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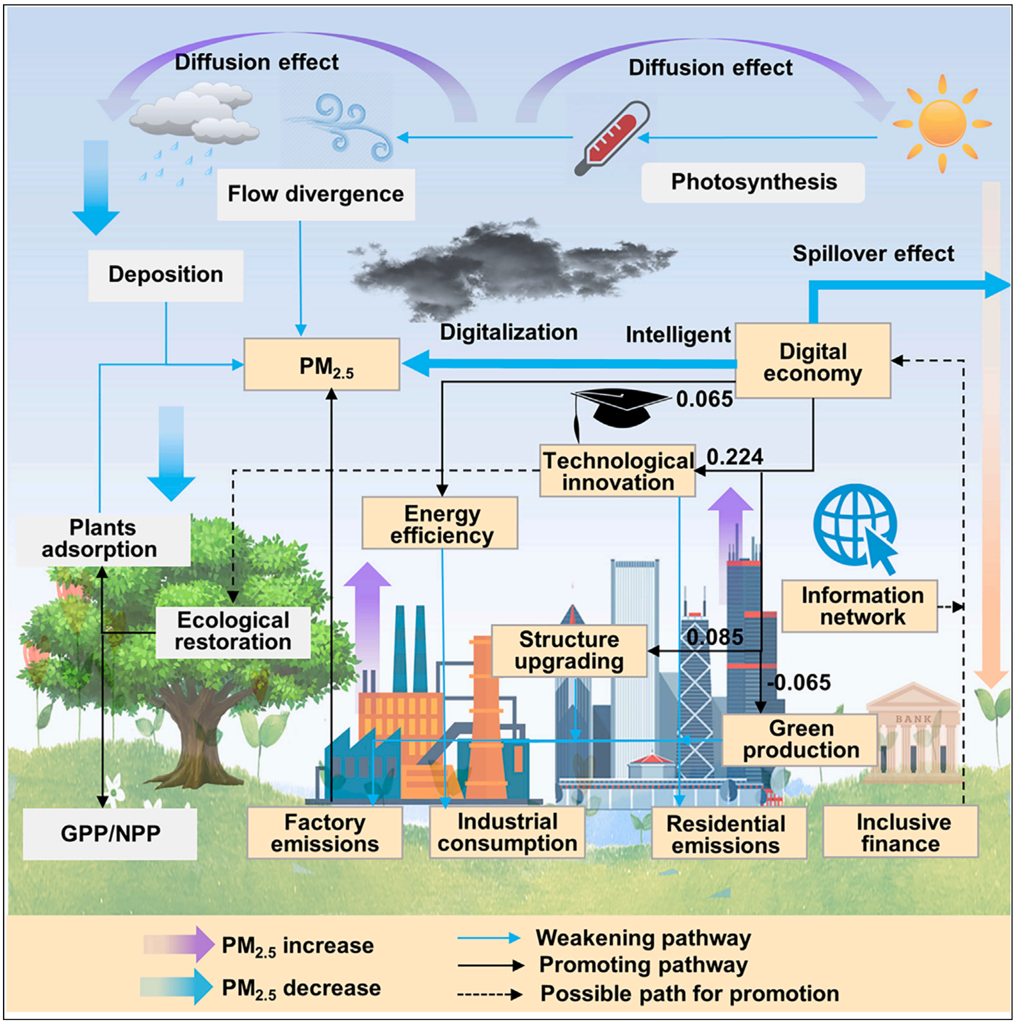

Guoen Wei, Yiting Yang, Ruzi Li, Yaobin Liu, Bao-Jie He

liuyaobin@ncu.edu.cn (Y.L.)
baojie.unsw@gmail.com (B.-J.H.)

Highlights

Digital economy significantly contributes to air pollution mitigation in China

Spillover effect of digital economy on air pollution mitigation exceeds direct effect

Digital economy mitigates $PM_{2.5}$ mainly via industrial optimization and green innovation

Digital economy impacts $PM_{2.5}$ differently through various scenarios at different scales

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Digital economy exhibits varying degrees of mitigation of air pollution in China: Total cities-economic subdivisions-urban agglomerations

Guoen Wei,[1,2] Yiting Yang,[2,3] Ruzi Li,[2,3] Yaobin Liu,[2,3,*] and Bao-Jie He[4,5,6,*]

SUMMARY

Air pollution is a challenge for many cities. The digital economy enhances support for environmental pollution management, while the mechanisms and scaling heterogeneity remain unclear. This study explored the contribution of digital economy development to $PM_{2.5}$ concentrations control in China and driving mechanisms in different economic subregions and urban agglomerations. Results show that the spillover transfer effect on air pollution mitigation far exceeded the direct effect at different scales. At the national scale, the air pollution mitigation effect of digital economy was mainly through empowering industrial structure optimization and green technology innovation, while it also affected economic subregions and urban agglomerations through varying scenario combinations of pathways with structural optimization, green production, resource allocation, and technology innovation. Research findings provide support for cross-regional joint management strategies of digital economy and air quality and designing regionally differentiated pollution control pathways in the digital economy dimension.

INTRODUCTION

Air pollution is a major challenge for almost all global cities. Along with unprecedented development of industrialization and urbanization in China, the extensive change of socio-economic activities in transportation,[1,2] indoor cooking and heating, and urban sprawl, pollution levels in the form of fine particulate matter have been significantly aggravated. The $PM_{2.5}$ pollution has brought serious impacts to the ecological environment[3,4] and residents' life and health.[2,5] The Action Plan for the Prevention and Control of Air Pollution (abbreviated as Action Plan) released in 2013.[6,7] However, the "Action Plan" implementation is still challenging, for example, due to the contradiction between development and protection.[8,9] Moreover, many studies have confirmed that pollution mitigation measures mainly focus on end-of-pipe control, while front-end process control, such as energy structure adjustment, enterprise technological innovation, and resource utilization improvement, is neglected.[6,10] These issues require further exploration to overcome a significant gap between China's long-term goal for combating pollution and the actual situation. How to further reduce $PM_{2.5}$ exposure is an important issue to be solved for achieving China's green living environment, sustainable urban construction (Goal 11, Sustainable Development Goals [SDGs]), and sustainable production mode (Goal 12, SDGs) and also helps to contribute China's experience to the global air pollution control ambitions.

The digital economy uses digital knowledge and information as key production factors to continuously improve the level of digitalization and intelligence of traditional industries. It is emerging as a key force in reorganizing global factor resource allocation, reshaping the global economic structure and changing the global competitive landscape.[11,12] The role of the digital economy in China's industrial green transformation,[13] economic growth,[14] government governance,[15] energy efficiency,[16] industrial technology innovation,[17] and reduction of carbon emissions[18] has been widely confirmed. However, little is known about whether digital economy contributes to haze mitigation in China, and the channel of the intrinsic linkage between the two.[19] This is the challenge that must be addressed to mitigate global haze pollution from the digital economy dimension.

Several variables may play a role in the mechanisms of the digital economy affecting haze governance, such as technological innovation, industrial structure, production efficiency, and clustering effects. On the one hand, the digital economy accelerates the integration of traditional socio-economic form and information technology, improve traditional production efficiency, and change traditional industrial structure, thereby reducing environmental pollution emissions. On the other hand, the digital economy forces enterprises to accelerate technological progress, structural optimization, and scale agglomeration by improving the transmission efficiency of information and changing the business

[1]School of Resources and Environment, Nanchang University, Nanchang 330031, China
[2]Central China Research Center for Economic and Social Development, Nanchang University, Nanchang 330031, China
[3]School of Economic and Management, Nanchang University, Nanchang 330031, China
[4]Centre for Climate–Resilient and Low–Carbon Cities, School of Architecture and Urban Planning, Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing 400045, China
[5]Institute for Smart City of Chongqing University in Liyang, Chongqing University, Liyang, Jiangsu 213300, China
[6]Lead contact
*Correspondence: liuyaobin@ncu.edu.cn (Y.L.), baojie.unsw@gmail.com (B.-J.H.)

