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Research paper

Does the digital economy reduce air pollution in China? A perspective from industrial agglomeration

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ABSTRACT

Based on the perspective of industrial agglomeration, this paper employs a dynamic panel model and mediating effects model to investigate the impact of digital economy's development on air pollution in 274 Chinese cities from 2011 to 2019. The main findings include: (1) The development of the digital economy reduces air pollution emissions in Chinese cities, and the elasticity of pollution reduction is greater in central and western China than in eastern China. (2) The nexus between industrial agglomeration and air pollution is inverted-N-shaped. (3) Mechanism tests show that the digital economy can effectively promote the degree of industrial agglomeration in each area, and it plays a positive role in abating pollution in eastern and central China through the positive externalities of industrial agglomeration, but the mediating effect of industrial agglomeration on pollution reduction is not significant in western China. (4) Diversified agglomeration is an active mediator of the digital economy's pollution reduction effect in eastern and central China. Accordingly, some policy implications are put forward for simultaneously promoting the development of the digital economy and reducing air pollution, impelling industrial agglomeration, and accelerating the green transformation in China.

1. Introduction

With the rapid development of the Chinese economy, air pollution has become one of the most concerning environmental problems in China which cannot be ignored due to the socioeconomic adversities that are likely to accompany such rising air pollution levels. It is noteworthy mentioning that as per the report "*State of Global Air 2020*", the death toll in China due to air pollution reached 238000 between 2010 and 2019. Thus, saving human life by mitigating air pollution is of utmost significance for the Chinese government. Generally, air pollution is regarded as severely harmful to the physical and mental health of the people, whereby Chinese policymakers have been interested in designing strategies that can reduce the extent of air pollution, improve the ecological environment, and promote coordinated development between the economy and the environment (Jahanger et al., 2022a). Accordingly, as a major developing country with large economic outputs and population size, China needs to explore new pathways leading to the green transformation of its economic growth through the reduction of air pollution, in particular (Jahanger et al., 2023b; Yang et al., 2023).

Although economic growth, industrial structure, energy consumption pattern, and environmental governance are acknowledged as important factors that affect air quality in China (Cui et al., 2021; Jahanger et al., 2023a; Jiang et al., 2022a; Liang and Yang, 2019; Yang et al., 2021), the rising digital economy may be thought of as a new mechanism for reconstructing economic and environmental development in China. Besides, from 2011 to 2019, China's overall air pollution level exhibited a diminishing trend which can be understood from the declining sulfur dioxide and dust emission levels in China (Fig. 1). On the other hand, the nation's digital economy rapidly developed within this time frame.

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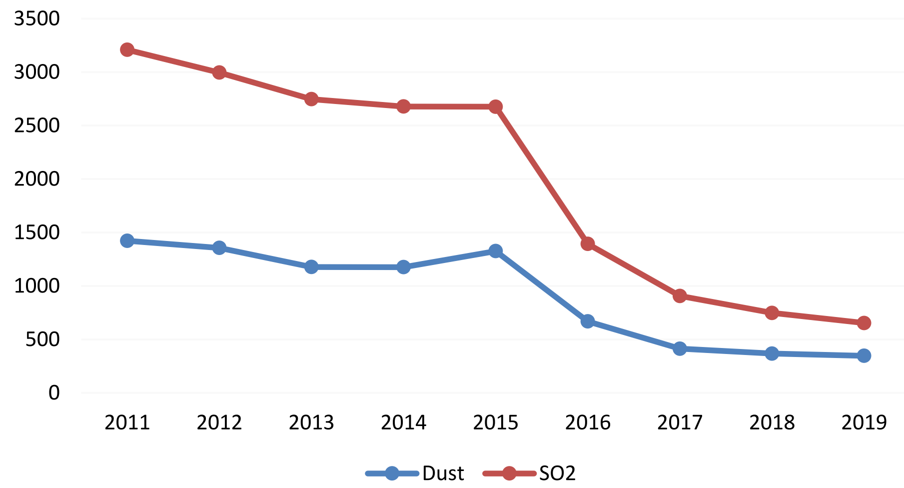

Fig. 1. Trends in sulfur dioxide and dust emissions.

Notably, the value added to China's digital economy increased from 9.5 trillion yuan in 2011 to 35.8 trillion yuan in 2019, which accounted for 36.2% of China's GDP in 2019. Hence, these contrasting trends tend to imply a correlation between China's air pollution level and the expansion of its digital economy.

Further, regarding the distribution of the digital economy across China, Beijing and Shanghai account for more than 50% of the Chinese GDP, and the digital economy in Guangdong, Zhejiang, Jiangsu, and Fujian provinces accounted for more than 40% of the GDP.[1] On the other hand, from the pollution concentration distribution maps concerning the two air pollutants (i.e., sulfur dioxide and dust) shown in Figs. 2 and 3, it can be seen that the most polluted places in China are Inner Mongolia, Shanxi, and Henan provinces, whose proportions of the digital economy in the local GDP are lower than the national average level (Jahanger et al., 2022b; Awan et al., 2022; Zeraibi et al., 2023; Usman and Jahanger, 2021). By contrast, the air quality in the developed eastern region, with the proportion of digital economy higher than the national average level, is not found to be worse than in other regions. These trends further suggest the possible air pollution-inhibiting impact of the digital economy in China. Hence, it is important to empirically examine whether or not the hypothesis of a negative correlation between the digital economy and air pollution in China holds.

Hence, the digital economy may be expected to provide an opportunity for China to realize green development so that the growth in the incidence of air pollution in Chinese cities can be controlled. Notably, the extant literature has shown that the development of a digital economy could suppress pollution by promoting the growth of the economy (Higon et al., 2017; Li et al., 2021; Jahanger et al., 2022c), improving total factor productivity (Amri et al., 2019; Guo et al., 2022), expanding trade openness (Asongu, 2018), promoting financial development (Khan et al., 2018; Tsaurai and Chimbo, 2019), and optimizing production process (Longo and York, 2005; Jiang et al., 2022b; Yu et al., 2023). In addition, several works in the literature have concluded that the development of a digital economy may efficiently reallocate the economic resources among different areas within an economy which, in turn, affects the quality of the environment.

Against this backdrop, it is necessary to analyze the effect of the digital economy on air pollution in China. Accordingly, based on the panel data of 274 cities in China from 2011 to 2019, this study considered a dynamic panel model and a mediating effect model to investigate the impact of the digital economy, in the view of industrial agglomeration, on city-level air pollution in China. Table A.1 in the appendix lists the selected Chinese cities of concern. The findings from this study can be expected to develop some policy implications for future pollution abatement in China. The specific research questions explored in this study are as follows:

(a) Can the development of the digital economy effectively improve the air quality in Chinese cities?

(b) Does digital economy development-led economic agglomeration exert favorable externalities to further reduce air pollution?

This study contributes to the extant literature in two major aspects. First, this paper discusses the effect of the digital economy on reducing air pollution, using unconventional air quality indicators. Contrary to the extant literature which has most documented studies that have considered Particulate Matter 2.5 (PM2.5) concentrations to proxy air pollution in China, we use industrial sulfur dioxide and industrial smoke dust concentrations instead. Using these different air pollution indicators not provides a different dimension to the literature on air quality determinants in China, but also allows an understanding of whether the air quality-influencing impacts of different macroeconomic factors, digital economy in particular, are homogeneous or heterogeneous across alternative types of air pollution. Second, since the previous studies have predominantly scrutinized the linear impact of the industrial sector on air pollution levels in China, the potential non-linearity concerning these variables has not been explored before. For assessing this non-linearity, this study checks whether the effect of industrial agglomeration on China's air pollution figures differs at different levels of industrial agglomeration.

Following the introduction, the subsequent sections discuss the literature, the methodology, and the results while, in the last section, the conclusion and suggested policy measures are presented.

2. Literature review and hypothesis development

2.1. Theoretical framework

Firstly, the theoretical underpinnings explaining the possible repercussions of the digital economy on air pollution are presented. Though the literature on the digital economy is enormous,

[1] Data from Specialized Think-tank for the Government Innovation and Development Platform for the Industry.

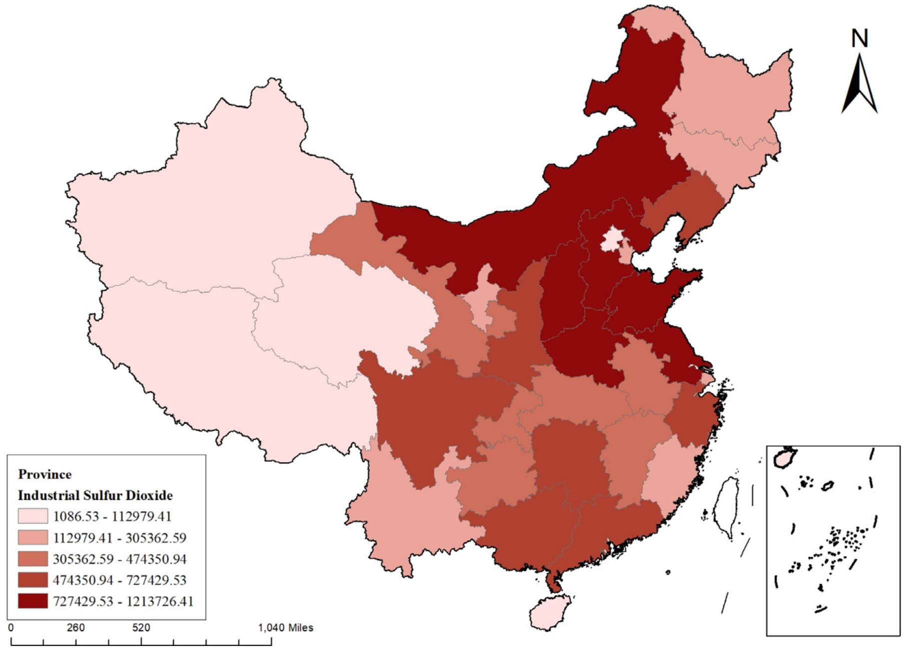

Fig. 2. Regional distribution map of sulfur dioxide concentration.

