. Mediation effect analysis

The transmission channel of how digital economy development affects smog pollution is further determined in this section. Tables 7 and 8 offer the estimated outcomes of mean causal mediating impact (ACME), mean direct impact (ADE) and total impact (TOTAL) and the 95% confidence interval. If the 95% confidence interval doesn't include 0, how the digital economy affects haze pollution passes the significance test of mediating effect; otherwise, it is insignificant. Columns (1) to (4) (Table 8) are generally test outcomes of the mediating effects of economic growth, industrial structure, innovation and entrepreneurship and government intervention. Columns (1) to (4) (Table 9) are test outcomes of the mediating effect of foreign investment, labour force, social consumption and science and education support. Specifically, the result in Column (1) (Table 8) exhibits that the overall impact of the digital economy on haze pollution is statistically different from zero when economic growth is taken as the intermediary variable. However, the average causal mediating effect of economic growth led to the standard deviation of haze pollution reduction by 0.0328, which was statistically significant (95% confidence interval), accounting for 12.6311% of the total effect and resulting in a higher total effect than the average direct effect. This finding shows that the economic transformation and upgrading of China has made some progress, the green attribute contained in per capita GDP is increasing and the digital economy has restrained haze pollution in the cause of promoting economic growth. The result in Column (2) shows that the average causal mediating effect of industrial structure leads to the standard deviation of haze pollution reduction by 0.0673 (statistically significant) when the industrial structure is used as the mediating variable, accounting for 22.8778% of the total effect. Hence, the digital economy growth can not only transform traditional industries with technology and knowledge but also introduce new industries to reduce the pollution attribute of industries.

Column (3) shows no statistical difference between the average causal mediating effect of innovation and entrepreneurship and zero despite its haze pollution reduction by 0.0101 standard deviation in quantity, resulting in larger total effects than ADE. The results also demonstrate that evidence of haze pollution restriction through innovation and entrepreneurship effect by the digital economy is unavailable. The digital economy of China is rapidly developing, but shortcomings in promoting the development of innovation and entrepreneurship remain. A few core technologies are available, and the application of industrialisation is insufficient. These reasons lead to the minimal effect of haze reduction. Column (4) shows that although government intervention reduces haze pollution by 0.0024 standard deviation in quantity, evidence regarding

digital economy restriction of haze pollution through government intervention effect is unavailable. The government intervention can lessen haze pollution, but the rapid growth of the digital economy does not affect the investment of government expenditure in environmental governance. In Column (1) of Table 9, the average causal mediating effect of FDI leads to the decreasing standard deviation of haze pollution by 0.0101, which is statistically significant, accounting for 4.2539% of the total effect. Thus, the total effect is higher than the average direct effect. The results show that digital economy significantly reduces haze pollution through FDI. The rise of digital technology can absorb high-quality FDI inflows and improve the environmental quality of China.

In Column (2) (Table 9), the standard deviation of smoke pollution caused by the average causal mediating effect of labour force change increased by 0.0175, which was statistically significant, accounting for -8.3578% of the total impact. Thus, the total impact is below the average direct effect. The digital economy growth has produced the labour substitution effect. The unemployment of a considerable amount of labour force leads to serious urban pollution. Column (3) shows no statistical difference between the average causal mediating effect of social consumption and zero despite its haze pollution reduction by 0.0034 standard deviation in quantity, resulting in a larger total effect than ADE. However, evidence regarding the suppression of haze pollution through social consumption effect due to the digital economy growth is unavailable, and the digital economy doesn't promote green consumption to improve environmental pollution. Similarly, Column (4) reveals no statistical difference between the average causal mediating effect of science and education support and zero, and evidence regarding suppression of haze pollution through science and education support effect due to digital economy is lacking. The results show the rapid digital economy growth cannot effectively reverse the haze reduction effect of science and education support. The Chinese government must reasonably guide the investment of science and education funds to accelerate the transformation of scientific and technological achievements.

Table 8.
Mediation effect analysis results.