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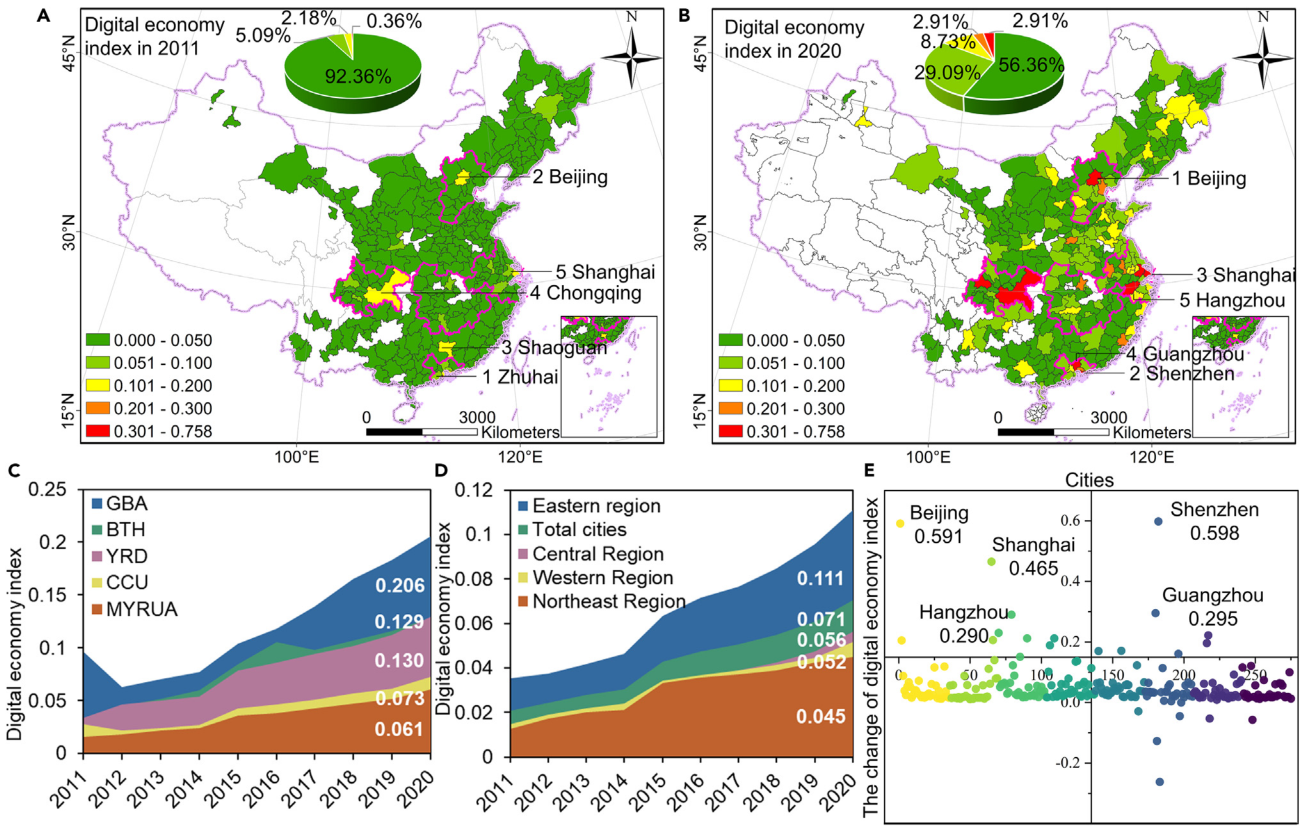

Figure 1. Spatiotemporal distribution of DEI in national cities from 2011€ to 2020

(A and B), the evolution of mean DEI in five major urban agglomerations (C), the evolution of mean DEI in four economic subdivisions (D), and change of DEI in the whole region (E).

environment. And then it contributes to clean technology innovation, saving consumption costs, improving energy use efficiency, and effectively curbing haze pollution.

Some studies have explored the association between the digital economy and air quality factors such as haze pollution and "reduction of pollution and carbon emissions" in China, offering support for a relationship existing between digital economy and air pollution as well as the possible green contribution of the digital economy.[20,21] Nevertheless, digital economy level, energy structures, socio-economic conditions, policy support for the digital economy, technological innovation foundation, and environmental policy trends all vary significantly across China's economic regions and urban agglomerations.[17,22,23] It is unclear whether the driving mechanisms of the digital economy and their contribution to air pollution management are applicable to all cities and whether there is regional heterogeneity across different types of economic subdivisions and urban agglomerations.[24] Thereby, it is necessity to investigate the regional heterogeneity of the contribution of the digital economy to haze governance, and how these complex transmission channels, such as technological innovation, structural optimization, efficiency improvement, and scale agglomeration, will shape the regionally differentiated mechanism combination for haze governance.

Based on the shortcomings of the existing research, several pressing research questions emerge. Firstly, does the digital economy make an effective contribution to $PM_{2.5}$ governance in China, and does this impact vary by region? Secondly, does the impact of the digital economy on $PM_{2.5}$ concentrations exhibit a spatial transmission effect? Finally, what are the transmission mechanisms of the digital economy on $PM_{2.5}$ governance in China, and do these mechanisms have significant scale differences across different regions? To fill these knowledge gap, our study quantified the spatiotemporal characteristics of the digital economy and $PM_{2.5}$ concentrations in 2011–2020 across China based on panel data and remote sensing datasets of 275 Chinese cities. Spatial panel Durbin model (SPDM) and partial differential equation (P.D.E) are used to quantify the heterogeneity of impact intensity and networked spillover effect of digital economy on air pollution, respectively. We also employed intermediary effect model to investigate the pathway combinations of the impact mechanism of digital economy on air pollution control in China's different regions. All analyses are built on different scales, including all urban areas, economic subregions, and urban agglomerations, to investigate the regional heterogeneity of the driving mechanisms (Figure S1). Through a systematic investigation of the mechanisms of digital economy on China's air pollution control, we provide a quantitative reference for increasing the contribution of the digital economy in China's clean air action and also contribute new experiences from China to the global sustainable urban air quality development.

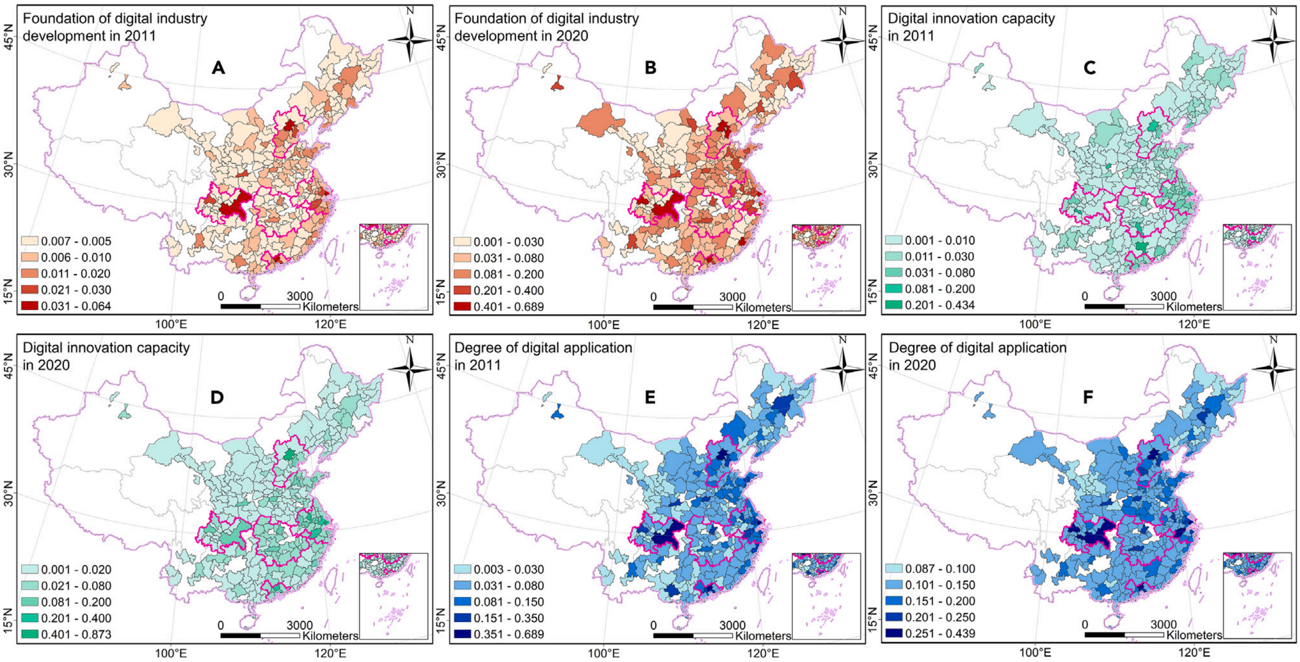

Figure 2. Spatial distribution of digital economy foundation
(A and B), digital innovation capability (C and D), and digital application degree (E and F) from 2011 to 2020.

