Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Digital Economy, Industrial Agglomeration as well as the Synergetic Development of Economy, Environment and Ecology

Mao Wu
Central University of Finance and Economics
Xinyang Zeng
Northwest University
Mengling Zhang
Zhangmengling7@163.com

Central University of Finance and Economics

Article

Keywords: Digital Economy, Economic Development, Environment and Ecology, Industry Agglomeration, Coordinated Development

Posted Date: May 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9436054/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Digital Economy, Industrial Agglomeration as well as the Synergetic Development of Economy, Environment and Ecology

Abstract

The contradiction between economic development and environmental as well as ecological protection is an important topic for mankind since industrialization. While the development of digital economy has provided new ideas to solve this problem. This paper adopts 280 prefecture-level cities and municipalities in China from 2011 to 2023 as the research object. We find that digital economy promotes the synergetic development of economy, environment and ecology. Digital economy facilitates economic development, but only when digital economy is developed can environment and ecology be promoted. Digital economy realizes the synergetic development of economy, environment and ecology by promoting the spillover effect of low-end industries and the agglomeration of high-end industries. Through the positive spillover effect of knowledge and technology, digital economy mitigates the regional inequality of the synergetic development of economy, environment and ecology, thus contributing to regional coordinated development.

Keywords Digital Economy; Economic Development; Environment and Ecology; Industry Agglomeration; Coordinated Development

Abbreviations

D	The digital economy
Dev	The synergetic development of economy, environment and ecology
Eco	Economy
Env	Environment and ecology
Capi	Social consumption per capita
Stru	Industrial structure
Fis	Proportion of fiscal expenditure to GDP
Tra	Highway transport volume
Edu	Education investment
Mark	Marketization index
Fdi	Foreign direct investment
Agg_m	The location entropy of manufacturing
Agg_s	The location entropy of producer services
Des	The inequality index for the synergetic development of economy, environment and ecology
Pop	The number of populations
Desw	The weighted inequality index for the synergetic development of economy, environment and ecology
Desk	The inequality index for the synergetic development of economy, environment and ecology in the province

1.Introduction

Since the industrial revolution, the the economy has made considerable progress due to the transformation of global economic mode , which has greatly improved people's well-being. However, the flip side of industrialization is the externalities of economic development, for a long time, in order to expanding production scale to ensure reproduction, human beings have grabbed a lot of resources from nature and created much pollution, resulting in the contradiction between

economy and environment. Due to the rapid development of industrialization, the demand of resource and energy increases, resulting in the raise of pollution and greenhouse gas emissions, makes the global environment to be worsen. Right now, there have been heavily pollution and greenhouse gas emissions around the world, leading to extreme climate risks. According to the report of the World Meteorological Organization (WMO), in 2024, the concentrations of greenhouse gas have reached the highest record. Climate variation also continues to intensify, the maximum extent of Arctic winter sea ice in 2025 has fallen to the lowest level since satellite observations began. So how to make economic progress while protect the environment has become a hot topic for all countries. As the largest industrial nation in the world, China faces serious resource and environmental pollution challenges in pursuiting rapid economic growth. Therefore, to prevent global warming while maintain economic development, it is of great importance to coordinate the development of economy, environment and ecology, and improve the quality of development.

The development of digital economy may provide new ideas to address contradiction between economic development and environmental as well as ecological protection. The rapid development of digital technologies has led the sustained and long-term development of the economy and society, which denotes that the digital economy is the newly growth pole of sustained economic growth (Zhang et al., 2022a). The interactive integration of digital economy and the real economy has brought about cleaner means of production and efficient vitality of economic development (Kan et al., 2022). Digital economy depends on the data elements (Guo et al., 2023), which is cleaner than the land, capital and other factors. Also, the development of digital economy can also facilitate information transmission and exchange, break the obstacle of "information cocoon room", reduce transaction costs by facilitating the transfer of information between the demand side and the supply side (Wu et al., 2023a), promotes the productive efficiency of the industry. What's more, the application of digital technology can also help the government in carrying out environmental governance promptly and efficiently. Through the intelligent environmental monitoring system, the government can obtain data about main environmental indicators such as air quality, water pollution and carbon emissions in time, enhancing the transparency and timeliness of environmental information, thereby making the governance more scientific and efficient.

Digital economy not only plays a significant role in the rapid economic development, but also contributes to forming an economic developing pattern which is environment-friendly, promoting the synergetic development of economy, environment and ecology. However, the existing research on the social impact of digital economy mainly focuses on economic growth (Afolabi, 2023), high-quality development (Guo et al., 2023), pollution reduction (Wu et al., 2023b) and carbon emissions reduction (Gao et al., 2023), but there lacks research on the synergetic development of economy and environment. The transformation of both production and life style in the context of digitalization has provided ideas for eliminating the contradiction between economic development and environmental and ecological protection. Therefore, this paper adopts 280 prefecture-level cities and municipalities in China from 2011 to 2020, explores whether the digital economy can promote the synergetic development of economy, environment and ecology and explores the mediating mechanisms on how digital economy promotes the synergetic development of economy, environment and ecology through industrial agglomeration. Furthermore, we also examine whether the digital economy can mitigate the regional inequality in the synergetic development of economy, environment and ecology. The study of these issues can provide a theoretical reference for us to address the contradiction between economic development and environmental as well as ecological

protection in the digital era, and contributes to bring about more welfare for the mankind.

2.Literature Review and Theoretical Hypothesis

2.1 The impact of digital economy on the synergetic development of economy, environment and ecology

Digital economy generally refers to an economic formation that uses data to take advantage of resources and promote productivity in direct or indirect way. There are multiple effects of digital economy on economic development. Digital economy plays a significant role in optimizing resource allocation through the efficient and rapid integration of massive information (Chen, 2022), improves the total factor productivity (Pan et al., 2021), promotes innovation and entrepreneurship (Nambisan et al., 2019), and contributes to industrial upgradation (Chang et al., 2023a), thereby promoting economic development (Guo et al., 2023). As for the components of digital economy, firstly, the construction of digital infrastructure fosters a favorable environment for economic development. Digital infrastructure can break through the geographical and temporal restrictions through the information interaction platform relying on the digital technology (Tian et al., 2024), which facilitates the flow of productive factors. Also, the construction of digital infrastructure will rationally allocate the resources of factors (Tang and Zhao, 2023), which is conducive to creating a favorable environment for economic growth and development, thus promote the efficient and intensive development of the economy (Li and Yang, 2025). What's more, digital infrastructure can also generate the spillover effects of knowledge and technology, thereby promoting industrial agglomeration and cooperation across the companies (Tian and Lu, 2023), thus reducing production costs, improving production efficiency, so as to promote economic growth. Secondly, as a kind of technology-intensive industry, the digital industry promotes the explosive growth of data, releases the vitality of innovation (Li et al., 2023b), thus fostering emerging industries. Also, digital technology acts on traditional industries with its high permeability, integration with traditional industries. So, it could improve the productive efficiency of both traditional and emerging industries (Chang et al., 2023b) and promoting economic growth. Third, digital finance provides financial support for economic development (Han et al., 2023). Relying on digital technologies such as big data, digital finance reduces the asymmetry of market information, digital financial institutions can accurately assess various market participants and establish credit investigation systems rapidly, thereby providing financial assistance to businesses and individuals who lack collateral for the loan (Wu et al., 2022). So, digital finance makes up for the shortcomings of traditional finance with efficient and convenient services. On the one hand, it would relieve the financing constraints of enterprises, thus promoting the innovative development of enterprises (Li et al., 2023a). On the other hand, digital finance can also reduce costs of financial service, so as to promote entrepreneurship (Li et al., 2022) and stimulating economic development (Guo et al., 2023).