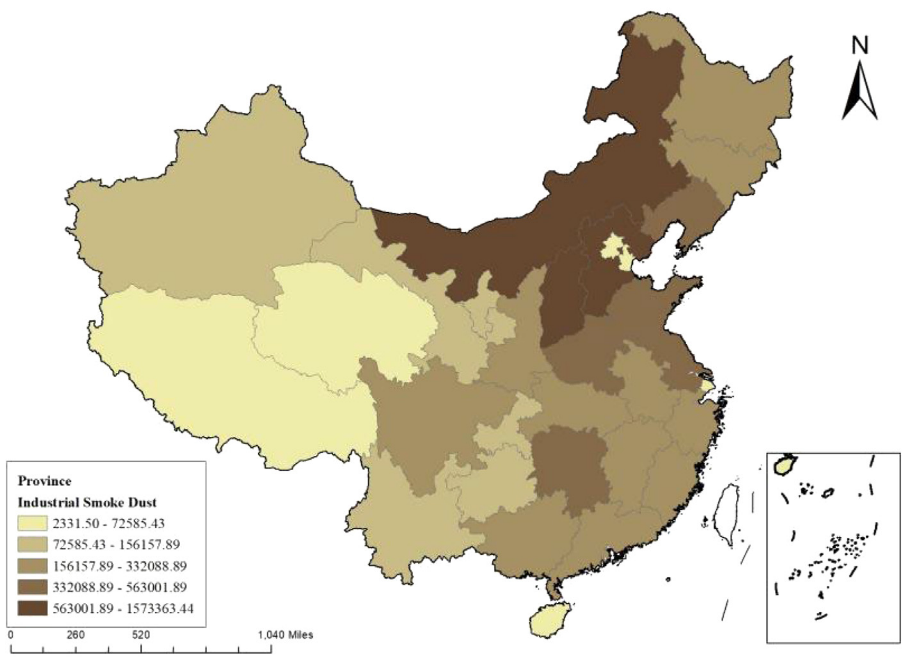

Fig. 3. Regional distribution map of dust concentration.

scholars have expressed different thoughts regarding the concept of it. Generally, there are three classifications as a digital economy: First, the digital economy originates from the goods and services provided by the information and communication industry, and the internet and software service industry (OECD, 2014; UN, 2017). Second, it is defined as economic activities based on the Internet and Information and Communications (ICT) (Bukht and Heeks, 2018) and consists of digital activities, ICT products, and services, online transactions, etc. (IMF, 2018). Third, overall economic activities that improve the efficiency and structure of the real economy are considered parts of the digital economy, which includes the information and communication industry and its contribution to the industry, agriculture, and services industries. However, irrespective of how it is measured, the digital economy essentially pushes forward the transformation of the economy and society toward modernization through the use of ICT (OECD, 2017).

The digital economy has emerged and brought about a new trend in modern living. It has upgraded traditional industries, cultivated new businesses, and then accelerated the green transformation of economic and social development. Specifically speaking, firstly, the development of the digital economy promoted dematerialization consumption and decarbonization production (Danish et al., 2018; Ozcan and Apergis, 2018a; Jahanger et al., 2022d). Besides, the progress of ICT has facilitated the popularity of hosting online activities such as shopping and video conferencing whereby people's travel frequency has reduced to greatly alleviate traffic jams and save energy. Further, the dematerialization consumption helps the labor and capital-intensive industries to turn knowledge and technology-intensive ones; consequently, this transformation can effectively save productive inputs (especially energy) and reduce pollution emissions.

On the other hand, the advancement in the digital economy can be expected to reduce pollution by promoting the technical innovation of industrial sectors, improving energy efficiency, and altering the energy structure (May et al., 2017). In the energy sector, the development of the digital economy can make renewable energy power generation technologies easier which, in turn, can make key breakthroughs by providing renewable electricity at comparatively lower costs compared with fossil energy-based electricity. Notably, the penetration of renewable energy into the power sector is often deemed necessary for improving environmental quality (Ahmadpour et al., 2021). Moreover, the development of the digital economy facilitates the supervision of environmental authorities. For instance, big data collects all kinds of real-time data on environmental misconduct, gives warnings of pollution emissions quickly, and prevents further pollution in the process. In addition, with access to a huge amount of environmental data accumulated, the authorities can formulate improved and more effective environmental rules and regulations. Besides, the public can use online media to pick up information and make an appeal to the government for safeguarding the environment (Bonson et al., 2019). Contrastingly, Heddeghem et al. (2014) pointed out that the digital economy would produce an "*energy rebound reaction*" to trigger more use of energy and therefore worsen the quality of the environment rather than improve it.

On the one hand, the digital economy is said to attract the labor force to large cities with more employment opportunities and higher income. Accordingly, promising businesses provide more employment opportunities and attract labor continuously flowing into large cities. Hence, digital economic activities can be assumed to contribute to employment generation in urban cities. However, enterprises prefer to locate in large cities for digital convenience. This is because enterprises are invisibly financed with the digital dividend from advanced information infrastructure in large cities and accelerated in intelligent upgrading to improve production efficiency and profit-earning. Therefore, the extent to which enterprises gather in large cities could exert a role in influencing pollution levels through the channel of industrial agglomeration.

Furthermore, the digital economy promotes specialized agglomeration and diversified agglomeration to exert a positive effect on pollution reduction. The rise in the internet penetration rate dramatically reduces the coordination cost for businesses and promotes the division of labor among enterprises (Fort, 2017). Specialized agglomeration can realize the scale effect in pollution treatment for similar contaminates from various firms in the same industry, and it cuts down any firm's expenditure on pollution abatement. Moreover, knowledge spillover across industries can help enterprises complement each other in sharing knowledge and technology, stimulating new ideas, applying new technologies, and providing favorable conditions for the progress of green technology (Ciccone, 2002). In addition, diversified agglomeration makes all kinds of enterprises symbiosis due to material exchange, that is, the by-products or wastes of some enterprises happen to be the raw materials or intermediate inputs of other enterprises, thus promoting the recycling of material resources for reducing pollution emissions (Ehrenfeld, 2003). Based on the above arguments, this paper proposes the following hypotheses:

Hypothesis 1. Digital economy can effectively reduce urban air pollution in Chinese cities.

Hypothesis 2. Digital economy changes the spatial distribution of production resources and exerts a significant effect on pollution reduction through industrial agglomeration.

Hypothesis 3. Digital economy attracts the inflow of various production resources, impels diversified agglomeration, speeds up green technological innovation, builds a recycling economic practice, and effectively alleviates pollution emissions.

Hypothesis 4. Digital economy promotes specialized division of labor, and exerts a positive effect on pollution reduction through the scale effect of specialized agglomeration.

2.2. Empirical evidence from extant literature

Among the previous empirical studies, Qi et al. (2022) used data city-level data from 286 Chinese cities to check the impact of the digital economy and air pollution indicators including PM2.5, sulfur, and nitrogen dioxide concentrations. The results indicated that the digital economy helps in lowering air pollution by reducing the concentration levels of the selected air pollution indicator. In particular, the results revealed that the air pollution-inhibiting effect is relatively higher in the case of sulfur dioxide concentrations and least in the context of nitrogen concentrations. Moreover, industrial upgrading was evidenced to reduce air pollutant concentration levels in China. Besides, the air pollution-mitigating effect of industrial upgrading was found to be relatively higher in urban agglomeration around the Yangtze River Delta. In another study on 225 prefecture Chinese cities for the period between 2011 and 2018, Wang and Chen (2022) concluded that the digital economy both directly reduces air pollution by reducing PM2.5 concentration levels and indirectly does the same jointly with higher natural resource consumption. Precisely, the authors argued that the digital economy is effective in neutralizing the air pollution boosting impact associated with natural resource consumption in China.

Zhou et al. (2021), on the other hand, used data concerning 30 Chinese provinces for the 2011–2018 period and also found evidence that the digital economy inflicts favorable air pollution-related outcomes by reducing haze pollution (i.e., inhibiting PM2.5 concentration levels), especially in provinces located across the eastern parts of China. Besides, the authors also asserted that the digital economy mediates the relationship between industrial structure and PM2.5 concentration levels to reduce haze pollution further. Che and Wang (2022), using data from 275 prefecture-level Chinese cities, concluded that irrespective of the proxy of the digital economy, enhancing digital economic activities result in lower levels of PM10 and PM2.5 concentration levels in China while upgrading industrial structure was found to inhibit air pollution, as well.