RESULTS

Evolution of China's digital economy

From 2011 to 2020, China's digital economy made great progress, with the average digital economy index (DEI) value increasing from 0.021 to 0.071 at an average annual growth rate of 14.61%. The proportion of medium-value cities (0.100<DEI<0.200) increased from 2.55% to 14.55% (Figure 1D). High-value central cities with strong digital economy potential (DEI>0.200) (Figure 2) gradually spread and clustered to China's strategic urban agglomerations (e.g., BeiJing-Tianjin-Hebei urban agglomeration [BTH], Yangtze river delta urban agglomeration [YRD], and Guangdong-Hong Kong-Macao greater bay area [GBA]) by 2020 (Figures 1A and 1B). The "spatial divide" of the digital economy was not alleviated and demonstrated significant regional disparities in development patterns and growth trends. Traditional regional disparities in China's economic subdivisions remained in the digital economy, with a DEI gap pattern of the Eastern region>Central region>West region>Northeast region (Figure 1D). Regarding urban agglomerations, GBA, YRD, and BTH maintained their leading positions in the digital economy (with mean DEI values of 0.206, 0.130, and 0.129 in 2020, respectively). They far exceeded Chengdu-Chongqing urban agglomeration (CCU) and middle reaches of the Yangtze River urban agglomeration (MRYRU) in all periods (Figure 1C). In particular, the YRD region formed a triple-legged networked pattern of Shanghai-Hangzhou-Suzhou with high DEI values (Figure 1B).

The growth trend of China's digital economy also exhibited significant regional heterogeneity (Figure 1E; Figure 3). From 2011 to 2020, 97.820% of Chinese cities witnessed an improvement in the digital economy. However, only a small percentage (10.910%) of them experienced high-speed development (DEI growth>0.100). It mainly included super first-tier cities (e.g., Beijing, Shanghai, Shenzhen, and Guangzhou) and some provincial capitals like Nanjing and Hangzhou. The digital economy of 86.91% of Chinese cities was in a state of initial improvement (DEI growth<0.100). In terms of urban agglomerations, the most significant improvement was observed in the GBA (average DEI increase 0.108), followed by eastern urban agglomerations such as BTH (average DEI increase 0.098) and YRD (average DEI increase 0.096). Along with the improvement in the degree of digital industry foundation and application (Figures 3B and 3D), some provincial capitals in Central and Western China also achieved significant digital economy development, such as Chengdu, Chongqing, and Wuhan, with DEI growth of 0.222, 0.196 and 0.171, respectively.

Evolution of China's $PM_{2.5}$ concentrations

$PM_{2.5}$ concentration levels in sampling cities across China decreased rapidly over the past decade, from 50.464 $\mu g/m^3$ to 30.901 $\mu g/m^3$, with an annual average decay rate of 5.17% (Figures 4D and 4E), and the proportion of severely polluted cities (average $PM_{2.5}$ concentrations>65 $\mu g/m^3$) decreased from 17.09% to zero (Figure 4C). However, haze pollution has not really disappeared entirely in China, where approximately 30.18% of sampling cities maintained a $PM_{2.5}$ concentration above 35 $\mu g/m^3$, the maximum permissible limit of the World Health Organization (WHO)'s global air quality guidelines, in 2020.[25,26] From a spatiotemporal perspective, $PM_{2.5}$ concentration exposure in China centered on the North China Plain over 2011–2020. In 2011, Xingtai, Hengshui, and Jiaozuo formed a high-value group, with $PM_{2.5}$ concentrations exceeding 89 $\mu g/m^3$ in the five worst-affected and most-polluted cities (Figure 4A). By 2020, the air quality and ecology

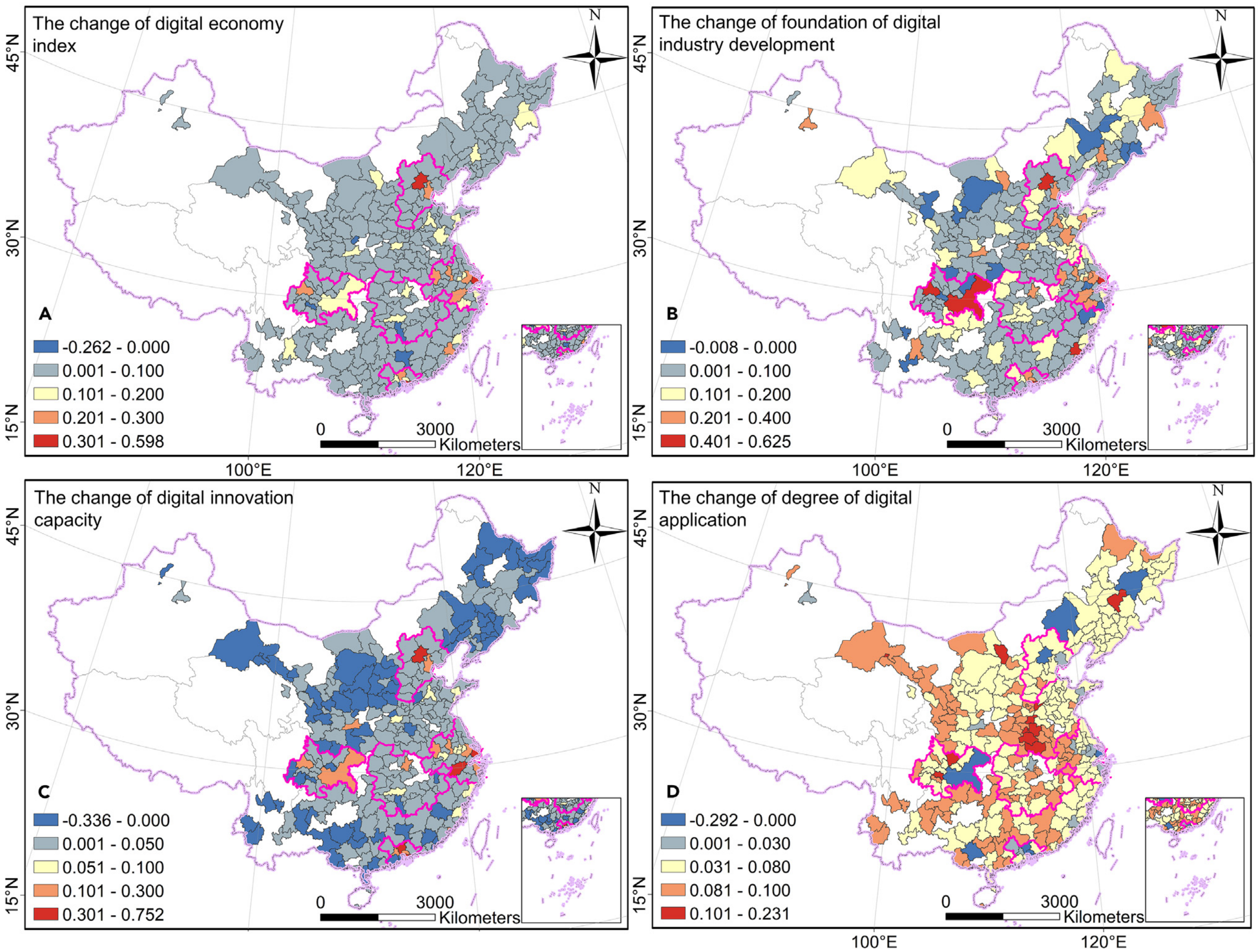

Figure 3. Spatial distribution of changes in the digital economy index

(A), digital economy foundation (B), digital innovation capability (C), and digital application degree (D) from 2011 to 2020.

of GBA, CCU, YRD, and MYRYU had significantly improved, whereas the North China Plain remained the epicenter of air pollution in China (Figure 4B).