	Pgdp	Isu	Riei	Gov
	(1)	(2)	(3)	(4)
ACME	-0.0328 (-0.0460, -0.0217)	-0.0673 (-0.0820, -0.0543)	-0.0101 (-0.0125, 0.0108)	-0.0024 (-0.0093, 0.0045)
ADE	-0.2265 (-0.2632, -0.1891)	-0.2265 (-0.2632, -0.1891)	-0.2265 (-0.2632, -0.1891)	-0.2265 (-0.2632, -0.1891)
TOTAL	-0.2593 (-0.2955, -0.2245)	-0.2937 (-0.3312, -0.2586)	-0.2271 (-0.2626, -0.1918)	-0.2288 (-0.2650, -0.1914)
Percentage mediated (%)	12.6311	22.8778	0.2646	1.0319
Control variables	Yes	Yes	Yes	Yes
Time fixed impact	Yes	Yes	Yes	Yes
City fixed impact	Yes	Yes	Yes	Yes
N	2200	2200	2200	2200

Table 9.
Mediation effect analysis results.

	Fdi	Emp	Soc	Tec
	(1)	(2)	(3)	(4)
ACME	-0.0101 (-0.0178, -0.0035)	0.0175 (0.0099, 0.0265)	-0.0034 (-0.0094, 0.0018)	-0.0013 (-0.0058, 0.0027)
ADE	-0.2265 (-0.2632, -0.1891)	-0.2265 (-0.2632, -0.1891)	-0.2265 (-0.2632, -0.1891)	-0.2265 (-0.2632, -0.1891)
TOTAL	-0.2365 (-0.2730, -0.1993)	-0.2090 (-0.2457, -0.1717)	-0.2298 (-0.2667, -0.1924)	-0.2277 (-0.2647, -0.1905)
Percentage mediated (%)	4.2539	-8.3578	1.4707	0.5557
Control variables	Yes	Yes	Yes	Yes
Time fixed impact	Yes	Yes	Yes	Yes
City fixed impact	Yes	Yes	Yes	Yes
N	2200	2200	2200	2200

6. Conclusion And Policy Implications

Based on theoretical analyses, the study employs the panel data from China's 275 cities from 2011 to 2018 for providing new evidence for how the digital economy affects urban haze pollution. Firstly, additional control variables proved that the digital economy can suppress haze pollution. Secondly, this paper analyses the heterogeneous haze reduction effect of digital economy growth in different cities considering social and economic differences of cities. Thirdly, the conclusion of this investigation is further strengthened by changing digital economy sub-indicators, eliminating the provincial capital cities and reducing the tail. Fourthly, aiming at the endogenous problem in the model, the instrumental variable method and the quasi natural experiment using the national big data comprehensive test area provide a new perspective on the impact of digital economy development on haze pollution. Finally, the mediating effect model is employed for verifying the transmission channel of digital economy growth to smoke pollution. Results reveal that the digital economy and its sub-categories can effectively suppress haze pollution. In addition, the impact at the city level is different. Specifically, the digital economy features an obvious repression on haze

pollution in non-resource, eastern and large cities. The national big data comprehensive experimental area has good policy effect and can reduce the level of haze pollution. The digital economy can significantly inhibit haze pollution through economic growth, industrial structure and FDI effects and promote haze pollution through labour force change effect.

The above conclusions have a certain policy significance for advancing the urban digital economy growth and alleviating environmental pollution and climate change. The digital economy growth restrains haze pollution. Thus, the Chinese government should continue to promote the research, development and application of big data, cloud computing and AI. Moreover, they should increase investment in Internet development and digital inclusive finance, expand the digital economy and consolidate the dividend advantage resulting from the digital technology application. The Chinese government should promote the construction of national comprehensive test area of big data and strengthen the ability of joint control and haze control in the region.

The digital economy growth in non-resource, eastern and large cities may rapidly improve urban haze pollution. Resource-based cities should reduce dependence on natural resources and minimise the resistance of technology applied in the field of the environment. Central and western cities and small cities should build application infrastructure and digital network systems in line with urban advantages and characteristics, improve network coverage and informatisation level and provide strict legal support to improve extensive economic growth mode.

Urban economic growth, industrial structure, FDI and labour force changes should be considered to reduce haze pollution effectively. Firstly, digital technology can be used to enable economic transformation and upgrading, the green attribute of economic growth can be improved and high-quality economic growth can be pursued. Secondly, the continuous extension and penetration of the new economy led by the Internet and the sector's digital transformation can be promoted, and the haze pollution can be reduced through industrial upgrading. Thirdly, attention should be given to the role of foreign investment in improving environmental pollution, focusing on the introduction of technology-intensive investment. Finally, the labour substitution effect due to the digital economy growth should be considered, the contradiction between labour supply and demand should be alleviated and the production and living pollution should be reduced.