Using sulfur dioxide emissions as the indicator of air pollution in China, Chen and Yan (2020) discovered that higher levels of e-commerce development, e-commerce application, and use of e-commerce services (three chosen proxies of the digital economy) reduce both sulfur dioxide concentration level and the ratio of sulfur dioxide emissions in the Chinese GDP. Besides, the authors also found that industrial output expansion aggravates the air quality in China by boosting sulfur dioxide emission-related indicators of air pollution. Similarly, Wan and Shi (2022) concluded that the digital economy helps in reducing the intensity of sulfur dioxide emissions in China. In addition, the authors further pointed out that the sulfur dioxide emission intensity-mitigating impact of the digital economy is relatively higher for medium-sized and resource-abundant Chinese provinces located across the eastern and southern regions of China.

Meanwhile, for studies featuring countries other than China, Zhang et al. (2022) explored the determinants of air quality in the BRICS (Brazil, Russia, India, China, and South Africa) and found that economic growth initially degrades air quality by boosting PM2.5 concentrations while ultimately improves air quality by impeding PM2.5 concentrations. On the other hand, Ozcan and Apergis (2018b) considered carbon dioxide emissions as indicators of air quality in China and 19 other emerging countries and found that greater internet penetration (symbolizing more digitalization of economic activities) results in lower levels of air pollution in the long-run. Moreover, the authors also found evidence regarding greater international trade reducing air pollution while economic growth and higher energy consumption were seen to boost the pollution levels in China. Likewise, in the context of 31 Sub-Saharan African nations, Evans and Mesagan (2022) argued that greater participation in ICT trade contributes to higher levels of pollution both in the short and long run.

2.2.1. Literature gap

The above summaries of the related literature reveal two key gaps. First, it is apparent that almost all previous studies have assessed the impact of the digital economy and industrialization on air quality in China by considering PM2.5 as the proxy for air pollution. Second, the potential non-linearity between industrialization and air pollution in China has not been explored in the preceding studies. Hence, this study bridges these two literature gaps by considering industrial sulfur dioxide and industrial smoke dust concentrations to quantify the extent of air pollution across different Chinese cities. Besides, considering the finding of ambiguous effects of the industrial sector on air pollution, this study explores whether the nexus between industrial agglomeration and air pollution in China varies at different levels of industrial agglomeration. Accordingly, instead of using linear models, this study considers non-linear models by including polynomials of the industrial agglomeration variable.

3. Methodology and research data

3.1. Empirical model

This paper examines the effect of the digital economy on reducing air pollution and then analyzes the path of the digital economy on air pollution through industrial agglomeration. First, based on previous studies in the relevant literature (Asongu, 2018), we consider the baseline model shown below:

$$\ln pol_{it} = \alpha_0 + \alpha_1 \ln dig_{it} + \alpha_2 ag_{it} + \alpha_3 (ag_{it})^2 + \alpha_4 (ag_{it})^3 + \alpha_5 X_{it} + \mu_i + \varphi_i + \varepsilon_{it} \quad (1)$$

where i and t refer to city and year respectively, *pol* means the emission intensity of air pollution which has two components: emission intensity of industrial sulfur dioxide and industrial smoke dust. The variable *dig* represents the digital economy index of city i. The variables ag, $(ag)^2$ and $(ag)^3$ refer to the degree of the industrial agglomeration, its quadratic term, and its cubic term, respectively. X represents the control variables, including per capita income (y), the proportion of secondary industry (ig), and the degree of economic openness (*open*). In addition, μ, ϕ and ε are individual fixed effect, time effect, and random error terms respectively.

Secondly, to examine the path of the digital economy on air pollution through industrial agglomeration, this paper uses the mediating effect model of stepwise regression by Baron and Kenny (1986). The model is given as follows:

$$\ln pol_{it} = \beta_0 + \beta_1 \ln dig_{it} + \beta_2 X_{it} + \eta_i + \vartheta_i + \xi_{it} \quad (2)$$

$$ag_{it} = \omega_0 + \omega_1 (ag_{it})^2 + \omega_2 (ag_{it})^3 + \omega_3 \ln dig_{it} + \omega_4 X_{it} + \theta_i + \lambda_i + \upsilon_{it} \quad (3)$$

This study uses a three-step strategy to test the path effect of industrial agglomeration considering the following: (1) digital economy reduces air pollution if $\beta_1 < 0$ and is statistically significant. (2) the impact of the digital economy on the industrial agglomeration (ag) is given by Eq. (3), and we can execute the next step if ω_3 is significant. (3) combining the results of Eq. (1), to estimate the type of mediation effect (partial mediation effect or complete mediation effect) based on the significance of α_1 and α_2.

3.2. Descriptions of variables and data sources

3.2.1. Explained variable

Although the relevant research works (shown in Section 2.2) mainly used PM2.5 as the metric of air pollution (this variable is being used in the Chinese weather alert system China since 2013), it cannot analyze the effect for a long time, which maybe bring the problem of time deviation to regression. Then some researchers used the NASA satellite data to estimate the PM2.5 degrees in Chinese cities, published by Columbia University or Dalhousie University; however, the NASA satellite data estimated deviates from actual data. Considering these data limitations and the relevant literature gaps, this study uses the emission intensity of industrial sulfur dioxide (so_2) and industrial smoke dust (sd) instead of PM2.5 to proxy the level of air pollution in the Chinese cities of concern.

3.2.2. Mainly explanatory variable

This paper uses annual series data to construct the China city digital economy development index ($\ln dig$) using the method proposed by IMF (2018). The variables considered include (i) the number of subscribers to internet service, (ii) persons employed in the sector of information transmission and computer service and software, (iii) revenue from telecommunication services, (iv) the number of subscribers to mobile telephone services, and (v) the China digital inclusive finance index is published by the Digital Finance Research Center of Peking University and Ant Financial Group.[2]

3.2.3. Intermediate variable

Considering the definition that the economic resources cluster in the limited space, this paper uses the number of employees per unit area to measure the extent of industrial agglomeration (Ciccone, 2002) in Chinese cities. Besides, based on the assumption of the non-linear relationship between agglomeration and air pollution exists, this paper introduces the linear term ag, the quadratic term $(ag)^2$, and the cubic term $(ag)^3$ of industrial agglomeration into the empirical model.

2 https://www.idf.pku.edu.cn/zsbz/index.htm

Table 1
Descriptive statistics of variables.
Source: Authors' computation.

Variables	Observations	Mean	Std. Dev.	Min	Max
lnso$_2$	2466	1.123	1.306	−6.059	4.464
lnsd	2466	0.8	1.303	−7.69	6.524
lndig	2466	8.614	0.956	0	12.8
ag	2466	0.749	1.73	0	24.82
lny	2466	10.7	0.576	8.773	13.06
ig	2466	46.84	10.69	0	89.34
open	2466	1.74	2.494	0	77.48
rdi	2464	2.204	0.891	0	6.62
rzi	2456	6.716	23.22	1.33	625.6
gov	2465	0.466	0.225	0.0689	1.541
lntfp	2466	0.26	0.659	−2.259	1.081

3.2.4. Control variables

This paper uses a set of control variables in the empirical models to overcome the issue of omitted variable bias. First, this paper uses the per capita national income ($\ln y_{it}$) as a control variable, which measures the level of affluence in the respective Chinese cities. In addition, the empirical models include the linear term $\ln y_{it}$ and the quadratic term $(\ln y_{it})^2$ of per capita income based on the "principles of the Environmental Kuznets Curve (EKC) hypothesis" which reveals the relationship of an inverted U-shaped curve between per capita income and environmental pollution. Second, this study uses the proportion of industrial output in GDP (*ig*) as a control variable. Lastly, this study uses the extent of opening up (*open*) as a control variable, measured by the proportion of foreign direct investments (FDI) in city-level GDP. This variable is included as a control following two key assumptions. Firstly, it is believed that biased technological change induced by regional openness could achieve pollution reduction through better energy efficiency (Li et al., 2016). Secondly, the phenomenon of "pollution refuge" could appear for some polluting industries from developed countries to shift to developing countries with the further advance of globalization (Shao et al., 2011). Consequently, controlling for the degree of opening up is deemed important.

3.3. Data and descriptive statistics

In addition, all the data, exclusive of the China city digital economy development index, are attained from the China City Statistical Yearbook from 2011 to 2019. And the relevant variables were logarithmically processed. The results of descriptive statistics are displayed in Table 1.

3.4. Estimation technique

We begin by estimating a static fixed effects model for conducting the F test and Hausman test. Overall, the fixed effects model can control the city-specific effects and year-specific effects, and alleviate the problem of multicollinearity. The first step of the econometric procedure involved the testing of the appropriateness of the model that is to be considered for discussing the results. With the result of the fisher-ADF method, it was found that all variables are stable, which means it passed the panel smoothness test. Besides, the results of the F test and Hausman test showed that the fixed effects model can be selected over the random effects model. For ensuring brevity, the outcomes from these tests are not reported.