In addition to economic development, digital economy can also promote the regulation of environmental ecology, thus contributing to the synergetic development of economy, environment and ecology. Firstly, through the construction of digital infrastructure, which accelerating the transmission of information, it could reduce information asymmetry and improve the efficiency of resource allocation (Pan and Yang, 2023), thus promoting economic growth while reducing the unnecessary loss caused by resource mismatch. At the same time, the construction of digital infrastructure helps the government to establish the ecological and environmental regulation system and information base with the help of information collection and processing technologies such as big data and cloud computing of digital enterprises, so as to facilitate proactively monitoring various

indicators related to environmental protection of the government (Wang and Li, 2024). By this way, it can formulate targeted policies to promote the protection of ecological and environment while ensuring timely and effective oversight of businesses, thus facilitating the transformation of the economic mode to be greener. Secondly, the digital economy can promote the optimization and upgrading of industrial structure (Xiong et al., 2023), thus helping to the protection of ecology and environment. On the one hand, the development of digital industrialization contributes to generating emerging industry and enterprises, while emerging industries which produces based on data elements consume fewer fossil fuels in the process of production, thus achieving the coordination of economic development as well as ecological and environmental protection. On the other hand, the digital economy can also promote the digitalization of industries, improve the intelligence of traditional industries, optimize the industrial chains, help to improve the accuracy and efficiency of production and service decisions (Liu and Liu, 2022),decrease the loss of resource (Fu, 2023), thereby promoting environmental and ecological protection. At the same time, the digitalization of industry will also transform the business mode, induce the emerging of online office mode, which reduces the utilization of resources and energy consumption, making the productive mode to be greener. Third, the digital economy contributes to ecology and environment protection through technological innovation (Lin et al., 2023; Huang et al., 2023; Liu et al., 2024). Technology innovation breaks through the constraints of diminishing marginal returns, transforms the economic mode to that relies on the input of resources and factors to be more intensive and greening, thus contributing to realizing the synergetic effect of economic development as well as environmental and ecological protection. Therefore, this paper puts forward the following hypothesis.

Hypothesis 1: Digital economy can promote the synergetic development of economy, environment and ecology.

2.2 The impact mechanism and spillover effect of digital economy on the synergetic development of economy, environment and ecology

Economic agglomeration refers to the concentration of economic activities in a certain spatial scope, and industrial agglomeration refers to the concentration of the same industry in a specific scope and the convergence of industrial capital and other factors. The impact of digital transformation on economic agglomeration and industrial agglomeration for different industries are also different. On the one hand, the industry in the central district of metropolis is upgrading and developing towards industrial digitalization, which promotes the transformation of economic structure and realized the agglomeration of high-end industries. On the other hand, low-end industries such as manufacturing are also diffusing from developed areas to developing areas. In this process, the digital economy has played an important role.

Firstly, the digital economy has brought about the digital welfare to people and contributed to industrial agglomeration (Wu et al., 2023b), especially in high-end industries. Digital economy promotes the interactive integration and coordinated development of upstream and downstream enterprises, optimize and upgrade algorithms through massive amounts of data, so the productive factors would flow to areas with a higher return on investment, thus realizing the agglomeration of high-end industries. Secondly, digital economy has made it easier for enterprises of high-end industries to communicate with each other, thus increasing the demand for face-to-face communication (Jiang et al., 2022), thus promotes the agglomeration of high-end industries such as producer services. Thirdly, the infrastructure of digital economy in metropolises is better than undeveloped areas, so the welfare brought by digital economy would provide technical support for

enterprises in metropolises (Wang et al., 2023). Thus, high-end industries tend to agglomerate in metropolises. Finally, digital economy also attracts a large number of laborers, especially high-skilled laborers, to areas where industries are agglomerated with the digital welfare and generous monetary remuneration (Li et al., 2024). The agglomeration of high-quality laborers will lead to the agglomeration of technology-biased enterprises and industries, resulting in the agglomeration of high-end industries (Shen and Zhang, 2024).

At the same time, due to the industrial upgradation caused by the digital economy, the cost of land and factors utilization in the developed areas of the digital economy would increase, resulting in the transfer of low-end and medium-end industries to less developed areas. In the process of industrial transfer, the digital economy has played an important role. Traditionally, communication with each other should be face to face, so geographical distance has become a shackle on knowledge and information exchange. The digital economy has broken down the geographical distance barriers of information exchange, replaced face-to-face communication with online communication, thus promoting the communication of information and technology. So digital economy reduces the negative impact caused by geographical distance and contributes to the spillover of knowledge and technology (Wu et al., 2024) . In this process, the digital economy has played a role through the "industrial transfer effect" and "industrial creation effect". "Industrial transfer effect" means that the low-end and medium-end industries are no longer confined to the peripheries when they spill over from the metropolises, but transfer to areas farther away. Because the digital economy has broken the restriction of geographical space, improves the convenience of information communication, promotes the spread of knowledge and information, so that economic activities would not be limited to a specific region (Qi et al., 2023). Therefore, digital economy has promoted the spillover of low-end and medium-end industries, such as manufacturing, to less developed regions, reduced industrial agglomeration of low-end and medium-end industries through knowledge spillover effect. "Industrial creation effect" means that the digital economy has contributed to the rapid development of information, software services and new media, broken down the barriers of knowledge and technology, decreased the difficulty in knowledge acquisition, thus lowering the entrance threshold of low-end and medium-end industries and effectively promoting entrepreneurship of low-end and medium-end industries, realizing the spillover effect of low-end and medium-end industries.

All in all, the digital economy promotes the agglomeration of high-end industries, reduces the low-end and medium-end industries agglomeration as well as facilitates the spillovers of low-end and medium-end industries, thus leading to two results: First, through the agglomeration of high-end industries and the transfer of low-end industries, metropolises with developed digital economy have achieved the industrial upgradation , promoted the transformation of economic modes to be more intensive, and realized more efficient utilization of resources, thus promoting economic development while reducing pollution (Gao and Peng, 2022) and energy consumption, thus promoting the synergetic development of economy, environment and ecology. Secondly, small and medium-sized cities as well as underdeveloped areas have also achieved economic development by receiving the transfer of industries from metropolises, although the production of low-end industries needs to consume energy and resources, and results in pollution. However, on the one hand, the spillover and dispersion of industries have reduced the energy consumption and pollution per area, the negative externalities of energy consumption and pollution are mitigated through interregional industrial dispersion. On the other hand, through digitalization, knowledge and technology also spills over to these small and medium-sized cities as well as other underdeveloped areas, which can

promote green technology innovation (Lin et al., 2023; Liu et al., 2024), thus realizing the green transformation of low-end industries, promoting the synergetic development of economy, environment and ecology. So, this paper puts forward the hypothesis.

Hypothesis 2: Digital economy promotes the agglomeration of high-end industries, reduces the agglomeration of low-end industries, and promotes the spillover effect of low-end industries, thus promoting the synergetic development of economy, environment and ecology.

3. Research Design

3.1 Model settings

In order to explore the effect of digital economy on the synergetic development of economy, environment and ecology, this paper sets the econometric regression model, which is shown as equations (1):

$$Dev_{it}=a_{00}+a_{01}D_{it}+\boldsymbol{X_{it}A_0}+\mu_i+e_t+\varepsilon_{it} \quad (1)$$

Where i is the subscript of city, t is the subscript of year, Dev_{it} is the synergetic development of economy, environment and ecology, and D_{it} is the digital economy. $\boldsymbol{X_{it}}$ is the matrix of control variables, $\boldsymbol{A_0}$ is the coefficient matrices of control variables, e_t denotes year fixed effect, μ_i denotes city fixed effect, α_{00} is the constant, α_{01} is the coefficient of digital economy, and ε_{it} is the random error term. If α_{01} is significantly greater than 0, it means that digital economy has significantly promoted the synergetic development of economy, environment and ecology.