$PM_{2.5}$ concentrations in economic subdivisions generally exhibited a pollution difference, following a gradient of Central region>Northeast region>Eastern region>Western region. The BTH was the most polluted, with an average $PM_{2.5}$ concentration above 42.47 $\mu g/m^3$ in 2020. The GBA, YRD, MYRYU, and CCU all witnessed reduced air pollution to a similar range (20–35 $\mu g/m^3$). Annual average $PM_{2.5}$ concentrations in all cities showed a decreasing trend, but there were significant differences in the degree of decrease. A significant improvement in air quality was observed in 13.455% of the cities ($PM_{2.5}$ reductions more than 30 $\mu g/m^3$), and 10.545% of the cities experienced a decrease of less than 10 $\mu g/m^3$. GBA demonstrated excellent performance in air quality mitigation, with a decline rate of 50.639%, followed by CCU, MYRYU, and BTH with a respective reduction of 47.405%, 46.463%, and 42.593% over the past decade. Air quality improvement in the central and eastern regions was also noteworthy, with a decrease rate of 41.374% and 39.513%, respectively.

Contribution of the digital economy to air pollution governance

Based on the Moran, Lagrange multiplier (LM), and likelihood ratio (LR) test results (Table S3), we use SPDM to investigate the mechanism of the digital economy's impact on air pollution. Across China, the pollution mitigation effect of the digital economy was not significant (Table S4). However, this is an inexact result based on point regression, and the P.D.E method needs to be utilized to witness the total effect of the digital economy on $PM_{2.5}$ concentrations.[38] The digital economy had a significant positive effect on mitigating $PM_{2.5}$ concentrations in China ($p < 0.01$). A 1% increase in DEI could lead to a 4.280% reduction in $PM_{2.5}$ concentrations (Table 1 column 2). The effects of anthropogenic and natural control variables on $PM_{2.5}$ concentrations were also investigated. For instance, import and export foreign trade (IET) and the scale of government fixed asset investment (FAI) significantly restrained $PM_{2.5}$ accumulation ($p < 0.01$). First, such a result is attributable to China's vigorous promotion of investment and trade-related environmental regulatory policies.[19] Second, advanced green recycling

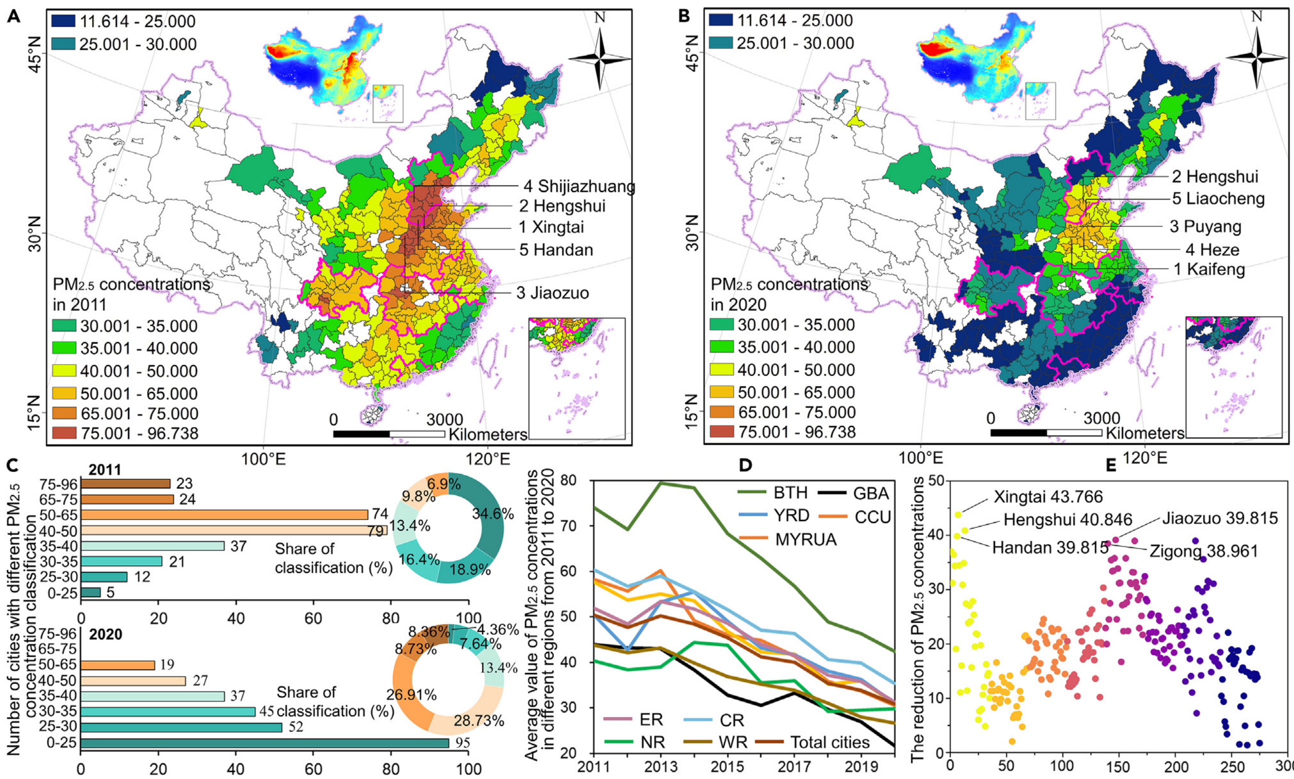

Figure 4. Spatial-temporal distribution of $PM_{2.5}$ concentrations from 2011€ to 2020

(A and B), number and proportion of cities classified with $PM_{2.5}$ concentrations (C), the evolution of mean values in five major urban agglomerations and four major economic subdivisions (D), and total reduction in $PM_{2.5}$ concentrations from 2011 to 2020 (E).

technologies and energy-saving and emission-reduction tools and strategies are disseminating through investment and trade, advantageous for controlling regional aerosol pollutants.

Spatial heterogeneity of the impact of the digital economy on $PM_{2.5}$ concentrations was also revealed (Table 1, Columns 2–5). Among economic subdivisions, the digital economy contributed the most to suppressing $PM_{2.5}$ concentrations in China's central cities, followed by eastern and western cities, with elastic coefficients of ln(DEI) of −4.349, −3.083, and −2.352, respectively. The digital economy in the northeast region significantly enhanced $PM_{2.5}$ concentrations ($p < 0.01$), with an elastic coefficient of ln(DEI) of 1.208. Possible reasons for this are as follows: i) digital economy development is dependent on digital infrastructure construction which may cause energy use and pollution emissions, challenging the northeast region with an underdeveloped digital economy to overcome the threshold[5,24]; ii) the Northeast region is mainly dominated by steel, machinery, automotive, and chemical industries, so that digital technology application could facilitate heavy industrial manufacturing capacity and efficiency, and thereby $PM_{2.5}$ concentrations increase.[27] Among urban agglomerations, the elastic coefficients of the digital economy were primarily negative, but the impact exhibited significant spatial heterogeneity (Table 2). The pollution reduction effects were more pronounced in MRYRU and YRD, achieving reduction of $PM_{2.5}$ concentrations of 3.192% and 2.266%, respectively, for each 1% increase in DEI. The pollution reduction effects were lower in GBA, BTH, and CCU, with ln(DEI) elastic coefficients of −0.614, −0.524, and −0.501, respectively.

Direct and spatial spillover effects of digital economy

The digital economy is capable of compressing spatial distances through improving inter-regional information transmission efficiency in breadth and depth. Typically, development of information and communications technology (ICT) promotes the cross-regional and low-cost dissemination of digital information.[28] These pathways facilitate the networked transmission feature of the digital economy and determine the necessity of examining the spatial spillover effects of the digital economy on air pollution governance. This investigation revealed that the spatial spillover effects on $PM_{2.5}$ concentrations were much higher than direct effects, in scenarios at national level, economic subdivisions, and urban agglomerations (Table 3). A 1% increase in DEI in all urban areas directly led to a reduction of 0.018% in local $PM_{2.5}$ concentrations but indirectly resulted in a reduction of 4.261% in $PM_{2.5}$ concentrations in adjacent areas ($p < 0.01$).