Declarations

-Ethical Approval:

Not applicable.

-Consent to Participate:

Not applicable.

-Consent to Publish:

Not applicable.

-Authors Contributions:

Shuai Che: Data curation, Investigation, Software, Visualization, Writing – original draft, Writing – review and editing. Jun Wang: Conceptualization, Methodology, Funding acquisition, Writing – original draft, Resources, Project administration, Supervision.

-Funding:

We acknowledge the financial support from the National Office for Philosophy and Social Sciences (No. 20BJL035) and the National Natural Science Foundation of China Youth Project (No. 71804190).

-Competing Interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

-Availability of data and materials

Not applicable.

References

1. Agarwal, S., Foo Sing, T., Yang, Y., 2020. The impact of transboundary haze pollution on household utilities consumption. *ENERG ECON* 85, 104591.

2. Andersen, A.D., Frenken, K., Galaz, V., Kern, F., Klerkx, L., Mouthaan, M., Piscicelli, L., Schor, J.B., Vaskelainen, T., 2021. On digitalization and sustainability transitions. *ENVIRON INNOV SOC TR.*
3. Ben Youssef, A., Boubaker, S., Dedaj, B., Carabregu-Vokshi, M., 2021. Digitalization of the economy and entrepreneurship intention. *TECHNOL FORECAST SOC* 164, 120043.
4. Calvano, E., Polo, M., 2021. Market power, competition and innovation in digital markets: A survey. *INF ECON POLICY* 54, 100853.
5. Chen, H., Hao, Y., Li, J., Song, X., 2018. The impact of environmental regulation, shadow economy, and corruption on environmental quality: Theory and empirical evidence from China. *J CLEAN PROD* 195, 200-214.
6. Chen, S., Zhang, Y., Zhang, Y., Liu, Z., 2019. The relationship between industrial restructuring and China's regional haze pollution: A spatial spillover perspective. *J CLEAN PROD* 239, 115808.
7. Cole, M.A., Elliott, R.J.R., Okubo, T., 2010. Trade, environmental regulations and industrial mobility: An industry-level study of Japan. *ECOL ECON* 69, 1995-2002.
8. Dong, F., Zhang, S., Long, R., Zhang, X., Sun, Z., 2019. Determinants of haze pollution: An analysis from the perspective of spatiotemporal heterogeneity. *J CLEAN PROD* 222, 768-783.
9. Feng, W., Yuan, H., 2021a. Haze pollution and economic fluctuations: An empirical analysis of Chinese cities. *Cleaner Environmental Systems* 2, 100010.
10. Feng, W., Yuan, H., 2021b. Haze pollution and economic fluctuations: An empirical analysis of Chinese cities. *Cleaner Environmental Systems* 2, 100010.
11. Feng, W., Yuan, H., 2021c. Haze pollution and economic fluctuations: An empirical analysis of Chinese cities. *Cleaner Environmental Systems* 2, 100010.
12. Feng, Y., Wang, X., Liang, Z., 2021a. How does environmental information disclosure affect economic development and haze pollution in Chinese cities? The mediating role of green technology innovation. *SCI TOTAL ENVIRON* 775, 145811.
13. Feng, Y., Wang, X., Liang, Z., 2021b. How does environmental information disclosure affect economic development and haze pollution in Chinese cities? The mediating role of green technology innovation. *SCI TOTAL ENVIRON* 775, 145811.