In order to verify that digital economy promotes the synergetic development of economy, environment and ecology through industrial agglomeration, we refer to Yang et al. (2023), adopts the robust mediating model to mitigate the endogenous problems of the mediating model, and sets the model as follows. First, test the correlation between industrial agglomeration and digital economy:

$$Agg_{it}=a_{10}+a_{11}D_{it}+\boldsymbol{X_{it}A_5}+\mu_i+e_t+\varepsilon_{it} \quad (2)$$

Where Agg_{it} indicates the industrial agglomeration, if a_{51} is significantly not 0, it indicates that digital economy has significantly affected industrial agglomeration. Then, we set the following models:

$$Dev_{it}=\beta_{00}+\beta_{01}Agg_{it}+\boldsymbol{X_{it}B_0}+\mu_i+e_t+\varepsilon_{it} \quad (3)$$

$$Dev_{it}=\beta_{10}+\beta_{11}Agg_{it}+\beta_{12}D_{it}+\boldsymbol{X_{it}B_1}+\mu_i+e_t+\varepsilon_{it} \quad (4)$$

We examine the correlation between industrial agglomeration and the synergetic development of economy, environment and ecology through the equation (3). If β_{01} is significantly not 0, it indicates that the industrial agglomeration is significantly correlated with the synergetic development of economy, environment and ecology. Furthermore, we add the core the explanatory variable to the equation (3), and the regression model is shown in the equation (4). If β_{11} is still not 0, and $\beta_{01}\times\beta_{11}>0$, it indicates that even if there exists the overestimation of indirect effect, the estimation bias caused by the overestimation do not challenge the conclusion that industrial agglomeration is significantly correlated with the synergetic development of economy, environment and ecology, and owing to a_{11} is not 0, it denotes the digital economy has a significantly impact on industrial agglomeration, and in turn industrial agglomeration is significantly correlated with synergetic development of economy, environment and ecology. So we can say digital economy has promoted the synergetic development of economy, environment and ecology through industrial agglomeration.

3.2 Variable selection and descriptive statistics

3.2.1 Explained variables

The explained variable in this paper is the synergetic development of economy, environment and ecology (*Dev*). Referring to Liu et al. (2022), this paper constructs the synergetic development of economy, environment and ecology from two aspects. The indicators are as follows:

(1) Economy (*Eco*): The secondary indicators of economy include economic development, economic vitality and economic intensity. Economic development is characterized by GDP per capita, the entrepreneurial activities characterized by the number of enterprises is the indicator of economic vitality, and the economic intensity is characterized by total factor productivity. The data of GDP per capita comes from the China City Statistical Yearbook, the number of enterprises comes from CEIC database. We refer to Zhao et al. (2020) to measure the total factor productivity, adopting employees and fixed assets as inputs and real GDP as output. Referring to Zhang et al. (2004), the variable fixed assets is calculated by perpetual inventory method, adopting the year 2000 as the base period, and the depreciation rate is 9.6%. The fixed assets in the t year are equal to the residual value of the newly added fixed assets investment in the year *t* plus the depreciation of the fixed assets in the year *t*-1. The output is the real GDP; we deflate the nominal GDP by GDP deflator of the province where the city is located and adopting the year 2000 as the base period to get the real GDP. We use the DEA-Malmquist method to measure the total factor productivity of cities

(2) Environment and Ecology (*Env*): Environment and ecology include four secondary indicators: environmental pollution, greening rate, pollution control and energy consumption. Environmental pollution includes industrial wastewater discharge per capita, industrial sulfur dioxide emissions per capita and industrial soot emissions per capita; The greening rate includes green area of park, green area per capita and green coverage rate in built-up areas; Pollution control includes domestic sewage treatment rate and harmless treatment rate of domestic garbage. The above data are all from the Statistical Yearbook of China City. For carbon emissions, we refer to the calculation of Yang et al. (2023). The energy consumption which is used to calculate carbon emission mainly includes liquefied petroleum gas, natural gas, electricity consumption and thermal energy consumption. Add up the carbon dioxide emitted by natural gas, liquefied petroleum gas, electric and thermal energy consumption to get the carbon emissions of each city.

Table 1

Indicators of synergetic development of economy, environment and ecology

Primary indicator	Secondary indicator	Tertiary indicator	Positive or negative
Economy	Economic development	GDP per capita	+
	Economic vitality	Entrepreneurial activity (number of enterprises per 100 people)	+
	Economic intensive	Total factor productivity	+
Environment and Ecology	Environmental pollution	Industrial wastewater discharge per capita	-
		Industrial sulfur dioxide emissions per capita	-
		Industrial soot emissions per capita	-
	Greening rate	Green area of park	+
		Green area per capita	+
		Green coverage rate in built-up area	+

	Pollution control	Domestic sewage treatment rate	+
		Harmless treatment rate of domestic garbage	+
	Energy consumption	Carbon dioxide emissions	-

Table 1 shows the sub-indicators for the synergetic development of economy, environment and ecology. We use the entropy weight method to measure the synergetic development of economy, environment and ecology.

3.2.2 Core explanatory variables

The core explanatory variable in this paper is the digital economy (D_{it}). this paper constructs the indicators of the digital economy index from three aspects:

Digital infrastructure, includes the density of Internet broadband users and the number of mobile phone user. The data comes from China City Statistical Yearbook.

Digital industry, includes revenue from postal and telecommunication service, practitioners in the information transmission, computer services and software industry. The data comes from China City Statistical Yearbook.

Digital finance, adopts the Peking University Digital Finance Inclusion Index (Guo et al., 2020) .

Table 2

Indicators of digital economy index

Primary indicator	Secondary indicator
Digital infrastructure	Density of Internet broadband access users
	Number of mobile phone users
Digital industry	Revenue from postal service
	Revenue from telecommunication service
	Practitioners in the information transmission, computer services and software industry
Digital finance	Digital financial inclusion index

Table 2 shows the sub-indicators for the digital economy index. We also use the entropy weight method to get the digital economy index.

3.2.3 Control variables

In order to prevent estimation bias caused by omitting variables, this paper refers to Liu et al. (2022), Zhao et al. (2020), adds the following control variables to the regression model:

(1) Social consumption per capita (*Capi*). (2) Industrial structure (*Stru*): Industrial structure has a great influence on the economic development and environmental protection. The more advanced of industrial structure, the more developed the of economy and the less pollution of environment. Referring to Zhang et al.(2022b), we set the structural industrial index as follows:

$$Ind_{it}=(Output1_{it}+2\times Output2_{it}+3\times Output3_{it})\div GDP_{it} \quad (5)$$

$Outputj_{it}$ indicates the added value of the industry j, $j\in\{1,2,3\}$.(3) Proportion of fiscal expenditure to GDP (*Fis*). (4) Highway transport volume (*Tra*).(5) Education investment (*Edu*). (6) Marketization index (*Mark*). (7) Foreign direct investment (*Fdi*).

3.2.4 Mediating variables

The mediating variables are spillover effect of low-end industries and agglomeration of high-end industries. In this paper, we use manufacturing to represent low-end industries, and use producer services to represent high-end industries. Referring to Wang et al. (2022), we use the location entropy to indicate industrial agglomeration:

$$Agg_{it}=\frac{E_{r,it}/E_{r,t}}{E_{it}/E_{t}} \tag{6}$$

Agg_{it} is the industrial agglomeration of city i in the year, $E_{r,it}$ is the practitioners in the industry r of city i in the year t, $E_{r,t}$ is the practitioners in the industry r of China in the year t, E_{it} is the amount of practitioners of city i in the year , E_t is all the employees in the t year of China. When industry r denotes manufacturing, Agg denotes the location entropy of manufacturing (Agg_m); when industry r denotes producer services, Agg denotes the location entropy of producer services (Agg_s). We select transportation, warehousing and postal services, financial services, leasing and business services, scientific research and technical services, geological exploration industries as well as information transmission, computer services and software industries to characterize producer services.

3.2.5 Data sources and descriptive statistics

Except for variables for which data sources are specifically indicated above, the data of variables are from China City Statistical Yearbook. The research sample of this paper is the panel data of 280 prefecture-level cities and municipalities from 2011 to 2023. Table 3 is the descriptive statistics of variables.