Besides, because pollution emissions may present an evident "snowball" effect in the time dimension, the generalized method of moments (GMM) is applied to deal with the time lag term. We used the system GMM technique to estimate the empirical model. This method is considered effective because it considers an arrangement of two simultaneous equations to link these equations by predicting a dynamic system GMM model (Haque, 2021). Furthermore, the choice of the GMM technique was motivated by the fact that this method effectively neutralizes the issue of endogenous covariates in the model by including the lagged level of the explained variable ($\ln pol_{t-1}$) as an explanatory variable in the model. In the context of our baseline model (shown in Eq. (1)), the GMM model specification can be shown as follows:

$$\ln pol_{it} = \rho_0 + \rho_1 \ln pol_{i,t-1} + \rho_2 \ln dig_{it} + \rho_3 ag_{it} + \rho_4 (ag_{it})^2 + \rho_5 (ag_{it})^3 + \rho_6 X_{it} + \mu_i + \varphi_i + \varepsilon_{it} \quad (4)$$

$$\ln pol_{it} = \gamma_0 + \gamma_1 \ln pol_{i,t-1} + \gamma_2 \ln dig_{it} + \gamma_3 X_{it} + \eta_i + \vartheta_t + \xi_{it} \quad (5)$$

$$ag_{it} = \sigma_0 + \sigma_1 (ag_{it})^2 + \sigma_2 (ag_{it})^3 + \sigma_3 \ln dig_{it} + \sigma_4 X_{it} + \theta_i + \lambda_t + \upsilon_{it} \quad (6)$$

In addition, the Hansen test was used to corroborate the effectiveness of the instrument variable instead of the Sargan test since Roodman (2009) argued that the Sargan test is not robust to deal with autocorrelation or heteroscedasticity problems. The regression analyses conducted in this study involved the use of the Stata 15 software.

4. Findings and discussion

4.1. Benchmark regression model's results

The results from the benchmark regression model (i.e., Eq. (1)) are reported in Table 2. The regression results concerning the static fixed effects model are shown in columns (1) and (2) of Table 2 while those concerning system GMM model are presented in columns (3) and (4). It is evident from the outcomes of the Arellano-Bond and Hansen tests from the static fixed effects model and the significance of explained variables shown in columns (1) and (2) that the use of the system GMM estimation method is justified. In addition, since the symbols of the estimated coefficients of most variables are consistent across both estimation techniques, we focus on the results of system GMM estimation.

First of all, the estimated coefficients of the digital economy ($\ln dig$) are negative and statically significant at the 1% level, as shown in columns (3) and (4) of Table 2, which indicates that Hypothesis 1 is proved that the development of China's digital economy can effectively reduce the emission intensities of industrial sulfur dioxide and industrial smoke dust. The possible causes of the finding of the decontamination effects of China's digital economy are as follows: In 2019, China's digital economy accounted for 36.2% of its GDP, and its penetration

Table 2
Baseline regression.
Source: Authors' computation.

Variables	Fixed effects		System GMM	
	(1) $lnso_2$	(2) lnsd	(3) $lnso_2$	(4) lnsd
$L.lnso_2$			0.7986***	
			(0.0850)	
L.lnsd				0.5820***
				(0.0771)
lndig	−0.0649***	−0.0887***	−0.0583***	−0.0925***
	(0.0246)	(0.0333)	(0.0220)	(0.0290)
ag	−0.2366***	−0.3632***	−0.2053***	−0.3906***
	(0.0746)	(0.0799)	(0.0655)	(0.0833)
$(ag)^2$	0.0168*	0.0340**	0.0221***	0.0411***
	(0.0102)	(0.0145)	(0.0075)	(0.0103)
$(ag)^3$	−0.0004	−0.0010**	−0.0006***	−0.0012***
	(0.0003)	(0.0005)	(0.0002)	(0.0003)
lny	1.8597**	3.5684**	0.8300	0.1144
	(0.8899)	(1.4947)	(0.6033)	(0.9842)
$(lny)^2$	−0.1104***	−0.1424**	−0.0362	−0.0030
	(0.0413)	(0.0681)	(0.0270)	(0.0461)
ig	0.0222***	0.0230***	0.0208***	0.0117***
	(0.0029)	(0.0043)	(0.0022)	(0.0030)
open	0.0236***	0.0245***	0.0424***	0.0380***
	(0.0053)	(0.0071)	(0.0097)	(0.0103)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	2466	2466	2192	2192
AR(1)-P			0.000	0.000
AR(2)-P			0.351	0.290
Hansen			0.180	0.202

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

rate in agriculture, industry, and service was 8.2%, 19.5%, and 37.8%, respectively. China has promoted the optimization of industrial structure and accelerated the elimination of industries with high pollution and energy consumption. In 2019, China's online retail sales of physical goods accounted for 20.7% of the total retail sales of consumer goods, and mobile payment services accounted for 101.431 billion transactions, up 67.57% year on year. The number of online education users increased by 22% year on year. Hence, based on these statistics, it can be said that digital technology directly satisfied consumers with services of social contact including online shopping, finance, education, and so on, which can be deemed helpful in reducing unnecessary use of time and energy; consequently, the air pollution levels are likely to decline. Furthermore, in 2019, the economic added value of China's industrial internet industry was 2.13 trillion yuan which was 47.3% higher than the previous year's level. The industrial internet is considered a new production mode with the deep integration of information technology and the industrial economy. Industrial digital equipment realizes digital perception, decision-making, and control through the intelligent upgrading of traditional industries, to optimize the production process, improve energy use efficiency, and, therefore, reduce the utilization of energy. Meanwhile, digital technology can assist regulatory authorities in environmental supervision, facilitate the public to appeal for environmental protection, and strengthen the policy implementation for pollution reduction in practice[3] whereby the development of the digital economy can aid in controlling air pollution further.

Secondly, the coefficients of the linear, quadratic, and cubic terms of industrial agglomeration (ag, ag ^{2}, and ag ^{3}) are negative, positive, and negative, respectively, and statically significant at the 1% level, which indicates that there is an "inverted N-shaped" curve relationship between industrial agglomeration and pollution emissions. This is a key finding this study contributes to the related literature to support the idea that although initially industrial agglomeration improves air quality, the impact gets reversed before once again improving air quality later on. Thus, the sustainability of industrial agglomeration policies is deemed necessary for abating air pollution in Chinese cities. These findings could be due to the following reasons: In the initial stage of economic development, considering the theoretical principles of the EKC hypothesis, industrial agglomeration speeds up, reaches a certain threshold, and achieves pollution reduction through the scale effect. Then, with the rapid development of the economy, the agglomeration of capital-intensive industries brings about a rise in pollution emissions. At this stage of economic transition, skilled laborers migrate to large cities for seeking better jobs and acquiring higher incomes, so it will impel the industrial agglomeration. Then it is knowledge sharing and technology spillover among talented individuals that give impetus to research and development investment-related initiatives for green technological development and cultivation of more energy-saving businesses. Also, with a further rise in the industrial agglomeration levels, the public is likely to pay more attention to environmental protection, whereby industrial enterprises could be tempted in adopting pollution reduction policies. On the whole, it can be claimed that industrial agglomeration plays a significant role in promoting pollution reduction in China.

Furthermore, to analyze the impact of industrial agglomeration on air pollution emission in different stages, this paper

[3] Data from Specialized Think-tank for the Government Innovation and Development Platform for the Industry. http://www.caict.ac.cn/kxyj/qwfb/bps/202007/t20200702_285535.htm.

Table 3
Robustness analysis.
Source: Authors' computation.

Variables	Add explanatory variables		Change the explained variable		Smaller sample	
	(1) $lnso_2$	(2) lnsd	(3) $lnpso_2$	(4) lnpsd	(5) $lnpso_2$	(6) lnpsd
$L.lnso_2$	0.8338*** (0.0387)				0.6393*** (0.0834)	
L.lnsd		0.5786*** (0.0326)				0.5863*** (0.0802)
$L.lnpso_2$			0.5856*** (0.0534)			
L.lnpsd				0.6356*** (0.0994)		
lndig	−0.0667** (0.0292)	−0.1006*** (0.0192)	−0.0908*** (0.0172)	−0.0841*** (0.0289)	−0.0858* (0.0440)	−0.0894*** (0.0294)
ag	−0.2160*** (0.0399)	−0.4250*** (0.0459)	−0.2696*** (0.0417)	−0.2647*** (0.0865)	−0.2943*** (0.0574)	−0.3900*** (0.0846)
$(ag)^2$	0.0246*** (0.0050)	0.0451*** (0.0061)	0.0318*** (0.0055)	0.0309*** (0.0106)	0.0318*** (0.0071)	0.0409*** (0.0103)
$(ag)^3$	−0.0007*** (0.0002)	−0.0013*** (0.0002)	−0.0010*** (0.0002)	−0.0010*** (0.0003)	−0.0009*** (0.0002)	−0.0012*** (0.0003)
gov	0.7333*** (0.1362)	0.2603** (0.1240)				
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	2191	2191	2192	2192	2144	2144
AR(1)-P	0.000	0.000	0.000	0.000	0.000	0.000
AR(2)-P	0.156	0.18	0.301	0.57	0.359	0.254
Hansen	0.14	0.136	0.371	0.206	0.489	0.593

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

calculates the inflection point values of industrial agglomeration. The result shows that the first and second inflection points of industrial sulfur dioxide emission are 622 people per squared km and 1833 people per squared km, respectively, and the first and second inflection points of industrial smoke dust emission are 698 people per squared km and 1555 people per squared km, respectively. It is important to note that most Chinese cities are below the first inflection point, however, Shanghai and Dongguan lie between the two inflection points, and Shenzhen city has crossed the second inflection point. The results show that for cities in the first and third stages of the inverted N-shaped curve, increasing the degree of industrial agglomeration can effectively restrain pollution emissions. But for Shanghai and Dongguan, increasing the degree of industrial agglomeration will bring greater pressure on reducing emissions in the short term, however in the long term, it will exert a positive effect on China's urban air pollution reduction through the effects of scale and techniques as the second inflection point is crossed.