The spillover-effect mechanism could be 2-fold: the synergistic improvement of regional production efficiency and the joint prevention and control of air pollution. The digital economy's ability to compress temporal and distance costs in technology, innovation, and information transmission leads to an improvement in transmission efficiency and fosters a synergistic enhancement of production efficiency among

Table 1. Regression analysis results of total effects for all cities and four major economic subdivisions

	Total cities	Eastern region	Northeast region	Central region	Western region
ln (DEI)	−4.280***	−3.083***	1.208***	−4.349***	−2.352**
	(-3.956)	(-2.804)	(3.404)	(-3.441)	(-2.345)
ln (GDP)	−1.805	−1.883	0.117***	10.799***	−5.746***
	(-1.183)	(-0.664)	(5.241)	(3.122)	(-3.344)
ln (EI)	0.570	−0.751	0.402	−0.189	−0.654*
	(1.210)	(-0.729)	(1.584)	(-0.486)	(-1.835)
ln (PU)	8.742**	27.818***	0.001	−14.458*	25.481***
	(2.352)	(2.826)	(0.003)	(-1.743)	(4.500)
ln (PD)	8.579***	4.048	0.020*	−6.257**	−1.539
	(3.968)	(1.657)	(1.931)	(-2.325)	(-1.401)
ln (IET)	−3.022***	−3.970*	−0.041***	−1.492**	−2.699***
	(-3.844)	(-1.707)	(-6.394)	(-2.374)	(-4.019)
ln (FAI)	−3.023***	−1.321	−0.350*	−1.747	−2.822**
	(-2.584)	(-0.889)	(-1.948)	(-1.535)	(-2.529)
ln (PRE)	0.021	−2.362*	−0.115**	−0.914	−0.645
	(0.020)	(-1.798)	(-2.000)	(-1.262)	(-0.385)
ln (HUM)	2.637***	10.127	0.815	22.432**	−2.141
	(4.013)	(1.240)	(0.306)	(2.581)	(-0.569)
ln (TEM)	2.847***	−15.510	0.387	18.635***	5.623***
	(5.680)	(-1.467)	(1.204)	(3.293)	(3.783)
ln (NDVI)	1.734	−11.190	1.628	15.044**	−5.414
	(1.530)	(-1.492)	(0.727)	(2.190)	(-1.598)
R2	0.971	0.984	0.849	0.977	0.689
sigma^2	0.004	0.003	0.011	0.002	0.023
log likelihood	3845.474	1300.602	273.212	1281.694	1.841

Note. *Statistical significance at 10% level; ** Statistical significance at 5% level; ***Statistical significance at 1% level; t-statistics in parentheses.

cities.[29] This productivity transfer effect is especially more apparent under the support of China's current regionally coordinated development strategies (e.g., "Western Development" and "Rise of Central China") and integration strategies such as the urban agglomerations construction strategies.[24] Development of the digital economy also promotes interconnection and sharing of environmental monitoring data and prevention and control standards. This facilitates regional resource conservation and pollution reduction and promotes joint prevention and governance measures of regional air pollutants.[5] For example, Wuxi city is a typical pioneer in China to develop a digital law enforcement system for regional atmospheric environment pollution.[30,31]

Across economic subdivisions, both direct and spillover effects were most pronounced in central and eastern cities. Elasticity coefficients of spatial spillover effects in the two regions were −4.300 and −3.038, respectively ($p < 0.01$). In comparison, the elasticity coefficient in the western region was −2.353 ($p < 0.05$), but the direct effect was not significant. Both direct and spatial spillover effects in the northeast region were significantly positive. This finding was synergistic with the spatially heterogeneous performance of the total effects of the digital economy in each subdivisions. Across urban agglomerations, both direct and spatial spillover effects exhibited a consistent order with the intensity of total effects. The inhibitory effect on both local and adjacent $PM_{2.5}$ concentrations ranked as MRYRU>YRD>GBA>BTH>CCU, with the elasticity coefficients of −4.300 and −2.353 in MRYRU and YRD, respectively. Moreover, in addition to using the queen contiguity matrix, the SPDM based on the "inverse distance" spatial weight matrix was implemented to confirm the validity of the findings. The confirmatory test results suggest that the research findings were robust and that no abrupt change for the regression coefficient of economic subdivisions and urban agglomerations in the aforementioned results system was observed, thus ensuring the robustness and reliability of the model.

Transmission paths of digital economy

The effect of potential mediating channels, such as structural optimization, green production, resource allocation, and technology innovation, on digital economy's impact on $PM_{2.5}$ concentrations was examined (Figure 5). Across China, digital economy had a very positive impact on industrial structure upgrading and green technological innovation, with elasticity coefficients of −0.085 and 0.224, respectively

Table 2. Regression analysis results of total effects for five strategic urban agglomerations

	BTH	YRD	GBA	CCU	MRYRU
ln (DEI)	−0.501*	−2.266***	−0.614***	−0.524*	−3.192*
	(-1.863)	(-3.275)	(-3.275)	(-1.799)	(-1.944)
ln (GDP)	0.059	5.012**	0.805*	0.541***	0.023
	(0.347)	(2.731)	(2.182)	(2.916)	(0.112)
ln (EI)	−0.089	−0.957*	−0.874	−0.015	0.098*
	(-0.938)	(-1.767)	(-1.646)	(-0.675)	(1.953)
ln (PU)	−0.222	0.181	−9.432**	−1.658***	−1.573*
	(-0.137)	(0.053)	(-2.997)	(-3.251)	(-1.725)
ln (PD)	0.359*	7.509***	1.591**	0.010	0.051
	(1.783)	(3.437)	(3.053)	(0.421)	(0.276)
ln (IET)	−0.422**	−2.981***	−0.489	−0.013	0.181**
	(-2.309)	(-3.752)	(-0.793)	(-0.851)	(2.168)
ln (FAI)	0.072	1.949***	−1.650*	−0.099*	−0.162
	(0.177)	(3.253)	(-1.960)	(-2.047)	(-0.876)
ln (PRE)	−0.141	1.125	−0.876**	−0.168**	−0.062
	(-0.836)	(1.476)	(-2.506)	(-2.893)	(-0.641)
ln (HUM)	1.738***	−17.178**	−0.226	0.576**	2.627*
	(4.194)	(-2.621)	(-0.164)	(2.193)	(1.924)
ln (TEM)	0.562	−9.495**	−13.458***	0.185	2.724**
	(0.778)	(-2.559)	(-3.995)	(1.531)	(2.339)
ln (NDVI)	−2.052*	3.559	8.601**	0.974***	0.331
	(-2.105)	(0.920)	(2.693)	(3.374)	(0.501)
R2	0.989	0.877	0.989	0.961	0.983
sigma^2	0.002	0.008	0.001	0.003	0.003
log likelihood	229.688	0.567	0.210	237.477	−41607.204

Note. *Statistical significance at 10% level; ** Statistical significance at 5% level; ***Statistical significance at 1% level; t-statistics in parentheses.

(Table S5). Both industrial structure upgrading (ISU) and green innovation effect (GIE) exhibited partial intermediate effects. This verified that the industrial structure optimization and green technological innovation were the two major transmission channels mediating the performance of the digital economy in China's air pollution management.

The transmission pathways exhibited considerable heterogeneity across different regions. The digital economy exerted partial intermediary effects on the governance of $PM_{2.5}$ concentrations in the eastern region through promoting ISU, energy use efficiency (ESE), and GIE, with an ESE intermediary intensity effect of −0.551. The digital economy exerted a partial intermediary impact in the northeast region through promoting GIE, while generating a masking effect through promoting ESE. Furthermore, the digital economy exerted a partial intermediary effect in the central region by promoting ISU and GIE, with an ISU intermediary strength of −1.292. Digital economy exhibited a full intermediary effect in the western region through promoting ISU with a strength reaching −2.018.

Across urban agglomerations, the digital economy exerted a full intermediary effect in the BTH through promoting ISU and a partial intermediary outcome through promoting GIE, with the intermediation strength of GIE reaching −0.236. Apart from ISU, which exhibits a full intermediary effect, ESE, GIE, and green total factor production efficiency (GTFP) all contribute to partial intermediary effects on air pollution governance in the YRD, with the intermediation strength of ESE reaching −0.269. The digital economy strongly promoted ISU, GTFP, and ESE in the GBA, with all three variables exerting partial intermediary effects, and GTFP exhibited the strongest intermediation strength (−0.919). The digital economy had strongly promoted various mediating variables in the CCU. Apart from the masking effect of ESE, all variables demonstrated partial intermediary effect, with the highest intensity observed in ISU (−1.781). In the MRYRU, the digital economy exerted a partial intermediary effect through promoting ISU and ESE, with ISU intermediation strength reaching −0.171.