Table 3

Descriptive statistics of variables

Variable		Observations	Mean	Standard Deviation	Minimum	Maximum
Core explanatory variable	*D*	3,640	0.2652	0.1225	0.0042	1.0864
Explained variable	*Dev*	3,640	0.4337	0.0964	0.0078	1.0000
Sub-indicator of explained variable	*Eco*	3,640	0.2287	0.0987	0.0267	0.7147
	Env	3,640	0.4292	0.0329	0.2358	0.6579
Control variable	*Capi*	3,640	2.173912	1.298885	0.0000	8.6156
	Stru	3,640	2.3145	0.1433	1.8311	2.8461
	Fis	3,640	0.2014	0.1007	0.0439	0.9155
	Tra	3,640	0.6123	1.3168	0.0002	28.6557
	Edu	3,640	80.8535	107.2524	2.0048	1227.9030
	Mark	3,640	8.5960	1.7773	3.3590	13.3560
	Fdi	3,640	7.3380	20.0151	0.0000	308.2563
Mediating variable	Agg_m	3,640	0.0370	0.0264	0.0000	0.5396
	Agg_s	3,640	0.0167	0.0103	0.0000	0.3714

4. Empirical Results

4.1 Baseline regression results

Table 4 shows the baseline regression results of digital economy on the synergetic development of economy, environment and ecology. It can be seen from the column (1) of Table 4 that the digital economy is positively correlated with the explained variable at 1% significance level without adding the fixed effect and the control variables to the model. Then, we add the time and city effect to the regression model of column (1), and the regression result is shown in column (2) of Table 4, indicating that the digital economy is still positively correlated with the explained variable at the 5% significance level,. Similarly, the result of column (3) is the regression result of the model that include the control variables to the regression equation of column (1), the digital economy is still positively correlated with the explained variable at the 1% significance level, indicating that inclusion of the control variables does not cause the substantial bias to the estimation results. Finally, we add the time and city fixed effect as well as control variables to the regression equation of column (1), and the result is shown in the column (4), showing that the synergetic development of economy,

environment and ecology is still significantly and positively correlated with digital economy, indicating that digital economy has played a significant role in promoting synergetic development of economy, environment and ecology.

Table 4

Baseline regression results

	(1)	(2)	(3)	(4)
D	0.0740***	0.1169**	0.3583***	0.3062**
	(5.1732)	(2.4727)	(6.1116)	(2.1722)
Capi			0.0137	-0.0457
			(1.0834)	(-0.9292)
Stru			0.0397***	-0.0128
			(2.9503)	(-0.2644)
Fis			0.0051***	0.0036
			(5.8769)	(0.8147)
Tra			0.0000	0.0000
			(0.2824)	(0.3617)
Edu			-0.0002***	-0.0002*
			(-5.1504)	(-1.9227)
Mark			0.0044**	0.0008
			(2.2371)	(0.5876)
Fdi			0.0119***	0.0054
			(5.4830)	(1.1410)
Constant	0.0740***	0.1169**	0.3583***	0.3062**
	(5.1732)	(2.4727)	(6.1116)	(2.1722)
City fixed effect	No	Yes	No	No
Year fixed effect	No	Yes	No	No
Observations	3,640	3,640	3,640	3,640
R-squared	0.0089	0.5997	0.5690	0.6062

Note: The t value calculated by the robust standard error clustered to the prefecture-level city level are in parentheses, "* * *", "* *" and "*" indicate the significance level of 1%, 5% and 10% respectively, the same below.

4.2 Endogenous tests

We've verified the promotion effect of digital economy on the synergetic development of economy, environment and ecology in the baseline regression. However, there may be endogenous problems in the estimation of baseline regression. Therefore, we carry out endogenous tests.

Table 5

Endogenous tests results

	(1)	(2)	(3)	(4)	(5)
Explained variable	*D*		*Dev*		
Lag term of *Dev*				0.8418***	
				(30.4785)	
D		0.3058**	1.8597***	0.1652***	
		(2.1724)	(3.2335)	(2.8252)	
Wof	0.0003***	0.0001			
	(6.7447)	(0.7191)			
"Smart City" Pilot					0.1652***
					(2.8252)
Control Variables	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes
Observations	3,640	3,640	3,640	3,360	3,640
R-squared	0.8683	0.6066	0.4595	0.7937	0.8683

Firstly, this paper applies 2SLS method. Referring to Tao and Ding (2022), this paper selects the word frequency which is related to digital economy in local government work reports (*Wof*) as the instrumental variable. Table 5 reports the regression results. The result of column (1) shows that the instrumental variables is positively correlated with digital economy at 1% significance level. Further, this paper tests the exogeneity of the instrumental variable, we take the instrumental variable as one of explanatory variables and add it to the equation (1). The results are shown in column (2) of Table

5. As can be seen from the table, the digital economy is still positively and significantly correlated with the explained variables at 5% significance level, while the instrumental variable has no significant correlation with the explained variable, indicating that there is no direct correlation between the instrumental variable and the explained variable, which verifies the exogeneity of the instrumental variable. The value of K-P rk Wald F is 201.675, which is greater that of Stock-Yogo statistics at 10% significance level, indicating that the instrumental variable is not weakly correlated with the core explanatory variable. Therefore, we estimate the digital economy index by the instrumental variable and replace the core explanatory variable with the estimated one. The result is shown in column (3), indicating that the digital economy fitted by instrumental variable is positive correlated with the explained variables at 1% significance level. So, digital economy still promotes the synergetic development of economy, environment and ecology after taking the possibly existing endogenous problems into consideration.

Secondly, accounting for issues of potential reverse causality and omitting variables, this study also performed dynamic model tests, namely including the lags of the dependent variable as explanatory variable in the regression. The results is in column (4) of Table 5. As can be seen from the table, the digital economy index is still positively correlated with the dependent variable at the 1% significance level, confirming the robustness of the conclusions in the baseline regression.

Thirdly, we carry out the exogenous shock tests, select the "smart city" pilot list in the Notice on Launching National Smart City Pilot Work issued by the Ministry of Housing and Urban-Rural Development in 2012. We replace the core explanatory variable with the exogenous shock variable of "smart city" pilot. If the district or county of the city are selected into the pilot list of "smart city", the exogenous shock variable is taken as 1, otherwise it is taken as 0. Before the test, we should conduct the parallel trend test. The results are shown in Fig.1. As can be seen from Fig.1, before the city was selected into the pilot list of "smart city", the regression coefficient is not significantly greater than. However, after being selected into the pilot list of "smart city", the regression coefficient is significantly greater than 0, indicating that the parallel trend test passes. Column (5) of Table 5 reports the result of exogenous shock test. From which it can be seen that the variable of exogenous shock is still positively correlated with the explained variables at 1% significance level. Therefore, the exogenous shock test passes.

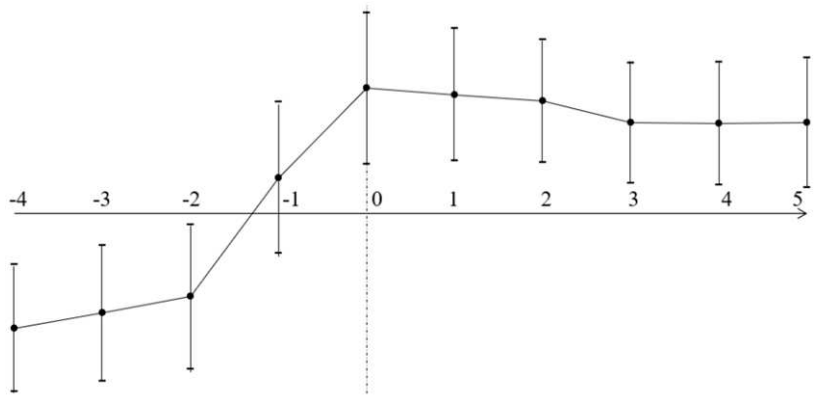


Fig.1 Parallel trend test of exogenous shocks

4.3 Robustness test

In order to verify the robustness of the conclusion, this paper also carries out the following robustness tests.

4.3.1 Robustness test of replacing construction method

In order to avoid the estimation bias that may be caused by the construction method, this paper carries out the robustness test of replacing construction method for variables. Replace the entropy method in baseline regression with principal component analysis (PCA). The regression results are shown in Table 6. Columns (1) and (2) are the results replacing the construction method of explained variables with principal component analysis, columns (3) and (4) are the results replacing the construction method of digital economy with principal component analysis, columns (5) and (6) show the results that both the explained variable and the core explanatory variable are constructed by principal component analysis. As can be seen from Table 6 that all of the 6 results indicate that digital economy is positively correlated with the explained variable at least at 10% significance level, thus verifying the conclusion of baseline regression in this paper.