Finally, regarding the findings concerning the control variables, the results show that the coefficient of per capita income is positive and that of its quadratic term is negative; however, neither of them is statically significant. It indicates that households would increase consumption with the fast growth in per capita income, and manufacturers scale up production to meet the demand, thus pollution emissions would increase as production ramps up. On the other side, the income effect enables the consumer to purchase luxury goods, for example, clean air, so they prefer to spend much time and effort in participation in public environment supervision. Therefore, the interaction of the two forces could be responsible for the insignificant impact of per capita income on pollution emissions. Then the coefficient estimate concerning the proportion of industry in GDP is positive and significant at a 1% level, which indicates industrialization is a major driver of pollution emissions in China. In addition, the coefficient of openness is also positive at a 1% significant level which means that more polluting industries from developed countries with strict environmental regulations seek China as a pollution refuge, and consequently environmental quality deteriorates. Thus, this finding validates the pollution haven hypothesis to label China as a pollution haven for foreign investors.

4.2. Robustness check results

Firstly, we start the robustness test by adding more control variables to our baseline model. We attempt to add fiscal decentralization into Eq. (1), measured by the ratio of budget revenue to budget expenditure at the city level. For one thing, under the mechanism of fiscal decentralization and political promotion, local governments face strict financial constraints and increased investment for economic growth in the short term; thus, neglecting the ecological environment. For the other thing, the central government attaches greater importance to the ecological environment as pollution issues become a social concern, fiscal decentralization ensures local authorities focus on environmental problems without interference, independently allocate budget for contaminants treatment, and achieve better pollution reduction performance. The result shows that the coefficient of fiscal decentralization index (gov) is significantly positive in Columns (1) and (2) of Table 3, which indicates that under fiscal decentralization, local authorities have a strong incentive to enhance economic growth instead of environmental improvement. More importantly, controlling for fiscal decentralization, digital economy development is still found to lower emissions of industrial sulfur dioxide and smoke dust, at the significance level of 5% and 1%, respectively, and it is consistent with the results of benchmark regression analysis. Further, the inverted-N-shaped association between industrial agglomeration and air pollution in China is also verified from this robustness analysis.

Secondly, we make the robustness test by substituting the per capita emission of industrial sulfur dioxide and industrial smoke

Table 4
Endogeneity analysis.
Source: Authors' computation.

Variables	Omitted variables		A phase lag	
	(1) lnso$_2$	(2) lnsd	(3) lnso$_2$	(4) lnsd
L.lnso$_2$	0.6193*** (0.0941)		0.6533*** (0.0765)	
L.lnsd		0.9345*** (0.0365)		0.5961*** (0.0773)
lndig	−0.0853** (0.0364)	−0.0375* (0.0226)		
L.lndig			−0.0746*** (0.0257)	−0.0783** (0.0313)
ag	−0.3338*** (0.0861)	−0.1145** (0.0519)	−0.2910*** (0.0695)	−0.3892*** (0.0802)
$(ag)^2$	0.0346*** (0.0108)	0.0126* (0.0070)	0.0315*** (0.0078)	0.0411*** (0.0098)
$(ag)^3$	−0.0010*** (0.0003)	−0.0004* (0.0002)	−0.0009*** (0.0002)	−0.0012*** (0.0003)
lntfp	−0.2232** (0.0981)	−0.0900** (0.0429)		
Control Variables	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	2192	2192	2192	2192
AR(1)-P	0.000	0.000	0.000	0.000
AR(2)-P	0.350	0.106	0.278	0.151
Hansen	0.357	0.182	0.483	0.381

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

(dust) for the emissions intensity of industrial sulfur dioxide and industrial smoke (dust), in light of the impact of air pollution on public health. The corresponding results are shown in columns (3) and (4) of Table 3. It is once again found that digital economy development exerts an air pollution-abating effect while the results once again verify the inverted-N-shaped relationship between industrial agglomeration and air pollution in China. Further, neither the symbols nor their significance levels concerning the other variables' coefficients exhibit considerable changes. Therefore, it can be claimed that the outcomes are robust for the cases of both per capita and intensity levels of air pollutants.

Lastly, we conduct the robustness test by shrinking the sample size. Since some cities have comparative advantages in agriculture, forestry, and animal farming in comparison with capital-intensive industries, and, therefore, are likely to discharge fewer air pollutants[4] we exclude those cities from our sample. The decision to shorten the sample was influenced by the understanding that retaining these relatively less-polluted cities in the sample could lower the overall level of pollution emissions in the original sample of cities whereby it can lead to an underestimation of the air pollution-abating impact of the digital economy. The corresponding results are shown in columns (5) and (6) of Table 3. Once again, it can be found that the development of the digital economy effectively reduces the emission intensity of industrial sulfur dioxide and industrial smoke dust, since the coefficients of explanatory variables are consistent with those from the benchmark regression in respect of the predicted signs and significance levels. Therefore, the main conclusions are still valid after shrinking the amount of sample whereby the robustness of the outcomes is further verified.

4.3. Endogeneity analysis results

We take the endogeneity problem into account from two underlying assumptions. First, it would cause estimation errors and second, it would result in incorrect conclusions from the regression outcomes. The endogeneity problem is probably caused by omitted variables. It is thought that technological progress is a critical factor in influencing ecological well-being, accelerated by the knowledge spillover effect of the digital economy development. Thus, it is possible to bring about the endogeneity problem in the benchmark regression by omitting the variable of technological progress. Hence, we use the Total Factor Productivity (TFP) as the metric of technological progress, and the TFP data on the city level in China from 2011 to 2019 is calculated by the method of Data Envelopment Analysis (DEA). The corresponding results are shown in columns (1) and (2) of Table 4.

Besides, the endogeneity problem might originate from bidirectional causality. The development of the digital economy exerts an effect on urban pollution emissions, and conversely, heavily polluted cities may also promote technological innovation necessary for industrial upgrading under the pressure from society. Thus, there may be a bidirectional causality between the digital economy and air pollution. Hence, to account for endogeneity concerns from reverse causation, we use a phase lag of the critical explanation variable as an instrument variable to treat the possible endogenous covariate (i.e., the digital economy variable). The corresponding results are shown in columns (3) and (4) of Table 4. The results, collectively, show that the coefficient symbols of critical explanatory variables are unchanged, albeit slight fluctuations in their significance levels can be observed. Hence, the endogeneity analysis verifies the conclusion that the development of the digital economy reduces air pollution while the nexus between industrial agglomeration and air pollution portrays an inverted N-shape.

4 The document "National Sustainable development Plan for Resource-based Cities (2013–2020)" is from http://www.gov.cn/zfwj/2013-12/03/content_2540070.htm,

Table 5
Test of the mediation effect of industrial agglomeration based on industrial sulfur dioxide emission intensity.
Source: Authors' computation.

Variables	Eastern China			Central China			Western China		
	(1) $lnso_2$	(2) ag	(3) $lnso_2$	(4) $lnso_2$	(5) ag	(6) $lnso_2$	(7) $lnso_2$	(8) ag	(9) $lnso_2$
$L.lnso_2$	0.7134***		0.6449***	0.8867***		0.8570***	0.5639***		0.5415***
	(0.0511)		(0.1349)	(0.0554)		(0.0581)	(0.1945)		(0.1923)
L.ag		0.3087***			0.0012			0.0094	
		(0.1041)			(0.0156)			(0.0312)	
lndig	−0.0800***	0.1099***	−0.0071	−0.1128***	0.0156**	−0.0977***	−0.0995**	0.0281***	−0.0723**
	(0.0294)	(0.0395)	(0.0848)	(0.0364)	(0.0079)	(0.0360)	(0.0450)	(0.0093)	(0.0334)
ag			−0.2510***			−0.3927**			−0.2892
			(0.0876)			(0.1900)			(0.5498)
$(ag)^2$		0.0889***	0.0258***		0.8093***	0.2202		0.4738***	−0.1919
		(0.0148)	(0.0094)		(0.0484)	(0.1362)		(0.0804)	(0.2825)
$(ag)^3$		−0.0026***	−0.0008***		−0.1554***	−0.0437*		−0.0629***	0.0444
		(0.0005)	(0.0003)		(0.0167)	(0.0254)		(0.0162)	(0.0427)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	784	784	784	936	936	936	472	472	472
AR(1)-P	0.000	0.006	0.002	0.000	0.009	0.000	0.001	0.013	0.001
AR(2)-P	0.648	0.132	0.892	0.11	0.408	0.133	0.344	0.124	0.36
Hansen	0.88	0.489	0.326	0.178	0.648	0.113	0.428	0.133	0.378

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

Table 6
Test of the mediation effect of industrial agglomeration based on the emission intensity of industrial smoke dust.
Source: Authors' computation.