14. Gan, T., Liang, W., Yang, H., Liao, X., 2020. The effect of Economic Development on haze pollution (PM_{2.5}) based on a spatial perspective: Urbanization as a mediating variable. *J CLEAN PROD* 266, 121880.
15. Gan, T., Yang, H., Liang, W., 2021a. How do urban haze pollution and economic development affect each other? Empirical evidence from 287 Chinese cities during 2000–2016. *SUSTAIN CITIES SOC* 65, 102642.
16. Gan, T., Yang, H., Liang, W., 2021b. How do urban haze pollution and economic development affect each other? Empirical evidence from 287 Chinese cities during 2000–2016. *SUSTAIN CITIES SOC* 65, 102642.
17. Gnanngnon, S.K., 2020. Internet and tax reform in developing countries. *INF ECON POLICY* 51, 100850.
18. Guo, B., Wang, Y., Zhang, X., Che, H., Zhong, J., Chu, Y., Cheng, L., 2020. Temporal and spatial variations of haze and fog and the characteristics of PM_{2.5} during heavy pollution episodes in China from 2013 to 2018. *ATMOS POLLUT RES* 11, 1847-1856.
19. Hao, Y., Zheng, S., Zhao, M., Wu, H., Guo, Y., Li, Y., 2020. Reexamining the relationships among urbanization, industrial structure, and environmental pollution in China—New evidence using the dynamic threshold panel model. *Energy Reports* 6, 28-39.
20. Hicks, R., Tingley, D., 2011. Causal mediation analysis. *STATA J* 11, 605-619.
21. Imbulana Arachchi, J., Managi, S., 2021. Preferences for energy sustainability: Different effects of gender on knowledge and importance. *Renewable and Sustainable Energy Reviews* 141, 110767.
22. Kosuke, Imai, Luke, Keele, Teppei, Yamamoto, 2010. Identification, Inference and Sensitivity Analysis for Causal Mediation Effects. *STAT SCI*.
23. Li, C., Ma, X., Fu, T., Guan, S., 2021. Does public concern over haze pollution matter? Evidence from Beijing-Tianjin-Hebei region, China. *SCI TOTAL ENVIRON* 755, 142397.
24. Li, X., Xu, Y., Yao, X., 2021. Effects of industrial agglomeration on haze pollution: A Chinese city-level study. *ENERG POLICY* 148, 111928.
25. Li, Z., Shao, S., Shi, X., Sun, Y., Zhang, X., 2019. Structural transformation of manufacturing, natural resource dependence, and carbon emissions reduction: Evidence of a threshold effect from China. *J CLEAN PROD* 206, 920-927.
26. Lin, B., Zhu, J., 2020. Policy effect of the Clean Air Action on green development in Chinese cities. *J ENVIRON MANAGE* 258, 110036.
27. Liu, X., Wang, Z., Sun, X., Zhang, L., Zhang, M., 2020a. Clarifying the relationship among clean energy consumption, haze pollution and economic growth—based on the empirical analysis of China's Yangtze River Delta Region. *ECOL COMPLEX* 44, 100871.
28. Liu, X., Wang, Z., Sun, X., Zhang, L., Zhang, M., 2020b. Clarifying the relationship among clean energy consumption, haze pollution and economic growth—based on the empirical analysis of China's Yangtze River Delta Region. *ECOL COMPLEX* 44, 100871.
29. Mackinnon, D.P., Krull, J.L., Lockwood, C.M., 2000. Equivalence of the Mediation, Confounding and Suppression Effect. *PREV SCI* 1, 173-181.