Table 6

Robustness test of replacing construction method

	(1)	(2)	(3)	(4)	(5)	(6)
variable	PCA *Dev*		*Dev*		PCA *Dev*	
D	3.1792***	3.2558**				
	(4.6289)	(2.0917)				
PCA *D*			0.0078*	0.0175***	0.0859*	0.1041***
			(1.7735)	(2.7805)	(1.9580)	(4.1158)
Control Variables	No	Yes	No	Yes	No	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,640	3,640	3,640	3,640	3,640	3,640
R-squared	0.2086	0.3439	0.6000	0.6065	0.1973	0.3375

4.3.2 Robustness test of replacing model

In order to avoid the estimation bias caused by model selection bias, this paper also conduct the robustness test of replacing model, and the results are shown on the Table 7. Column (1) is the random effect model (RE), which sets two-way random effects of city and year. Column (2) is the regression changing the fixed effect, replace the city fixed effect with the province fixed effect, and others keep unchanged. Column (3) is the interactive fixed effect model (IFE), where the interactive fixed effect denotes the city fixed effect plus and year fixed effect, we add this fixed effect to the equation (1). All the regression results of columns (1) to (3) show that the digital economy is significantly and positively correlated with the explained variables , verifying the conclusion of baseline regression.

Table 7

Robustness test of replacing model

	(1)	(2)	(3)	(4)	(5)	(6)
Model	RE	FE	IFE	SAR	SEM	SAC
D	1.4255**	0.3100***	0.1817***	0.3117**	0.3045**	0.3099**
	(2.2787)	(4.8580)	(4.2116)	(2.2366)	(2.1916)	(2.1203)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Spatial lag term of *Dev*				1.4178*		0.6708
				(1.9367)		(0.0457)
λ					1.0912**	
					(2.1450)	
City effect	Random	No	Fixed	Fixed	Fixed	Fixed
Year effect	Random	Fixed	Fixed	Fixed	Fixed	Fixed
Province effect	No	Fixed	No	No	No	No
City effect×Year effect	No	No	Fixed	No	No	No
Observations	3,640	3,640	3,640	3,640	3,640	3,640
R-squared	0.3250	0.5936	\	0.0122	0.0081	0.0111

Furthermore, considering the possible spatial correlation of variables, this paper also conducts the spatial econometric tests. We select the spatial distance matrix the weighted matrix. The spatial

distance matrix is the matrix whose element in column *i* of row *j* is the spherical distance between city *i* and city *j*. Before the spatial econometric regression, we carry out the Moran index test. The results show that from 2011 to 2023, there exists the spatial correlation of digital economy and the explained variables at 1% significance level, so spatial econometric regression can be carried out. In this paper, we select spatial autoregression model (SAR), spatial error model (SEM) and spatial autocorrelation model (SAC), and the results are shown in columns (4), (5) and (6) of Table 7 respectively, indicating that digital economy is still significantly and positively with the explained variable at 5% significance level after considering the spatial correlation of variables, thus verifying the conclusion of baseline regression.

Therefore, after the endogenous and robustness test, the conclusion that digital economy promotes the synergetic development of economy, environment and ecology is still significantly valid, which proves that the conclusion of baseline regression is robust and verifies the Hypothesis 1 of this paper.

4.4 Sub-indicator test

The previous part of the paper has conducted the empirical examination of whether the digital economy promotes the synergetic development of economy, environment and ecology. Then, this paper will conduct yhe empirical analysis about the sub-indicators of the digital economy on the explained variable.

Table 8 reports the regression results of digital economy on the sub-indicator of the explained variable. Column (1) is the regression result of digital economy on economy, which shows that digital economy is positively correlated with economy at 1% significance level. The result in column (2) shows that digital economy has no significant impact on environment and ecology. Further, we add the quadratic term of digital economy to the regression equation of column (2), and the result is shown in column (3). From the column, it can be seen that the digital economy is negatively correlated with the explained variable at 10% significance level, while the quadratic term of the explained variable is positively correlated with digital economy at 1% significance level, which indicates that the digital economy may have a "U"-shaped influence on the environment and ecology. That is to say, if digital economy is undeveloped, it would suppress the development of environment and ecology. While if digital economy is developed, it would improve the development level of environment and ecology. Furthermore, referring to Wu et al. (2024), this paper adopts the threshold model to investigate the how digital economy in different level of development affects the environment and ecology. Through calculation, we find that the optimal number of thresholds is 1, and the threshold value of digital economy is 0.3808. The results are shown in the column (4). indicating that digital economy has a negative impact on the environment and ecology when it is less than the threshold value, and has a positive impact on the environment and ecology when it is greater than the threshold value. Therefore, if digital economy is undeveloped, it can only promote economic development, but does not improve the development of environment and ecology. While when digital economy is developed, it would contribute to the synergetic development of economy, environment and ecology.

Table 8

Sub-indicator test of the explained variable

	(1)	(2)	(3)	(4)
Explained variable	*Eco*	*Env*	*Env*	*Env*
D	0.4569***	-0.0351	0.0911*	
	(6.1359)	(-0.9342)	(1.9050)	
D^2			-0.1204***	

			(-3.0247)	
D (low value)				-0.3416*
				(-1.8066)
D (high value)				0.1521***
				(5.8048)
Control Variables	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
Observations	3,640	3,640	3,640	3,640
R-squared	0.6940	0.3842	0.3859	0.3454

4.5 Heterogeneity test

We classify cities according to the tier of cities to characterize the economic development and their developing potentials, and select the resource type of city to characterize the environment and ecology. We then analyze the regional heterogeneity.

According to the China Research Data Services (CNRDS), the 280 prefecture-level cities are classified into first-tier, second-tier, third-tier, fourth-tier and fifth-tier cities, and the regression results are shown in Table 9. As can be seen from Table (1) and (2), in first-tier and second-tier cities, the regression coefficient of digital economy on the explained variable is not significant, which is due to the well infrastructure and advanced industrial structure in first-tier and second-tier cities, pollution is relatively less. So, even though the digital economy is relatively well-developed in these cities, since the industrial structure of these cities is not dominated by the secondary sector which is energy-intensive and high-polluting, it is hard for digital economy in significantly promoting the development of the economy, environment and ecology in first-tier and second-tier cities. From the column (3), (4) and (5) in the Table 9, it can be seen that the digital economy plays a significant role in promoting the synergetic development of economy, environment and ecology in the third-tier, fourth-tier and fifth-tier cities. Most third-tier, fourth-tier and fifth-tier cities are dominated by low-value-added, energy-intensive, and low-end industries The digital economy has advanced the industrial structure (Chang et al., 2023) and played a vital role in economic development. At the same time, digital economy has contributed to information sharing and promoted the spread of technology both within and across industrial chains, facilitating technological innovation among enterprises, thus reducing energy consumption and resource utilization, thereby promoting the synergetic development of economy, environment and ecology.

Table 9

Development of city heterogeneous tests

	(1)	(2)	(3)	(4)	(5)
City	First-tier	Second-tier	Third-tier	Fourth-tier	Fifth-tier
D	0.1293	0.0033	0.4852***	0.2340***	0.6699*
	(0.8385)	(0.0290)	(3.6912)	(3.7638)	(1.7944)
Control Variables	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes
Observations	52	312	1,170	1,755	351
R-squared	0.9171	0.6230	0.6203	0.1561	0.6342