Variables	Eastern China			Central China			Western China		
	(1) lnsd	(2) ag	(3) lnsd	(4) lnsd	(5) ag	(6) lnsd	(7) lnsd	(8) ag	(9) lnsd
L.lnsd	0.7090***		0.6763***	0.5716***		0.5724***	0.5773***		0.5640***
	(0.0428)		(0.0964)	(0.1088)		(0.1099)	(0.1580)		(0.1589)
L.ag		0.3087***			0.0012			0.0094	
		(0.1041)			(0.0156)			(0.0312)	
lndig	−0.1351***	0.1099***	−0.0339	−0.1660***	0.0156**	−0.1218**	−0.1413***	0.0281***	−0.0883**
	(0.0294)	(0.0395)	(0.0454)	(0.0503)	(0.0079)	(0.0501)	(0.0465)	(0.0093)	(0.0439)
ag			−0.3341***			−0.6688*			−0.4247
			(0.0835)			(0.3754)			(0.5200)
$(ag)^2$		0.0889***	0.0347***		0.8093***	0.2708		0.4738***	−0.0318
		(0.0148)	(0.0092)		(0.0484)	(0.2608)		(0.0804)	(0.2613)
$(ag)^3$		−0.0026***	−0.0010***		−0.1554***	−0.0307		−0.0629***	0.0189
		(0.0005)	(0.0003)		(0.0167)	(0.0480)		(0.0162)	(0.0393)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	784	784	784	936	936	936	472	472	472
AR(1)-P	0.000	0.006	0.000	0.000	0.009	0.000	0.000	0.013	0.000
AR(2)-P	0.156	0.132	0.119	0.312	0.408	0.294	0.793	0.124	0.765
Hansen	0.44	0.489	0.378	0.107	0.648	0.101	0.712	0.133	0.692

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

4.4. Mechanism analysis

4.4.1. The intermediary effect test of industrial agglomeration

The results of benchmark regression showed that the development of the digital economy could effectively alleviate air pollution in China's cities, while there is a non-linear relationship between industrial agglomeration and air pollution. In fact, the development of the digital economy accelerates the inflow of production factors to large cities and has been reshaping China's economic geography. If the development of the digital economy can attract a continuous influx of economic resources, then its impact on pollution reduction could be further strengthened through the positive external performance of industrial agglomeration, and it indicates that the development of the digital economy development and urbanization strategy implementation can complement each other. If the digital economy is not conducive to industrial agglomeration, then the decentralization of economic resources would weaken the air pollution reduction effect of the digital economy, and it indicates that the development of the digital economy counters the urbanization strategy followed in China. Therefore, it is necessary to test whether industrial agglomeration could be a mediator between the digital economy's impact on air pollution reduction. So we divide the samples into three groups (the cities of eastern regions, central regions, and western regions) to test whether the mediation effect for industrial agglomeration is closely related to the regional economic development level. And the results of the regression are shown in Tables 5 and 6, in which the explained variables are industrial sulfur dioxide and industrial smoke dust, respectively.

The first column, fourth column, and seventh column in the two tables show that the digital economy can significantly reduce the emission intensity of industrial sulfur dioxide and industrial smoke dust in all three regions, and the elasticity of pollution reduction in the eastern region is smaller than in the other two regions. And the second column, fifth column, and eighth column in the two tables show that the digital economy plays a positive role in promoting industrial agglomeration in these areas. Then the third column and sixth column in both two tables show that the industrial agglomeration in eastern and central regions can significantly reduce the emissions of industrial sulfur dioxide and industrial smoke dust, presenting a complete mediating effect in the east region but a partial mediating effect in the central regions. In particular, the proportion of mediating effect in total effect is almost 5.46% for the industrial sulfur dioxide in central regions and 6.28% for industrial smoke dust. At last, the ninth column shows that the intermediary effect of industrial agglomeration on emission reduction is not significant in the western regions.

Hence, the outcomes from the mechanism tests show that although industrial agglomeration is promoted by the development of digital economy in all three regions of concern, it takes the role of a mediator of digital economy development's pollution reduction impact only in the eastern and central regions in China but not in the western region. This could be because of the relatively low extent of industrial agglomeration in Chinese cities located in the western areas. Since we found statistical evidence regarding only the direct pollution reduction effect of digital economy development, our Hypothesis 2 can be deemed valid. Besides, the empirical conclusion is in accord with the actual condition of China's economic development. Firstly, resource-based enterprises that have accumulated in western China, due to its abundant reserves of natural resources in this region, these enterprises have been automated and upgraded using digital technology, and make excessive productive factors outflow to other industries. It advances the adjustment of industrial structures in the area and consequently promotes local pollution reduction. Although the digital economy acts as a driver in industrial agglomeration, it is difficult to reach the threshold to exert an effect of pollution reduction in western China possibly due to the low employment density in the western parts, and only the digital economy takes effect in pollution reduction.

Secondly, in central China, more people subscribe to internet services. Consequently, there is more dematerialization consumption, cultivation of new businesses to meet the demand, acceleration in the rate of the transformation from capital-intensive industries to technology-intensive industries, and finally greater saving of energy. Moreover, the intelligent upgrading of manufacturers forced by the digital economy provides more job opportunities that attract skilled labor inflow, especially to cities in central China. Hence, when industrial agglomeration reaches a certain threshold, manufacturers in this region could scale up production and afford lower pollution treatment costs per unit of product, so that pollutant emission intensity decreases. Hence, the digital economy not only shows a direct effect on pollution reduction but also exerts an indirect effect on it through industrial agglomeration in central China.

On the other hand, the promising future encourages skilled laborers to immediately migrate to cities in eastern China, who obtain information at very little cost through the internet. As talented laborers and manufacturers come together, a specialized division of labor is prompted, and enterprises could purchase intermediate inputs at lower cost instead of producing by themselves, then save energy for the improvement of production efficiency. And the symbiotic relationship between enterprises would make it possible that the intermediate products that some enterprises use can be by-products from other enterprises, based on that, it could establish a recycling economy mode and reduce resource waste as well as pollution emissions. Therefore, the digital economy achieves energy saving and pollution reduction through the scale effect and technological effect of industrial agglomeration in eastern China.

4.4.2. The further mediating effect test of diversified agglomeration and specialized agglomeration

Although the digital economy can promote industrial agglomeration and significantly reduce pollution emissions by exerting the positive externalities of agglomeration in eastern and central China, the empirical analysis of part 4.4.1 does not distinguish between specialized agglomeration and diversified agglomeration, which may act as a heterogeneous mediator between the digital economy and air pollution. Therefore, we will further divide it into specialized agglomeration and diversified agglomeration, and test the mediating effect of the digital economy on pollution reduction. The conclusions provide policy implications for the further development of the digital economy further, control of air pollution, and promotion of the process of industrial agglomeration in various cities across China.

This study, following Duranton and Puga (2000), uses the number of people employed in an industry[5] to construct the relative indices of specialized agglomeration (*rzi*) and diversified agglomeration (*rdi*). The relative index of specialized agglomeration is given by $rzi_i = \max_j (S_{ij}/S_j)$, while the relative index of diversified agglomeration is given by $rdi_i = 1/\sum_j \left|S_{ij} - S_j\right|$, where S_{ij} represents the proportion of the employment of industry j in the total employment of the city i, S_j represents the proportion of the employment of industry j in the total employment of the country. Intuitively, the larger the value of the two indices, the higher the degree of specialization or diversification of agglomeration relative to the national level.

The results of the mediation effect test for diversified agglomeration based on the emission intensity of industrial sulfur dioxide and industrial smoke dust are shown in Tables 7 and 8 respectively. The first column, fourth column, and seventh column in the two tables show that the development of the digital economy can significantly reduce the emission intensity of industrial sulfur dioxide and industrial smoke dust in eastern, central, and western parts of China. Further, the second column, fifth column, and eighth column in the two tables show that the digital economy plays a positive role in promoting diversified agglomeration of those areas. Then the third column in both two tables shows that the diversified agglomeration in eastern regions can significantly reduce the emissions of industrial sulfur dioxide and industrial smoke dust at 1% and 10% significant levels, respectively, which means that there is the existence of a complete mediating effect. Then the sixth column in both two tables shows that there is a partial mediating effect in central China, and the proportion of mediating effect in total effect is almost 43.51% for industrial sulfur dioxide and 29.25% for industrial smoke dust. Lastly, the ninth column in both two tables shows that the mediation effect of diversification agglomeration is not significant in western China.

[5] 19 sectors include agriculture, forestry, animal farming, fishery, mining, manufacturing, production, and supply of electricity, heating power, gas and water, construction, wholesale and retail trades, transport, storage and post, hotels, and catering service, services of information transmission, software and information technology, financial industry, real estate, leasing, and business service, management of water conservancy, environment, and public facilities, services to household, repair, and others, education, health and social service, culture, sports and entertainment, public management, social security, and social organization.

Table 7
Testing the mediating effect of diverse agglomeration based on industrial sulfur dioxide emission intensity.
Source: Authors' computation.

Variables	Eastern China			Central China			Western China		
	(1) lnso$_2$	(2) rdi	(3) lnso$_2$	(4) lnso$_2$	(5) rdi	(6) lnso$_2$	(7) lnso$_2$	(8) rdi	(9) lnso$_2$
L.lnso$_2$	0.7134*** (0.0511)		0.8366*** (0.0799)	0.8867*** (0.0554)		0.9647*** (0.0285)	0.5639*** (0.1945)		0.5374*** (0.1620)
L.rdi		0.0379** (0.0149)			0.0361 (0.0236)			−0.0245 (0.0215)	
lndig	−0.0800*** (0.0294)	0.0218*** (0.0039)	−0.0225 (0.0617)	−0.1128*** (0.0364)	0.0219*** (0.0069)	−0.0913** (0.0364)	−0.0995** (0.0450)	0.0156** (0.0070)	−0.0869** (0.0385)
rdi			−0.2682** (0.1273)			−2.2812* (1.3098)			−0.0231 (0.3812)
(rdi)^2		0.2717*** (0.0118)	0.1310*** (0.0445)		0.2652*** (0.0261)	0.9422* (0.5670)		0.3516*** (0.0128)	−0.0605 (0.1423)
(rdi)^3		−0.0214*** (0.0021)	−0.0170*** (0.0045)		−0.0191*** (0.0053)	−0.1126 (0.0712)		−0.0362*** (0.0033)	0.0096 (0.0152)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	784	782	783	936	934	935	472	472	472
AR(1)-P	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.004	0.000
AR(2)-P	0.648	0.609	0.843	0.11	0.643	0.816	0.344	0.276	0.359
Hansen	0.88	0.88	0.501	0.178	0.729	0.77	0.428	0.173	0.235

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

Table 8
Testing the mediating effect of diversified agglomeration based on the emission intensity of industrial smoke and dust.
Source: Authors' computation.