DISCUSSION

The digital economy is a relatively new economic form, dating from the 21st century. This study has analyzed the contribution of the digital economy on air pollution governance in China. The results indicate that boosting the digital economy could be an effective solution to air pollution, but the contribution exhibited considerable heterogeneity at the levels across the scales of all urban areas, economic subdivisions,

Table 3. Decomposition of direct effects and spatial spillover effects

	Total cities	Eastern region	Northeast region	Central region	Western region
Total effect	−4.280***	−3.083***	1.208***	−4.349***	−2.352**
	(-3.956)	(-2.804)	(3.404)	(-3.441)	(-2.345)
Direct effect	−0.018***	−0.045***	0.141***	−0.050***	0.001
	(-2.779)	(-2.803)	(7.106)	(-3.052)	(0.057)
Spatial spillover effect	−4.261***	−3.038***	1.067***	−4.300***	−2.353**
	(-3.953)	(-2.797)	(3.142)	(-3.438)	(-2.391)
	BTH	YRD	GBA	CCU	MRYRU
Total effect	−0.501*	−2.266***	−0.614***	−0.524*	−3.192*
	(-1.863)	(-3.275)	(-3.275)	(-1.799)	(-1.944)
Direct effect	−0.085**	−0.144***	−0.050**	−0.066**	−0.146*
	(-2.239)	(-4.360)	(-2.838)	(-2.606)	(-1.755)
Spatial spillover effect	−0.416	−2.122**	−0.564***	−0.457**	−3.046*
	(-1.753)	(-3.197)	(-3.289)	(2.793)	(-1.941)

Note. *Statistical significance at 10% level; ** Statistical significance at 5% level; ***Statistical significance at 1% level; t-statistics in parentheses.

and urban agglomerations. The study also verified that less-developed regions (e.g., western regions) can achieve breakthroughs in air pollution governance by stimulating the digital economy. The reason why the digital economy in the northeast region significantly promotes the growth of $PM_{2.5}$ concentrations may be 2-fold. On the one hand, the environmental governance performance of the digital economy may have a threshold effect, and the development of the digital economy is highly dependent on digital infrastructure construction. They may generate new energy consumption and pollution emissions in the process of infrastructure construction, posing challenges for the northeast region with an underdeveloped digital economy to overcome the threshold. On the other hand, Northeast region is mainly dominated by steel, machinery, automotive, and chemical industries. The increased application of digital technologies has further facilitated the enhancement of heavy industrial manufacturing capacity and efficiency, potentially resulting in overall improvements in $PM_{2.5}$ particulate matter emissions in the Northeast region to some extent (Figure 6).

A networked spillover transmission effect on $PM_{2.5}$ control generally far exceeded local direct effects. We believe that the spillover-effect mechanism of the digital economy on $PM_{2.5}$ concentration in China is mainly reflected in two aspects: the synergistic improvement of regional production efficiency and the joint prevention and control of air pollution. On the one hand, several studies have provided evidence of the digital economy's ability to compress temporal and distance costs in technology, innovation, and information transmission through digital platforms. This leads to an improvement in transmission efficiency and fosters a synergistic enhancement of production efficiency among cities. This production efficiency transfer effect is especially more apparent under the support of China's current regional coordinated development strategies (e.g., "Western Development" and "Rise of Central China") and integration strategies such as urban agglomerations construction strategies. On the other hand, the development of the digital economy promotes the interconnection and sharing of environmental monitoring data and prevention and control standards. It facilitates regional resource conservation and pollution reduction and promotes joint prevention and governance measures of regional air pollutants. This yields a practical value in that strengthening urban data and information exchange and technology sharing should be an important strategy to curb regional air pollution emissions (Figure 6).

Through industrial structure upgrading and technological innovation, the digital economy plays an important role in enhancing the effectiveness of air pollution control in China's cities, consistent with the findings of Deng et al. (2022). The digital economy had differentiated impacts on $PM_{2.5}$ concentrations through different scenario combinations of intermediate channels such as structural optimization, green production, resource allocation, and technology innovation. Particularly in GBA and YRD, digital applications and technological innovations have facilitated the reduction of business transaction costs, fostering growth in GTFP and business clustering and improving resource savings and emission reductions.[13] Based on regional disparities in industrial structure, the international division of labor status, the level of science and education, energy consumption structure, and environmental background, various economic subdivisions and urban agglomerations have formed differentiated transmission channels and critical pathways for the impact of the digital economy on $PM_{2.5}$ concentrations. This provides theoretical support for implementing differentiated air pollution governance strategies in different regions of China in the digital economy era. Therefore, it is imperative to develop varying locally adapted strategies and policies for digital economy development in air pollution control to release the environmental welfare effects of the digital economy (Figure 7). Overall, this study offers evidence to support the implementation of efficient, precise, and location-specific management strategies for controlling $PM_{2.5}$ concentrations in China, from the perspective of the digital economy.

Our research has three policy implications. First, to drive China's air pollution management and sustainable urban development, it is essential to provide policy, financial, technological, intellectual, information, and infrastructure support for enhancing the digital industry foundation, digital innovation capacity, and the degree of digital application. Second, recognizing the widespread networked spillover effect of the digital economy on pollution management,[42] there should be a focus on constructing a robust digital network system and

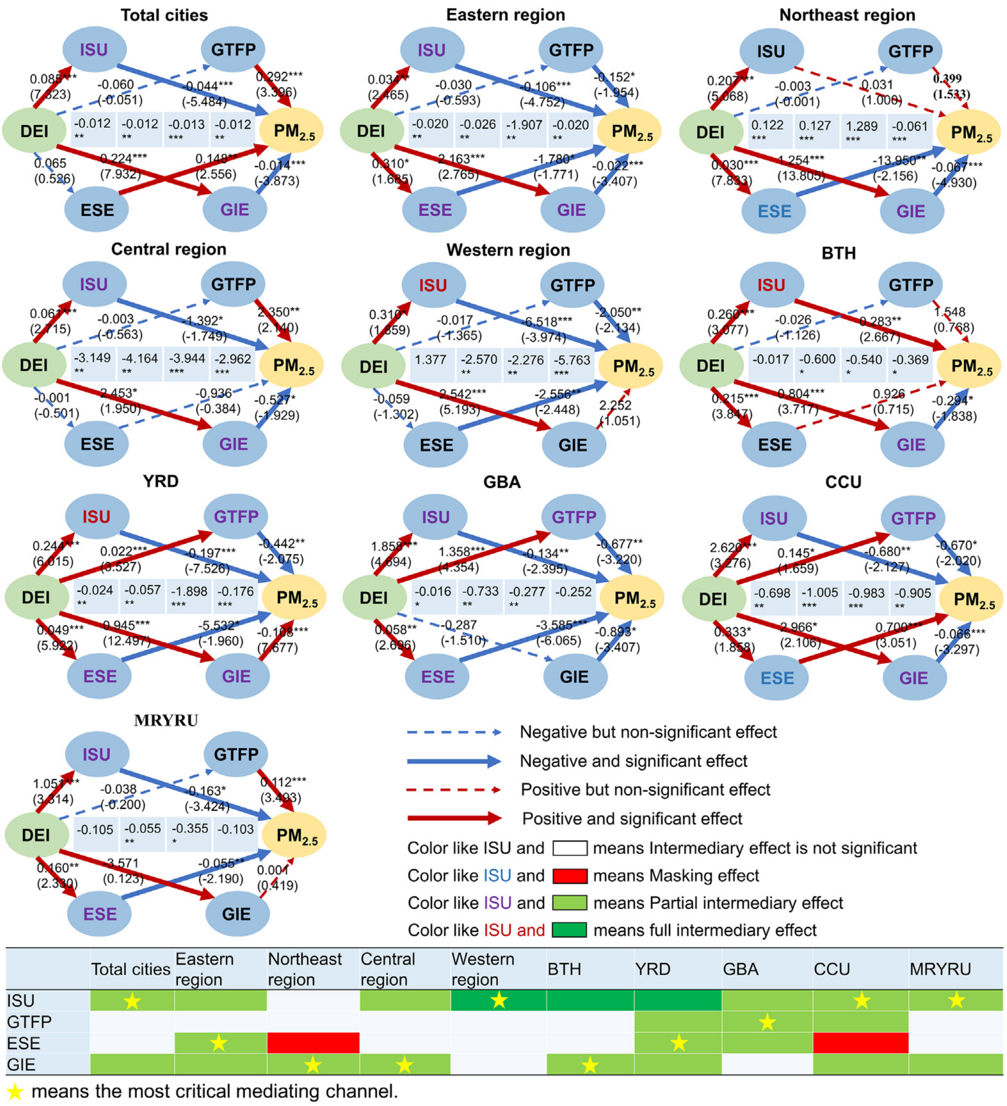

Figure 5. Transmission pathways and intermediary impacts of the digital economy on $PM_{2.5}$ concentrations at different scales (The box shows the c_1 values based on Equation 3: from left to right are ISU, GTFP, ESE, and GIE)

cross-regional joint control mechanism of air pollution. This approach should align with the concept of "interaction" and encompass all cities, economic regions, and urban agglomerations. Third, the importance of developing region-specific strategies and policies for the digital economy's role in $PM_{2.5}$ concentrations governance should be emphasized. Tailoring these strategies to local contexts is crucial for harnessing the environmental benefits of the digital economy (Figure 7).