4.6 Mediating tests

Table 11 reports the mediating test of digital economy in promoting the synergetic development of economy, environment and ecology by the spillover effects of manufacturing. From column (1) of Table 11, it can be seen that the digital economy is negative correlated with the location entropy of manufacturing at the 1% significance level, indicating that the digital economy has significantly suppressed the agglomeration of manufacturing and promoted the spillover of low-end industries characterized by manufacturing to the undeveloped regions. In order to avoid the estimation bias

caused by endogenous problems, we refer to the 2SLS method in the regression in Table 5, and use instrumental variables in Table 5 to estimate the digital economy and take it into the regression model. The result is reported in column (2), showing that the digital economy estimated by instrumental variables is still negatively correlated with the location entropy of manufacturing, which indicates that the negative correlation between digital economy and location entropy of manufacturing is still significant after considering endogenous problems. Then we explore the correlation between the location entropy of manufacturing and the explained variables. The regression result is reported in column (3) of Table 11. As can be seen from the table, the location entropy of manufacturing is negatively correlated with the explained variables at 5% significance level. Furthermore, we include the core explanatory variable to the regression equation of column (3), and the results are shown in column (4) of Table 11. showing that the location entropy of manufacturing is still negatively correlated with the explained variable at 5% significance level even if the indirect effect is overestimated in the mediating model. However, the regression coefficient of the digital economy in column (4) of Table 11 is less than that in column (4) of Table 4, meaning that the promotion effect of digital economy on the explained variables is partly suppressed by the mediating variable, and there is a negative correlation between digital economy and manufacturing agglomeration. Therefore, we can take it for granted that digital economy can promote the synergetic development of economy, environment and ecology by suppressing the agglomeration of manufacturing industry and promoting the spillovers of low-end industries characterized by manufacturing. In order to prevent the possibly existing reverse causality and omitting variables, which may lead to the estimation bias of regressions in columns (3) and (4), this paper takes the lag terms of the explained variables as explanatory variables, adds it to the regression equations in columns (3) and (4) to run the regression. The results are shown in columns (5) and (6) respectively. As can be seen from the table, after taking the possible reverse causality and omitting variables into account, the location entropy of manufacturing is still negatively correlated with the explained variables at 10% significance level, which verifies the robustness of the conclusions in columns (3) and (4). Therefore, the conclusion that digital economy promotes the synergetic development of economy, environment and ecology through the spillover effect of low-end industries characterized by manufacturing holds robustly.

Table 11

Mediating tests of manufacturing agglomeration

	(1)	(2)	(3)	(4)	(5)	(6)
Explained variable	Agg_m			Dev		
Lag term of *Dev*					0.8442***	0.8396***
					(51.7811)	(51.4484)
Agg_m			-0.0318**	-0.0313**	-0.0887*	-0.0894*
			(-1.9997)	(-1.9932)	(-1.7339)	(-1.7496)
D	-0.2834***	-0.3380*		0.3017**		0.1649***
	(-2.8181)	(-1.9157)		(2.1752)		(3.6564)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,640	3,640	3,640	3,640	3,360	3,360
R-squared	0.0827	0.1048	0.6059	0.6090	0.7929	0.7939

Table 12 reports the mediating test of digital economy promoting the synergetic development of economy, environment and ecology by facilitating the agglomeration of producer services. As can be seen from column (1) of Table 12, the digital economy and the location entropy of producer services are positively correlated at 1% significance level, indicating that the digital economy has

significantly facilitated the agglomeration of high-end industries characterized by producer services, promoted the industrial intensification. At the same time, in order to avoid the estimation bias caused by the endogenous problems of the regression in column (1), we still use the instrumental variable in Table 5 to estimate the digital economy and replace the digital economy with it in the regression model of column (1) in Table 12. The result is shown in column (2), indicating that the digital economy estimated by instrumental variables is still positively correlated with the location entropy of producer services at 1% significance level, which verifies the robustness of the regression result in column (1). Column (3) in Table 12 examines the correlation between the location entropy of producer services and the explained variable, and the result show that they are positively correlated at 1% significance level. Then, we add the core explanatory variable to the regression in column (3), the regression result is shown in column (4) of Table 12, indicating that the location entropy of producer services is still positively correlated with the explained variable at 5% significance level, which means that even if there is has an overestimation of indirect effect in the mediating model, the location entropy of producer services is still significantly and positively correlated with the explained variable. Similarly, the regression coefficient of digital economy in this column is less than that in column (4) of Table 4. Therefore, we can take it for granted that digital economy facilitates the high-end industrial agglomeration characterized by producer services, and promotes the industrial intensification, thus contributing to the synergetic development of economy, environment and ecology. Further, we add the lag term of the explained variable as the explanatory variable to the regression equations in columns (3) and (4), and the results are shown in columns (5) and (6) respectively. The results suggest that the location entropy of producer services is still significantly positively correlated with the explained variables after considering the possible reverse causality and omitting variables, which verifies the robustness of the conclusions in columns (3) and (4). Therefore, the conclusion that digital economy facilitates the synergetic development of economy, environment and ecology by promoting the agglomeration of high-end industries characterized by producer services established robustly.

Table 12

Mediating tests of producer service agglomeration

	(1)	(2)	(3)	(4)	(5)	(6)
Explained variable	Agg_s				Dev	
Lag term of *Dev*					0.8465***	0.8419***
					(52.0766)	(51.7364)
Agg_s			0.3013***	0.3394**	0.2324*	0.2210*
			(2.6562)	(2.0921)	(1.7946)	(1.7035)
D	0.0192***	0.0271*		0.1564***		0.1650***
	(5.6543)	(1.7068)		(6.3062)		(3.6547)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,640	3,640	3,640	3,640	3,360	3,360
R-squared	0.0459	0.0429	0.5297	0.5600	0.7928	0.7937

So, through the results of Table 11 and Table 12, we've proved the Hypothesis 2 of this paper.

5. Further discussions

On the basis of verifying that digital economy promotes the synergetic development of economy, environment and ecology, this paper further discusses whether digital economy can mitigate the inequality of the synergetic development of economy, environment and ecology between regions, so as to achieve regional coordination. We construct the inequality index, referring

to Akita and Miyata (2010). The construction method is that the synergetic development economy, environment and ecology of the city minus the mean value of the explained variable that year of all prefecture-level cities in the province or autonomous region where this city is located, which is

$$Des_{it}=(Dev_{it}-\frac{1}{s_k+1}\sum_{i=u}^{u+s_k}\frac{Pop_{it}}{\sum_{i=u}^{u+s_k}Pop_{it}}Dev_{it})^2 \tag{7}$$

Where *Des* is the inequality index, k is the subscript of the province where city i is located, s_k is the number of prefecture-level cities in the province where city i is located except itself, and Pop_{it} is the number of populations in the year t of city i. The regression result is reported in column (1) of Table 13. As we can see that there is a negative correlation between the digital economy and the inequality index at 10% significance level. That is to say, the digital economy has mitigated the regional inequality of the explained variable among cities. However, the construction method of Eq. (7) inevitably leads to the bias caused by weights of the city into considerations, but the cities with large population weights may be less difference from the mean value of the explained variable in the province. Therefore, we construct the weighted inequality index (*Desw*), which takes the proportion of the population in this prefecture-level city to that of the province as the weight, namely:

$$Desw_{it}=\frac{Pop_{it}}{\sum_{i=u}^{u+s_k}Pop_{it}}(Dev_{it}-\frac{1}{s_k+1}\sum_{i=u}^{u+s_k}\frac{Pop_{it}}{\sum_{i=u}^{u+s_k}Pop_{it}}Dev_{it})^2 \tag{8}$$

Column (2) in Table 13 reports the regression result, which shows that the digital economy is still significantly and negatively correlated with the weighted inequality index at 5%, suggesting that the digital economy mitigates the inequality of the explained variable holds robustly.

Then, we sum up the equation (10) by province, so as to construct the inequality index in the province, and replace the explained variables in column (2) with the inequality index in the province. The construction method is as follows:

$$Desk_t=\sum_{i=u}^{u+s_k}\frac{Pop_{it}}{\sum_{i=u}^{u+s_k}Pop_{it}}(Dev_{it}-\frac{1}{s_k+1}\sum_{i=u}^{u+s_k}\frac{Pop_{it}}{\sum_{i=u}^{u+s_k}Pop_{it}}Dev_{it})^2 \tag{9}$$

Column (3) in Table 13 reports the regression results. The results show that the digital economy has mitigates the inequality index in the province at 1% significance level and realized the regional coordination development in terms of economy, environment and ecology.

Table 13

Result of the digital economy on the regional inequality of variables

	(1)	(2)	(3)	(4)	(5)
Model	Panel data fixed effect model			SDM	
Variable	*Des*	*Desw*	*Desk*	*Dev*	
				Main	Spatial
D	-0.0055*	-0.0003**	-0.0044***	0.2562***	0.2522***
	(-1.8205)	(-2.1094)	(-4.2199)	(9.2998)	(8.6990)
Control Variables	Yes	Yes	Yes	Yes	Yes
Space lag term of Dev				0.5967	
				(1.1317)	

City fixed effect	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
Observations	3,640	3,640	3,640	3,640
R-squared	0.0150	0.0410	0.1537	0.0040

Note: "Main" means the regression of explanatory variable in the local area on the explained variable in the local area, "Spatial" means the regression of explanatory variable in the local area on the explained variable in the surrounding areas, we can also take it for granted that "Spatial" denotes the regression of explanatory variable in the surrounding areas on the explained variable in the local area.