Variables	Eastern China			Central China			Western China		
	(1) lnsd	(2) rdi	(3) lnsd	(4) lnsd	(5) rdi	(6) lnsd	(7) lnsd	(8) rdi	(9) lnsd
L.lnsd	0.7090*** (0.0428)		0.7572*** (0.0636)	0.5716*** (0.1088)		0.9346*** (0.0413)	0.5773*** (0.1580)		0.5978*** (0.1476)
L.rdi		0.0379** (0.0149)			0.0361 (0.0236)			−0.0245 (0.0215)	
lndig	−0.1351*** (0.0294)	0.0218*** (0.0039)	−0.0244 (0.0485)	−0.1660*** (0.0503)	0.0219*** (0.0069)	−0.0644* (0.0346)	−0.1413*** (0.0465)	0.0156** (0.0070)	−0.0963** (0.0431)
rdi			−6.6660* (3.8118)			−2.2175* (1.2063)			−0.3236 (0.6514)
(rdi)^2		0.2717*** (0.0118)	2.5051* (1.4205)		0.2652*** (0.0261)	0.9128* (0.5072)		0.3516*** (0.0128)	0.0633 (0.2204)
(rdi)^3		−0.0214*** (0.0021)	−0.2721* (0.1536)		−0.0191*** (0.0053)	−0.1093* (0.0623)		−0.0362*** (0.0033)	−0.0034 (0.0219)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	784	782	783	936	934	935	472	472	472
AR(1)-P	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.004	0.000
AR(2)-P	0.156	0.609	0.108	0.312	0.643	0.464	0.793	0.276	0.968
Hansen	0.44	0.88	0.451	0.107	0.729	0.49	0.712	0.173	0.738

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

The results of the mediation effect test for specialized agglomeration based on the emission intensity of industrial sulfur dioxide and industrial smoke dust are shown in Tables 9 and 10, respectively. The statistical insignificance of the coefficients could not verify the mediating effect of specialized agglomeration on the digital economy to pollution reduction in all three regions. Hence, it can be said that the digital economy can promote diversified agglomeration to achieve pollution reduction in eastern and central areas, but it cannot reduce pollution through diversified agglomeration in the west. Besides, since the mediating effect of specialized agglomeration is not significant all over China, our Hypothesis 3 is proven but Hypothesis 4 is not valid. There are two reasons to explain the results as follows:

First, the agglomeration of homogeneous manufacturers does not facilitate cross-industry technological exchange and slows down the pace of green research and development-related investments; finally, it does not achieve the expected pollution reduction effect. Specialized agglomeration is characterized by the accumulation of abundant homogeneous manufacturers in a

Table 9
Testing the mediating effect of specialized agglomeration based on industrial sulfur dioxide emission intensity.
Source: Authors' computation.

Variables	Eastern China			Central China			Western China		
	(1) lnso$_2$	(2) rzi	(3) lnso$_2$	(4) lnso$_2$	(5) rzi	(6) lnso$_2$	(7) lnso$_2$	(8) rzi	(9) lnso$_2$
L.lnso$_2$	0.7134***		0.6366***	0.8867***		0.8894***	0.5639***		0.4626**
	(0.0511)		(0.0417)	(0.0554)		(0.0605)	(0.1945)		(0.2142)
L.rzi		0.1020**			0.3184***			0.0413**	
		(0.0413)			(0.0780)			(0.0176)	
Lndig	−0.0800***	0.0702	−0.0988***	−0.1128***	0.1062***	−0.1056***	−0.0995**	0.1313*	−0.1074**
	(0.0294)	(0.0889)	(0.0283)	(0.0364)	(0.0393)	(0.0357)	(0.0450)	(0.0738)	(0.0481)
rzi			−0.0498			0.0328			0.2625
			(0.0676)			(0.0360)			(0.2465)
(rzi)^2		0.1410***	0.0073		0.0493***	−0.0014		0.5588***	−0.0550
		(0.0050)	(0.0103)		(0.0037)	(0.0017)		(0.1042)	(0.0773)
(rzi)^3		−0.0027***	−0.0001		−0.0006***	0.0000		−0.0728***	0.0019
		(0.0001)	(0.0002)		(0.0001)	(0.0000)		(0.0231)	(0.0057)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	784	778	781	936	926	931	472	470	471
AR(1)-P	0.000	0.008	0.000	0.000	0.031	0.000	0.001	0.000	0.000
AR(2)-P	0.648	0.749	0.500	0.110	0.601	0.19	0.344	0.237	0.752
Hansen	0.880	0.408	0.994	0.178	0.303	0.76	0.428	0.783	0.218

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

limited space. Although specialized agglomeration decreases pollution through the scale effect for treating similar contaminants, it would bring about a net increase of contaminants with the expanding production in the long term. In addition, the agglomeration of homogeneous enterprises leads to technical imitation instead of technical innovation for enhancing competitive advantage at very little cost, and it would gradually weaken the effect of pollution reduction. So specialized agglomeration is not an active mediator of the digital economy development to pollution reduction.

Second, the diversified agglomeration expands the variety of intermediate inputs for enterprise pollution abatement, reserves skilled labor, and builds a recycling economic system by waste reuse. Diversified agglomeration enhances in parallel with the development of the digital economy, and attracts an influx of skilled laborers into large cities for better employment chances and higher incomes. It is convenient for manufacturers which have more options of talents and intermediate inputs for treating contaminants. Moreover, the frequent exchange of information from various industries speeds up green technology progress which is critical to improving the ecological environment continuously. Finally, industrial waste or by-products produced can be reused by other enterprises as inputs, which can reduce waste resources and pollution emissions by establishing recycle economic mode.

Lastly, it is worth noting that the digital economy not only shows a direct effect on decontamination but also exerts an indirect effect on it through diversified agglomeration in central China, compared with its indirect pollution reduction through diversified agglomeration in eastern China. The development of the digital economy in central China promotes high-grade adjustment of industrial structure, improves the efficiency of manufacturing, and simultaneously saves energy and reduces pollution emissions. Moreover, it advances industrial agglomeration to attract an inflow of skilled workers and investments and improves enterprises' efficiency in treating contaminants for abundant intermediate goods and talent reservoirs. Thus, the air pollution reduction effect of the digital economy is significant in central China. However, the comparatively mature economy has a reasonable industrial structure and superior production techniques in eastern China, and the digital economy would cultivate new businesses based on its advantage, enhance diversified agglomeration, enlarge the scale of industries and accelerate the pace of green R&D and its commercial application. So there is a significant mediating effect of diversified agglomeration in eastern China.

5. Conclusions and policy implications

Based on the panel data of Chinese cities from 2011 to 2019, this article constructs a dynamic panel model and mediating effect model to investigate the impact and mechanism, through industrial agglomeration, of China's digital economy development on air pollution, and the following conclusions are drawn. First, the development of China's digital economy can effectively reduce the emission intensity of industrial sulfur dioxide and industrial smoke dust as well as the per capita emissions level of these air pollutants, which is conducive to improving urban air quality, and the elasticity of pollution reduction in the east is smaller than other areas. Second, industrial agglomeration initially impedes air pollution, then boosts air pollution, and ultimately inhibits air pollution again whereby the nexus between industrial agglomeration and air pollution in China depicts an inverted-N-shaped association. Third, in eastern China, the development of the digital economy reduces pollution emissions by promoting industrial agglomeration. This not only verified a direct effect on pollution reduction but also indicated that the digital economy exerts an indirect effect on decontamination through industrial agglomeration in central China. But, in the western region, only the direct air pollution-abating impact of digital economy development was verified. Fourth, diversified agglomeration, instead of specialized agglomeration, acts as a positive mediator of digital economy development's pollution reduction impact in eastern and central areas, but not in the western area.

Our results offer some useful policy implications concerning air pollution abatement in China. Firstly, China should promote the coordination of the digital economy and environmental governance so that the development of its digital economy can simultaneously contribute to air quality improvement. In central and

Table 10
Testing the mediating effect of specialized agglomeration based on the emission intensity of industrial smoke and dust.
Source: Authors' computation.