Limitations of the study

This study exhibits certain limitations which necessitate further investigation. The $PM_{2.5}$ concentrations based on inter-annual variations may induce potential biases that stem from seasonal fluctuations. Subsequent studies may examine the impact of digital economic micro-activities on $PM_{2.5}$ concentrations in specific and predetermined seasons. Environmental policy regulation, as an important human control variable, has not been incorporated in this study. Future research may endeavor to incorporate such factors as "environmental regulation level" and "environmental regulation performance" to control their regulating impact on $PM_{2.5}$ concentrations in cases where data availability permits. In addition, some of the sustainable construction policies attached to the development of the digital economy (e.g., recycling industry support policies, urban environmental governance policies) also contribute to urban air cleaning. In the future, based on the availability of data, it can be incorporated into the intermediary variable system to enhance the description of the impact path of the digital economy. Additionally, the discussion of the quantitative relationship between the digital economy, air pollution, and urban sustainability is not addressed in this study. The future study will focus on the contribution mechanism of the digital economy to the regional SDG targets by achieving pollution control.

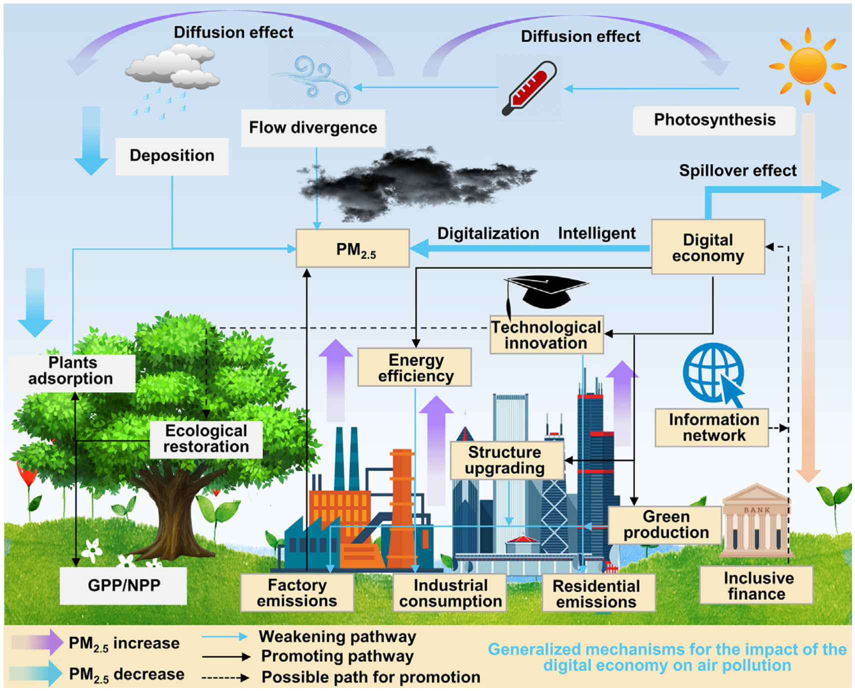

Figure 6. Driving mechanisms of the digital economy for $PM_{2.5}$ concentrations governance

These avenues are integral to enabling a more thorough comprehension of the interdependent relationships between the digital economy and $PM_{2.5}$ concentrations.

Conclusion

Boosting the digital economy could be an effective solution to air pollution, but the contribution exhibited considerable heterogeneity across the urban areas, economic regions, and urban agglomerations. The study also verified that developing regions can achieve breakthroughs in air pollution governance by stimulating the digital economy. A networked spillover transmission effect on $PM_{2.5}$ control generally far exceeded local direct effects, in all urban areas across China, economic regions, or urban agglomerations. The digital economy had differentiated impacts on $PM_{2.5}$ concentrations through different scenario combinations of intermediate channels such as structural optimization, green production, resource allocation, and technology innovation. In the digital economy era, differentiated air pollution governance strategies are crucial for various regions in China. This study provides evidence advocating for targeted, precise, and region-specific approaches to manage $PM_{2.5}$ concentrations in China, emphasizing the role of the digital economy.

STAR★METHODS

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110091.