In order to explore the mediating mechanism on how digital economy promotes the synergetic development of economy, environment and ecology and mitigating the inequality between regions, we use Spatial Dobbin Model (SDM), which is set as follows:

$$Dev_{it}=\gamma_{00}+\gamma_{01}D_{it}+\gamma_{02}\boldsymbol{W}Dev_{it}+\gamma_{03}\boldsymbol{W}D_{it}+\boldsymbol{X_{it}G_0}+\boldsymbol{WX_{it}H_0}+\mu_i+e_t+\varepsilon_{it} \quad (10)$$

Where $\boldsymbol{W}$ is the spatial weighted matrix. We still select the spatial distance matrix the weighted matrix. The regression results are reported in columns (4) and (5) of Table 13. As we can see that both main and spatial term of digital economy are positively correlated with the synergetic development of economy, environment and ecology. These results suggest that digital economy can not only promote the synergetic development of economy, environment and ecology in the local area, but also spill over to surrounding areas through the technology, information and knowledge led by digital economy. Digital economy has facilitated the reform and upgradation of industries in the surrounding areas, which contributes to the development of the synergetic development of economy, environment and ecology in both local area and surrounding areas, thus promoting the coordinated development among regions and reducing the regional inequality in the synergetic development of economy, environment and ecology among regions.

6. Conclusions and policy recommendations

This paper selects 280 prefecture-level cities and municipalities in China from 2011 to 2023 as research samples. Based on theoretical analysis, this paper constructs the synergetic development of economy, environment and ecology and the digital economy index through entropy weight method, empirically explores the effect and mediating mechanisms of digital economy on synergetic development of economy, environment and ecology by using panel data fixed effect model and robust mediating model, and further discusses the effect of digital economy on regional inequality in the synergetic development of economy, environment and ecology. The study found that:

Firstly, digital economy has significantly promoted the synergetic development of economy, environment and ecology, and this conclusion is robustly established after the endogenous tests such as 2SLS, lagging all the explanatory variable, dynamic panel date model test, exogenous shock test, and robustness test of replacing variable construction method and regression models.

Secondly, digital economy significantly promotes the economic development, but it has a threshold effect on environment and ecology. When digital economy is undeveloped, digital economy deteriorates environment and ecology, while when digital economy is developed, it promotes the development of environment and ecology.

Thirdly, heterogeneity tests show that the promotion of digital economy to the synergetic development of economy, environment and ecology are mainly in small-sized and medium-sized cities such as third-tier, fourth-tier and fifth -tier cities, but has no significant impact the synergetic development of economy, environment and ecology in first-tier and second-tier cities.

Fourthly, the research on the mediating mechanisms shows that the digital economy has

facilitates the synergetic development of economy, environment and ecology by suppressing the agglomeration of manufacturing, promoting the spillover effect of low-end industries characterized by manufacturing and the agglomeration of high-end industries characterized by producer services.

Fifthly, exploration of on how digital economy affects the regional inequality in the synergetic development of economy, environment and ecology find that the digital economy mitigates the regional inequality in the synergetic development of economy, environment and ecology and contributes to the regional coordinated development. Through the spillover effect of knowledge and technology, digital economy fosters the coordinated industrial upgradation across regions, promotes the synergetic development of economy, environment and ecology in the surrounding areas, thus facilitates the regional coordination.

Based on the above conclusions, this paper puts forward the following policy suggestions:

First, establish a strong foundation for the growth of the digital economy by bolstering the development of digital infrastructure. create a strong basis for the growth of the digital economy.

Second, when promoting the integration of digital economy and real economy, we should pay attention to the combination of economic benefits and environmental benefits.

Thirdly, the high-end industrial agglomeration should be rewarded to create a good environment for the development of the digital economy. For low-end industries, spillover dispersion is encouraged to reduce centralized pollution emission. According to the level of urban development and the resource type, elaborate and targeted policies are adopted to narrow the development differences between regions and promote the synergetic development of economy, environment and ecology.

References

Afolabi J. A. Advancing digital economy in Africa: The role of critical enablers [J]. Technology in Society, 2023,75: 102367. https://doi.org/10.1016/j.techsoc.2023.102367.

Akita T., Miyata S. The bi-dimensional decomposition of regional inequality based on the weighted coefficient of variation. Lett Spat Resour Sci , 2010,3: 91-100. https://doi.org/10.1007/s12076-010-0040-x.

Chang H., Ding Q., Zhao W., Hou N., Liu W. The digital economy, industrial structure upgrading, and carbon emission intensity -- empirical evidence from China's provinces [J]. Energy Strategy Reviews. 2023a, 50: 101218. https://doi.org/10.1016/j.esr.2023.101218.

Chang K., Zhang H., Li B. the impact of digital economy and industrial agglomeration on the changes of industrial structure in the Yangtze River Delta [J/OL]. Journal of the Knowledge Economy. [2023b-08-07]. https://doi.org/10.1007/s13132-023-01448-w.

Chen L., Lu Y., Meng Y., Zhao W. Research on the nexus between the digital economy and carbon emissions - Evidence at China's province level [J]. Journal of Cleaner Production. 2023, 10: 137484.

Chen P. Relationship between the digital economy, resource allocation and corporate carbon emission intensity: new evidence from listed Chinese companies [J]. Environmental Research Communications. 2022,7(4): 075005.

Fan G., Wang X., Zhang L., Zhu H. Contribution of Marketization to China's Economic Growth [J]. Economic Research Journal, 2003(03):9-18+89. https://kns.cnki.net/kcms2/article/abstract?v=f2Ae6OvU-JJWWf43_RTtZqr91r83aV46P3lxA6WwIMKvu9Z7Fpb6VmnC6VYjImbqHlm1_yK2thiI_KxjN0H8Cb5c4I9j5HSGC4j4w0vJGgX29qV3utozDLVx68w4Yb2rDH_V39NZc_8=&uniplatform=NZKPT&language=CHS.

Fu X. An empirical assessment of the impact of digital economy and environmental regulation on regional water resources efficiency in the context of COP26 [J]. Environmental Science and Pollution Research. 2023, 30(11): 30933-30947. https://doi.org/10.1007/s11356-022-24343-4.

Gao W., Peng Y. Energy saving and emission reduction effects of urban digital economy: technology dividends or structural dividends? [J] Environmental Science and Pollution Research. 2023, 30(13): 36851-36871. https://doi.org/10.1007/s11356-022-24780-1.

Guo B., Wang Y., Zhang H., Liang, C., Feng Y., Hu F. Impact of the digital economy on high-quality urban economic development: Evidence from Chinese cities [J]. Economic Modelling. 2023,120: 106194.

Guo F., Wang J., Wang F., Kong T., Zhang X., Cheng Z. Measuring China's digital financial inclusion: Index compilation and spatial characteristics [J]. China Economic Quarterly, 2020, 19(04): 1401-1418. https://doi.org/10.13821/j.cnki.ceq.2020.03.12

Han Y., Li Y., Wang Q. Digital finance, environmental regulation, and green development efficiency of China [J]. Frontiers in Environmental Science, 2023,11: 1131058. https://doi.org/10.3389/fenvs.2023.1131058

Huang X., Zhang S., Zhang J., Yang K. Research on the impact of digital economy on regional green technology innovation: Moderating effect of digital talent aggregation [J]. Environmental Science and Pollution Research. 2023,30(29):74409-74425. https://doi.org/10.1007/s11356-023-27279-5

Jiang, X., Wang, X., Ren, J., Xie Z., Digital economy, agglomeration, and entrepreneurship in Chinese cities [J]. Managerial and Decision Economics, 2022,44(01):359-370.