Variables	Eastern China			Central China			Western China		
	(1) lnsd	(2) rzi	(3) lnsd	(4) lnsd	(5) rzi	(6) lnsd	(7) lnsd	(8) rzi	(9) lnsd
L.lnsd	0.7090*** (0.0428)		0.7064*** (0.0957)	0.5716*** (0.1088)		0.9431*** (0.1342)	0.5773*** (0.1580)		0.5805*** (0.1566)
L.rzi		0.1020** (0.0413)			0.3184*** (0.0780)			0.0413** (0.0176)	
lndig	−0.1351*** (0.0294)	0.0072 (0.0889)	−0.1337** (0.0570)	−0.1660*** (0.0503)	0.1062*** (0.0393)	−0.0714* (0.0432)	−0.1143** (0.0465)	0.1313* (0.0738)	−0.1048** (0.0447)
rzi			0.0180 (0.0676)			0.0566 (0.0350)			0.0470 (0.2024)
$(rzi)^2$		0.1410*** (0.0050)	−0.0002 (0.0093)		0.0493*** (0.0037)	−0.0018 (0.0017)		0.5588*** (0.1042)	0.0279 (0.0892)
$(rzi)^3$		−0.0027***	−0.0000		−0.0006*** (0.0001)	0.0000 (0.0000)		−0.0728*** (0.0231)	−0.0050 (0.0078)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	784	778	781	936	926	931	472	470	471
AR(1)-P	0.000	0.008	0.000	0.000	0.031	0.005	0.000	0.000	0.000
AR(2)-P	0.156	0.749	0.065	0.312	0.601	0.556	0.793	0.237	0.971
Hansen	0.44	0.408	0.18	0.107	0.303	0.337	0.712	0.783	0.729

Note: The standard errors are between brackets.
*Significance at the 10% level.
**Significance at the 5% level.
***Significance at the 1% level.

western areas, it is necessary to improve information infrastructure, continuously narrow the "digital divide", push ahead with comprehensive industrial restructuring and upgrading, and effectively reduce pollution emissions with the rapid development of the digital economy. On the other hand, in eastern China, it is in urgently needed to encourage the innovation and application of green technologies, improve the environmental governance of local authorities with the application of digital technology, and simultaneously enhance public participation in environmental supervision.

Secondly, China should accelerate the development of the digital economy and industrial agglomeration process, and deploy pollution control strategies according to the actual conditions. In the eastern area, policy-makers should create a favorable atmosphere for cross-industry communication and cooperation, build a circular economic system by taking advantage of diversified agglomeration, and gradually push forward the green transformation of the Chinese energy sector. Particularly in the central region, local authorities should offer subsidies for companies specialized in pollution abatement and energy management, and make the best use of the scale effect from industrial agglomeration to lower social costs associated with decontamination. In the western area, local government should continuously improve information infrastructure, steadily promote industrial restructuring and upgrading, accelerate the digital transformation of enterprises, and develop and utilize various renewable energy resources to replace fossil energy to impede air pollution in the future.

Thirdly, China should promote inter-regional exchanges and cooperation in respect of developing its digital economy further. The central and western areas, in particular, should undertake the industrial transfer from the eastern area and upgrade traditional industries with digital technologies. In this regard, the eastern region should export advanced green technologies to the central and western areas through frequent exchanges and cooperation. Furthermore, all over China, it is essential to strengthening efforts in promoting digital economy development in an environmentally-sustainable manner.

Data unavailability contributed to a couple of the limitations faced in this study. Accordingly, we could not include more Chinese cities in our sample and also could not use air pollution-related data from different industries. Besides, it is unclear whether the recommended policies would hold for other global economies with similar macroeconomic features as China. Hence, future studies can look to build on these limitations to conduct more comprehensive analyses.

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CRediT authorship contribution statement

Liu Wu: Conceptualization, Data curation, Software, Visualization, Validation, Project administration, Formal analysis, Investigation and original draft. **Xiaowen Wan:** Conceptualization, Data curation, Software, Visualization, Validation, Project administration, Formal analysis, Investigation and original draft. **Atif Jahanger:** Methodology, Resources, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. **Mengyi Li:** Writing – review & editing. **Muntasir Murshed:** Original draft, Methodology, Writing – original draft. **Daniel Balsalobre-Lorente:** Writing – review & editing.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Appendix

See Table A.1.

Table A.1
List of selected Chinese cities.
Source: Authors' computation.

No.	Province	City	No.	Province	City	No.	Province	City	No.	Province	City
1	Beijing	Beijing	70		Nanjing	139		Naning	208		Qingdao
2	Tianjin	Tianjin	71		Wuxi	140		Liuzhou	209		Jinan
3		Shijiazhuang	72		Xuzhou	141		Guilin	210		Zibo
4		Tangshan	73		Changzhou	142		Wuzhou	211		Zaozhuang
5		Handan	74		Suzhou	143		Beihai	212		Yantai
6		Zhangjiakou	75	Jiangsu	Nantong	144		Fangchenggang	213		Weifang
7	Hebei	Baoding	76		Lianyungang	145	Guangxi	Qinzhou	214		Jining
8		Cangzhou	77		Huaian	146		Guigang	215	Shandong	Linyi
9		Qinghuangdao	78		Yancheng	147		Yulin	216		Taian
10		Xingtai	79		Yangzhong	148		Hezhou	217		Liaocheng
11		Langfang	80		Zhengjiang	149		Baise	218		Hezhe
12		Chengde	81		Suqian	150		Hechi	219		Dezhou
13		Taiyuan	82		Hangzhou	151		Laibin	220		Binzhou
14		Datong	83		Jiaxing	152		Chongzuo	221		Dongying
15		Yangquan	84		Huzhou	153	Hainan	Haikou	222		Weihai
16		Jincheng	85		Zhoushan	154		Shanya	223		Rizhao
17	Shanxi	Shuozhou	86	Zhejiang	Jinhua	155	Chongqing	Chongqing	224		Zhengzhou
18		Xinzhou	87		Shaoxing	156		Chengdu	225		Kaifeng
19		Jinzhong	88		Wenzhou	157		Zigong	226		Luoyang
20		Lvliang	89		Taizhou	158		Panzhihua	227		Pingdingshan
21		Linfen	90		Lishui	159		Luzhou	228		Anyang
22		Yuncheng	91		Quzhou	160		Deyang	229		Puyang
23		Tongliao	92		Ninggo	161		Mianyang	230		Xinxiang
24		Ulanqab	93		Xuancheng	162		Guangyuan	231	Henan	Jiaozuo
25		Ordos	94		Suzhou	163		Suining	232		Hebi
26		Bayannur	95		Chuzhou	164		Neijiang	233		Xuchang
27	Inner Mongolia	Huhehaote	96		Chizhou	165	Sichuan	Leshan	234		Luohe
28		Baotou	97		Fuyang	166		Nanchong	235		Sanmenxia
29		Wuhai	98		Luan	167		Yibin	236		Nanyang
30		Chifeng	99		Hefei	168		Guangan	237		Shangqiu
31		Shenyang	100	Anhui	Bengbu	169		Dazhou	238		Xinyang
32		Dalian	101		Huainan	170		Ziyang	239		Zhoukou
33		Anshan	102		Tongling	171		Meishan	240		Zhumadian
34		Fushun	103		Maanshan	172		Bazhong	241		Changsha
35		Benxi	104		Huaibei	173		Yaan	242		Zhuzhou
36		Dandong	105		Wuhu	174		Guiyang	243		Xiangtan
37	Liaoning	Jinzhou	106		Anqing	175		Liupanshui	244		Hengyang
38		Yingkou	107		Huangshan	176	Guizhou	Zunyi	245		Shaoyang
39		Fuxin	108		Fuzhou	177		Anshun	246	Hunan	Yueyang
40		Liaoyao	109		Sanming	178		Kunming	247		Changde
41		Tieling	110		Nanping	179		Zhaotong	248		Zhangjiajie
42		Chaoyang	111		Ningde	180		Qujing	249		Yiyang
43		Panjing	112	Fujian	Putian	181	Yunnan	Yuxi	250		Yongzhou
44		Huludao	113		Quanzhou	182		Baoshan	251		Chenzhou
45		Jilin	114		Zhangzhou	183		Lijiang	252		Loudi
46		Siping	115		Longyan	184		Lincang	253		Huaihua
47		Liaoyuan	116		Xiamen	185		Xian	254		Guangzhou
48	Jilin	Tonghua	117		Nanchang	186		Tongchuan	255		Shenzhen
49		Baishan	118		Jingdezheng	187		Baoji	256		Zhuhai
50		Baicheng	119		Pingxiang	188		Xianyang	257		Shantou
51		Songyuan	120		Jiujiang	189	Shaanxi	Weinan	258		Foshan
52		Harbin	121		Xinyu	190		Hanzhong	259		Shaoguan
53		Qiqihar	122	Jiangxi	Yingtan	191		Ankang	260		Heyuan
54		Mudanjiang	123		Ganzhou	192		Shangluo	261		Meizhou
55		Jiamusi	124		Yichun	193		Yanan	262		Huizhou
56		Jixi	125		Shangrao	194		Yulin	263		Shanwei
57	Heilongjiang	Hegang	126		Ji'an	195		Lanzhou	264	Guangdong	Dongguan
58		Shuangyashan	127		Fuzhou	196		Jiayuguan	265		Zhongshan
59		Qitaihe	128		Wuhan	197		Jinchang	266		Jiangmen
60		Heihe	129		Huangshi	198		Baiyin	267		Yangjiang
61		Yichun	130		Shiyan	199		Tianshui	268		Zhanjiang
62		Daqing	131		Jingzhou	200	Gansu	Jiuquan	269		Maoming
63	Shanghai	Shanghai	132	Hubei	Yichang	201		Zhangye	270		Zhaoqing
64	Ningxia	Yinchuan	133		Ezhou	202		Wuwei	271		Qingyuan

(*continued on next page*)

Table A.1 (*continued*).

65		Wuzhong	134		Jingmen	203		Dingxi	272		Chaozhou
66		Zhongwei	135		Xiaogan	204		Longnan	273		Jieyang
67		Guyuan	136		Huanggang	205		Pingliang	274		Yunfu
68	Xinjiang	Urumqi	137		Xianning	206		Qingyang			
69		Kelamayi	138		Suizhou	207	Qinghai	Xining			

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