30. Noda, H., Kano, S., 2021. Environmental economic modeling of sustainable growth and consumption in a zero-emission society. *J CLEAN PROD* 299, 126691.
31. Olena-Ivanna, H., Andrii, H., Stanislav, B., Viktoriia, H., 2021. Theoretical and Methodological Bases of the Study of the ilmpact of Digital Economy on World Policy in 21 Century. *Technological Forecasting & Social Change* 166.
32. Pouri, M.J., 2021. Eight impacts of the digital sharing economy on resource consumption. *Resources, Conservation and Recycling* 168, 105434.
33. Qu, W., Qu, G., Zhang, X., Robert, D., 2021. The impact of public participation in environmental behavior on haze pollution and public health in China. *ECON MODEL* 98, 319-335.
34. Ren, S., Hao, Y., Xu, L., Wu, H., Ba, N., 2021. Digitalization and energy: How does internet development affect China's energy consumption? *ENERG ECON* 98, 105220.
35. Sareen, S., Haarstad, H., 2021. Digitalization as a driver of transformative environmental innovation. *ENVIRON INNOV SOC TR.*
36. Shao, S., Yang, L., 2014. Natural resource dependence, human capital accumulation, and economic growth: A combined explanation for the resource curse and the resource blessing. *ENERG POLICY* 74, 632-642.
37. Shi, T., Zhang, W., Zhou, Q., Wang, K., 2020. Industrial structure, urban governance and haze pollution: Spatiotemporal evidence from China. *SCI TOTAL ENVIRON* 742, 139228.
38. Song, Y., Zhao, C., Zhang, M., 2019. Does haze pollution promote the consumption of energy-saving appliances in China? An empirical study based on norm activation model. *Resources, Conservation and Recycling* 145, 220-229.
39. Wang, C., Wang, Z., Zhang, X., 2021. Speciated atmospheric mercury during haze and non-haze periods in winter at an urban site in Beijing, China: Pollution characteristics, sources, and causes analyses. *ATMOS RES* 247, 105209.
40. Wang, S., Tang, Y., Du, Z., Song, M., 2020. Export trade, embodied carbon emissions, and environmental pollution: An empirical analysis of China's high- and new-technology industries. *J ENVIRON MANAGE* 276, 111371.
41. Wang, T., Huang, X., Wang, Z., Liu, Y., Zhou, D., Ding, K., Wang, H., Qi, X., Ding, A., 2020. Secondary aerosol formation and its linkage with synoptic conditions during winter haze pollution over eastern China. *SCI TOTAL ENVIRON* 730, 138888.
42. Wang, X., Yin, C., Shao, C., 2021. Relationships among haze pollution, commuting behavior and life satisfaction: A quasi-longitudinal analysis. *Transportation Research Part D: Transport and Environment* 92, 102723.
43. Wu, H., Hao, Y., Ren, S., Yang, X., Xie, G., 2021. Does internet development improve green total factor energy efficiency? Evidence from China. *ENERG POLICY* 153, 112247.
44. Wu, H., Xia, Y., Yang, X., Hao, Y., Ren, S., 2021. Does environmental pollution promote China's crime rate? A new perspective through government official corruption. *STRUCT CHANGE ECON D* 57, 292-307.
45. Xie, Z., Du, S., Ma, T., Hou, J., Zeng, X., Li, Y., 2021. High time-resolved characterization of airborne microbial community during a typical haze pollution process. *J HAZARD MATER* 415, 125722.
46. Xu, C., Zhao, W., Zhang, M., Cheng, B., 2021a. Pollution haven or halo? The role of the energy transition in the impact of FDI on SO₂ emissions. *SCI TOTAL ENVIRON* 763, 143002.
47. Xu, C., Zhao, W., Zhang, M., Cheng, B., 2021b. Pollution haven or halo? The role of the energy transition in the impact of FDI on SO₂ emissions. *SCI TOTAL ENVIRON* 763, 143002.
48. Xu, Y., Fan, X., Zhang, Z., Zhang, R., 2020. Trade liberalization and haze pollution: Evidence from China. *ECOL INDIC* 109, 105825.
49. Yang, F., Wen, X., Aziz, A., Luhach, A.K., 2021. The need for local adaptation of smart infrastructure for sustainable economic management. *ENVIRON IMPACT ASSES* 88, 106565.
50. Yang, X., Wu, H., Ren, S., Ran, Q., Zhang, J., 2021. Does the development of the internet contribute to air pollution control in China? Mechanism discussion and empirical test. *STRUCT CHANGE ECON D* 56, 207-224.
51. Yi, M., Wang, Y., Sheng, M., Sharp, B., Zhang, Y., 2020. Effects of heterogeneous technological progress on haze pollution: Evidence from China. *ECOL ECON* 169, 106533.
52. Yu, Y., Qian, T., Du, L., 2017. Carbon productivity growth, technological innovation, and technology gap change of coal-fired power plants in China. *ENERG POLICY* 109, 479-487.
53. Zhang, F., Wang, F., Yao, S., 2021. High-speed rail accessibility and haze pollution in China: A spatial econometrics perspective. *Transportation Research Part D: Transport and Environment* 94, 102802.
54. Zhang, J., Wang, J., Yang, X., Ren, S., Ran, Q., Hao, Y., 2020. Does local government competition aggravate haze pollution? A new perspective of factor market distortion. *SOCIO-ECON PLAN SCI*, 100959.
55. Zhao, C., Zhang, M., Wang, W., 2019. Exploring the influence of severe haze pollution on residents' intention to purchase energy-saving appliances. *J CLEAN PROD* 212, 1536-1543.

56. Zhou, H., Jiang, M., Huang, Y., Wang, Q., 2021. Directional spatial spillover effects and driving factors of haze pollution in North China Plain. Resources, Conservation and Recycling 169, 105475.

57. Zhou, Q., Zhang, X., Shao, Q., Wang, X., 2019. The non-linear effect of environmental regulation on haze pollution: Empirical evidence for 277 Chinese cities during 2002–2010. J ENVIRON MANAGE 248, 109274.

58. Zhou, Q., Zhong, S., Shi, T., Zhang, X., 2021. Environmental regulation and haze pollution: Neighbor-companion or neighbor-beggar? ENERG POLICY 151, 112183.

Figures

Figure 1

Research flow chart