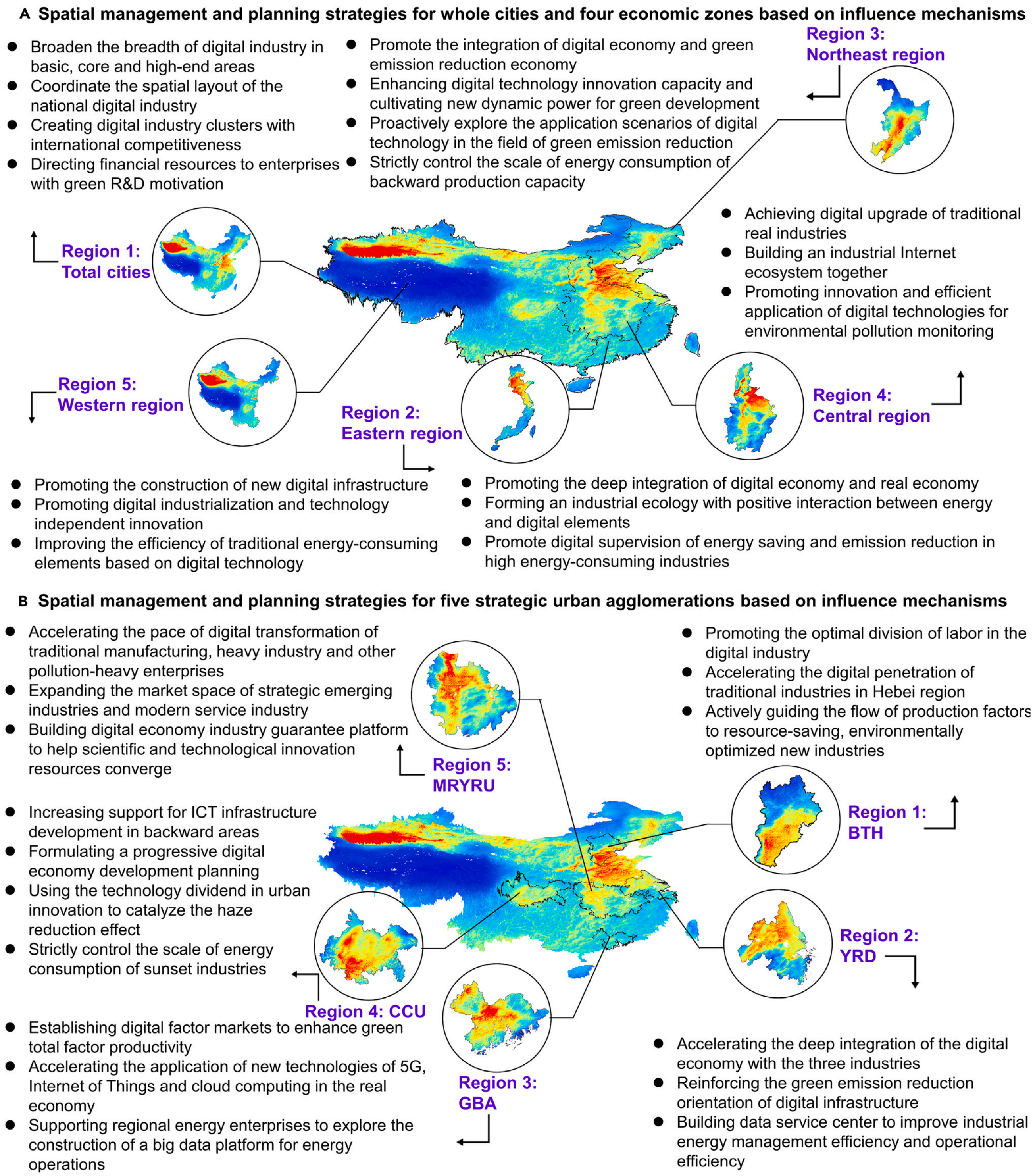

Figure 7. Schematic diagram of policies by regions and urban agglomerations

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AUTHOR CONTRIBUTIONS

G.W.: conceptualization, data curation, formal analysis, funding acquisition, data curation, and formal analysis. G.W. and Y.Y.: methodology, software, investigation, and writing – original draft. Y.L. and R.L.: supervision, validation, project administration, resources, and visualization. Y.L. and B.-J.H.: writing – review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
$PM_{2.5}$ concentrations	Atmospheric Environment Analysis Group, Dalhousie University	http://fizz.phys.dal.ca/~atmos/martin/?page_id=140
Digital economy index	CSMAR database; China National Intellectual Property Administration; Peking University; China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.csmar.com/ https://www.cnipa.gov.cn https://idf.pku.edu.cn https://data.cnki.net/
Per capita GDP	China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Energy intensity	China City Statistical Yearbook; China Energy Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Population urbanization	China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Population scale	China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Openness	China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Investment scale	China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Precipitation	National Earth System Science Data Center	http://www.geodata.cn/index.html
Humidity	National Earth System Science Data Center	http://www.geodata.cn/index.html
Temperatures	National Earth System Science Data Center	http://www.geodata.cn/index.html
NDVI	Resource and Environment Science Data Platform, Chinese Academy of Sciences	https://www.resdc.cn
Industrial structure upgrading index	China City Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Green innovation effect	CSMAR database; China National Intellectual Property Administration	https://data.csmar.com/ https://www.cnipa.gov.cn
Energy use efficiency	China City Statistical Yearbook; China Energy Statistical Yearbook; China Environmental Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Green total factor production efficiency	China City Statistical Yearbook; China Energy Statistical Yearbook; China Environmental Statistical Yearbook; Provincial and municipal statistical yearbooks	https://data.cnki.net/
Software and algorithms		
Stata	StataCorp LLC	https://www.stata.com/
Matlab	MathWorks.Inc	https://www.mathworks.com/products/matlab.html
Python	Python Software Foundation	http://www.python.org
Google Earth Engine	Google Cloud Platform	https://developers.google.cn/earth-engine/
ArcGIS	Environmental Systems Research Institute	https://www.esri.com/en-us/arcgis/products/index

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Guoen Wei (dg1927034@smail.nju.edu.cn).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- This paper analyzes existing, publicly available data which are available in supplemental information. The detailed data associated with the article are available from the lead contact on reasonable request.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Study area

A total of 275 prefecture-level cities in China were selected to investigate the pollution mitigation effects of the penetration of the digital economy. The study area was subdivided into four major economic subdivisions based on economic development levels, East, Central, West and Northeast. They correspond to China's four major regional development strategies, namely, the trailblazing development of the eastern region, large-scale development in the western region, the rise of the central region, and the full revitalization of the northeast. The study area also covered five national strategic urban agglomerations, including BTH, YRD, GBA, CCU, and MRYRU, which represented the core strength of China's industrial structure, scientific and educational capacity, transportation infrastructure, and strategic development (Figure S1).

Digital economy index account

The Digital Economy Index (DEI) is the core explanatory variable to quantify digital economy development. Based on the Digital Economy Report 2021[32] and Annual Report on the Development of Global Economy Competitiveness,[33] an evaluation system for China's digital economy was constructed by integrating three dimensions of the digital economy – the digital industry foundation (DIF), digital innovation capability (DIC), and digital application degree (DAD) (Table S1; Figure S3).[24,34] Among them, DIF reflects the level of urban digital infrastructure construction; DIC reflects the application innovation capability of the digital economy in terms of digitalization and intelligence level of industries, and DAD reflects the application of digital industrialization and its degree of integration with the real economy.[35,36] Figure S2 depicts an analytical pathway for understanding the mechanism and scale heterogeneity related to the digital economy's contribution to air pollution governance in China. An entropy-weighted TOPSIS model was used to quantitatively evaluate the DEI of the Chinese city layer.[37]

Impact effect analysis

The Spatial panel Durbin model (SPDM) was used to evaluate the total pollution mitigation effect of digital economy, given its ability to measure exogenous and endogenous spatial interaction effects. This allows the model to adapt to different data generation processes.[36] The SPDM is expressed as：

$$PM_{2.5it} = \rho WPM_{2.5it} + a_1 DEI_{it} + a_2 H_{it} + \theta_1 WDEI_{it} + \theta_2 WH_{it} + \alpha_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 1)}$$

where $PM_{2.5it}$ is the explained variable, including the measurement of $PM_{2.5}$ concentrations of city i in year t. The explanatory variables consist of DEI_i and H_i (including natural and human-controlled variables)[39,40]; ρ, a, and θ are parameters to be estimated; ε is a normally distributed random disturbance term; W is the spatial weight matrix; α_i and λ_t are individual effects and time effects, respectively. To reduce sample heteroskedasticity and variable fluctuations, logarithmic transformation is applied to variables in regression analysis, in which the variance inflation factor (VIF) test, Lagrange multiplier (LM) test, likelihood ratio (LR) test, and model operations were employed to detect multicollinearity.

Spillover effect analysis

P.D.E was used to quantify the direct and spatial spillover effects of the digital economy on $PM_{2.5}$ concentrations. This method decomposes the total effect of variables into direct and spillover effects to reveal the transmission impact of the development of the local digital economy on air pollution governance in neighboring areas and to verify the spatial network externalities of the digital economy.[38]

Intermediary effect analysis

The impact of the digital economy on technological innovation through ICT and financial agglomeration effects has been demonstrated, and innovation is an important factor for mitigating air pollution.[5] By enhancing the flow of production elements and resolving information asymmetry, the digital economy can contribute to the advancement and rationalization of the industrial structure, and then reduce air pollution from the dimension of industrial form.[15] By improving the efficiency of energy use from both the consumption and allocation sides through technological innovation and industrial optimization, the digital economy reduces an important source of air pollution.[3] The accelerated flow of clean technology and information further optimizes the production efficiency of enterprises and regions, which reduces the sources of air pollution from the resource allocation dimension.[23] Overall, these variables has been used and validated individually in existing studies, but the combination logic among them and their variability across regions remain unconcerned.[35,41] To test the transmission paths and intermediary channels, the intermediary effect model was constructed (Eq-2 and Eq-3). The paths examined in this model included the transmission paths and effects of structural optimization, green production, resource allocation, and technological innovation.

$$M_{it} = \delta WM_{it} + b_1 DEI_{it} + b_2 H_{it} + \sigma_1 WDEI + \sigma_2 WH_{it} + \alpha_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 2)}$$

$$PM_{2.5it} = \varphi WPM_{2.5it} + c_1 DEI_{it} + c_2 M_{it} + \mu_1 WDEI_t + \mu_2 WM_t + \mu_3 WH_{it} + \alpha_i + \lambda_t + \varepsilon_{it} \quad \text{(Equation 3)}$$

where M_{it} is an intermediate variable. The steps of the intermediary impact test are listed as follows: (i) a_1 is significant, otherwise the intermediary impact does not exist; (ii) if b_1, c_1, and c_2 are all significant, and b_1, c_2 have the same sign as c_1, then there is a partial intermediary impact; if b_1, c_2, and c_1 have opposite signs, there exists a masking effect; if b_1 and c_2 are statistically significant, but c_1 is not significant, it indicates the presence of a complete intermediary impact. The strength of the intermediary impact is calculated as b_1c_2.

QUANTIFICATION AND STATISTICAL ANALYSIS

All statistical analyses were performed in Stata, Matlab, Python, Google Earth Engine and ArcGIS.