Kan D., Lyu L., Huang W., Yao W. Digital economy and the upgrading of the global value chain of China's service industry [J]. Journal of Theoretical and Applied Electronic Commerce Research, 2022, 17(04): 1279-1296. https://doi.org/10.3390/jtaer17040065

Li J., Ye S., Zhang Y. How digital finance promotes technological innovation: Evidence from China [J]. Finance Research Letters. 2023a,58: 104298.

Li S., Gao L., Han C., Gupta B., Alhalabi W., Almakdi S. Exploring the effect of digital transformation on Firms' innovation performance [J]. Journal of Innovation & Knowledge. 2023b, 8(1): 100317. https://doi.org/10.1016/j.jik.2023.100317.

Li S., Yang T. The impact of digital infrastructure on air quality: Mediating role of public environmental attention and industrial development[J]. Journal of Environmental Management, 2025, 373: 123893. https://doi.org/10.1016/j.jenvman.2024.123893.

Li X, Chen Z, Chen Y. The impact of digital talent inflow on the co-agglomeration of the digital economy industry and manufacturing[J]. Systems, 2024, 12(8): 317. https://doi.org/10.3390/systems12080317.

Li Z., Zhu J., He J. The effects of digital financial inclusion on innovation and entrepreneurship: A network perspective [J]. Electronic Research Archive. 2022, 30 (12):4697-4715. https://doi.org/10.3934/era.2022238.

Lin Y., Wang Q., Zheng M. Nexus among digital economy, green innovation, and green development: evidence from China [J/OL]. Emerging Markets Finance and Trade. [2023-10-16].

Liu L., Liu M. How does the digital economy affect industrial eco-efficiency? Empirical evidence from China [J]. Data Science in Finance and Economics. 2022, 2(4):371-390. https://doi.org/10.3934/DSFE.2022019.

Liu T., Xu Z., Zhang K.The impact of digital finance on the synergy of economic development and ecological environment [J]. Modern Finance and Economics-Journal of Tianjin University of Finance and Economics, 2022,42(02):21-36. https://doi.org/10.19559/j.cnki.12-1387.2022.02.002.

Liu Y., Xie Y., Zhong K. Impact of digital economy on urban sustainable development: Evidence from Chinese cities [J]. Sustainable Development, 2024, 32(01): 307-324. https://doi.org/10.1002/sd.2656.

Ma K. Digital inclusive finance and corporate green technology innovation [J]. Finance Research Letters, 2023,55: 104015. https://doi.org/10.1016/j.frl.2023.104015

Nambisan S., Wright M., Feldman M. The digital transformation of innovation and entrepreneurship: Progress, challenges and key themes [J]. Research Policy. 2019, 48(8): 103773.

Pan W., Xie T., Wang Z., Ma L. Digital economy: An innovation driver for total factor productivity [J]. Journal of Business Research. 2022,139: 303-331. https://doi.org/10.1016/j.jbusres.2021.09.061.

Pan Y., Yang M. Research on the impact of digital infrastructure on the allocation efficiency of green resources in the service industry[J/OL]. American Journal of Economics and Sociology. [2023-08-20].

Qi Y., Niu Y., Zhou Z. Digital economy empowering the development level of Chinese manufacturing industry [J]. Economic Computation and Economic Cybernetics Studies and Research, 2023,57(4): 243-258.

Shen Y., Zhang X. The impact of artificial intelligence on employment: the role of virtual agglomeration [J]. Humanities & Social Sciences Communications. 2024, 11(1): 122. https://doi.org/10.1057/s41599-024-02647-9.

Tang J., Zhao X. Does the new digital infrastructure improve total factor productivity? [J]. Bulletin of Economic Research. 2023, 75(4): 895-916. https://doi.org/10.1111/boer.12388.

Tang Song, Wu Xuchuan, Zhu Jia. Digital finance and enterprise technological innovation-structural characteristics, mechanism identification and effect difference under financial supervision [J]. Journal of Management World, 2020,36(05):52-66+9.

Tao C., Ding Y. How does the digital economic policy affect the innovation of manufacturing enterprises: From the perspective of suitable supply [J]. Contemporary Finance & Economics. 2022, (3): 16-27. https://doi.org/10.13676/j.cnki.cn36-1030/f.2022.03.001.

Tian X, Lu H. Digital infrastructure and cross-regional collaborative innovation in enterprises[J]. Finance Research Letters, 2023, 58: 104635. https://doi.org/10.1016/j.frl.2023.104635.

Tian J., Wang Y., Sun S. Two Sides of a Coin: Digital Economy and the Supply of Basic Public Services [J/OL]. Journal of the Knowledge Economy. Access on: 2024-02-17. https://doi.org/ 10.1007/s13132-024-01743-0.

Wang J., Dong X., Dong K. How does ICT agglomeration affect carbon emissions? The case of Yangtze River Delta urban agglomeration in China [J]. Energy Economics, 2022,111: 106107. https://doi.org/10.1016/j.eneco.2022.106107.

Wang M, Zhang M, Chen H, et al. How does digital economy promote the geographical agglomeration of manufacturing industry?[J]. Sustainability, 2023, 15(2): 1727. https://doi.org/10.3390/su15021727.

Wang S., Li J. Nonlinear spatial impacts of the digital economy on urban ecological welfare performance: evidence from China [J]. Frontiers in Ecology and Evolution, 2024,12: 12:1361741. https://doi.org/10.3389/fevo.2024.1361741.

Wu H., Han M., Shen, Y. Technology-driven energy revolution: the impact of digital technology on energy efficiency and its mechanism [J]. Frontiers in Energy Research, 2023a,11: 1242580. https://doi.org/10.3389/fenrg.2023.1242580

Wu L., Wan X., Jahanger A., Li M., Murshed M., Balsalobre-Lorente D. Does the digital economy reduce air pollution in China? A perspective from industrial agglomeration [J]. Energy Reports. 2023b,9: 3625–3641.

Wu M., Guo J., Tian H., Hong Y. Can Digital Finance Promote Peak Carbon Dioxide Emissions? Evidence from China [J]. International Journal of Environmental Research and Public Health. 2022, 19: 14276. https://doi.org/10.3390/ijerph192114276.

Wu M., Ma Y., Gao Y., Ji Z. The impact of digital economy on income inequality from the perspective of technological progress-biased transformation: evidence from China [J/OL]. Empirical Economics. [2024-02-19]. https://doi.org/10.1007/s00181-024-02563-6.

Xiong M., Zhang F., Zhang H., Wang H. Digital economy, credit expansion, and modernization of industrial structure in China [J]. Finance Research Letters. 2023,58: 104500.

Yang G., Ding Z., Wu M., Gao M., Yue Z., Wang H. Can digital finance reduce carbon emission intensity? A perspective based on factor allocation distortions: Evidence from Chinese cities[J]. Environmental Science and Pollution Research. 2023, (3): 38832–38852.

Zhang J., Wu G., Zhang J. The Estimation of China's provincial capital stock: 1952-2000 [J]. Economic Research Journal, 2004(10):35-44. https://kns.cnki.net/kcms2/article/abstract?v=f2Ae6OvU-JJtP4ZnTJRHQ0aITC7NKuqXe-9J1F-ye8LVTGt6crYgJd-KopVjjG-d4edmDJkdczT1ToqdnW2Xwuz-PW0rSaSIfK8nTeU13vX_oqHsc3zpH7aJLDFPpIQrL54JH5zH8gg=&uniplatform=NZKPT&language=CHS.

Zhang J., Zhao W., Cheng B. et al. The Impact of digital economy on the economic growth and the development strategies in the post-COVID-19 era: Evidence from countries along the "Belt and Road" [J]. Frontiers in Public Health, 2022a, 10: 856142. https://doi.org/10.3389/fpubh.2022.856142

Zhang W., Liu X., Wang D., Zhou J. Digital economy and carbon emission performance: Evidence at China's city level [J]. Energy Policy. 2022b,165: 112927.

Zhao T., Zhang Z., Liang S. digital economy, entrepreneurship, and high-quality economic development：Empirical evidence from urban China [J]. Journal of Management World, 2020,36(10):65-76. https://doi.org/10.19744/j.cnki.11-1235/f.2020.0154.

Funding

This work receives no external support.

Data availability

All data are available from the corresponding author upon request.

Conflict of interest statement

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

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed Consent

This article does not contain any studies with human participants performed by any of the authors