



OPEN Unveiling the impact of synergy between digitalization and greening on urban employment in China

Qiangyi Li^{1,2,3}, Jiexiao Ge^{1✉} & Houbao Fan⁴

Digitalization and greening are two major characteristics of economic and social development, and promoting the deep synergy of these two factors has significant practical relevance for employment. However, the question of whether synergy between digitalization and greening promotes or hinders employment has not been answered in the literature. Therefore, a synergistic framework was first constructed for urban greening and digitalization based on green pulling and the digital empowerment mechanism. By using data from 281 cities in China from 2011 to 2021, the synergistic effects of digitalization and greening on employment and its underlying mechanisms were explored in this study. The findings revealed that (1) the synergistic development of these two factors can indeed promote employment, and this result remains valid after numerous robustness tests are performed. (2) Mechanism analysis revealed that the synergy can enhance employment by promoting regional innovation and entrepreneurship and increasing human capital investment. (3) Heterogeneity analysis showed that there was a more significantly positive effect on employment in the tertiary industry, in eastern and central regions, and among governments with a greater preference for innovation. (4) Further research has shown that this synergy has a prominent spatial spillover effect on employment, and it remains valid after the matrix is replaced. These results offer policy references for fully unleashing the employment-creating effect of the synergy between digitalization and greening and thereby achieving high-quality development.

Keywords Digitalization and greening, Regional innovation and entrepreneurship, Coupling coordination, Spatial spillover effect

Decent work has important implications for sustainable development goals and human well-being¹. Thus, employment issues have always been long-term concerns of many politicians and policy-makers around the world. However, data from the World Bank show that the global unemployment rate reached 6.2% in 2021 (data.worldbank.org.cn), and phenomena such as divorces, suicides, and crimes caused by high unemployment rates seriously hinder social progress^{2,3}. Therefore, how to increase employment and improve the well-being of people is a globally common challenge. As one of the important socio-economic targets, China has also promoted high-quality full employment through the implementation of the employment priority strategy⁴. However, owing to increased economic downturn pressure, the disappearance of demographic dividends, and inequality in public services due to urban sprawl, the employment situation in the labor market is not optimistic. Specifically, in recent years, the registered urban unemployment rate in China has remained high, fluctuating around the level of 4.1% since 2003. And the national overall unemployment rate reached 5.1% in 2021. This implies that the employment issue is still a major challenge in China. It is crucial to explore effective ways to alleviate the severe employment situation in China.

Digitalization and greening are significant characteristics of global economic and social development⁵. Digitalization has become a key driver of technological innovation and efficiency enhancement, and incorporating green development into the digitalization process can facilitate the realization of environmentally

¹School of Economics and Management, Guangxi Normal University, Guilin 541006, China. ²Key Laboratory of Digital Empowerment Economic Development, Education Department of Guangxi Zhuang Autonomous Region, Guangxi Normal University, Guilin 541004, China. ³The Center for Guangxi High-Quality Industrial Development Research, Liuzhou 545616, Guangxi, China. ⁴School of Applied Economics, Jiangxi University of Finance and Economics, Nanchang 330013, China. ✉email: gejiexiao@stu.gxnu.edu.cn

friendly digital development^{6,7}. Thus, the synergistic development of these two is not merely a simple sum of two trends, but a process of mutual promotion and deep integration. In this process, digitalization empowers green development. Through technological innovation, industrial upgrading, and other means, digitalization enhances resource utilization efficiency and promotes the development of a green economy^{6,8}. Meanwhile, greening pulls digital transformation. As the application of digital technology also brings about more resource consumption and carbon emissions, green development poses higher requirements for it. It emphasizes that the application in production, life, ecology, and other fields needs to shift to an environmentally friendly model^{7,9}. In the process of synergistic development between digitalization and greening, many high-carbon industries face a series of issues, such as changing production methods and technological processes. Therefore, employees in related industries will also experience competition, elimination, and adjustment of their job positions¹⁰. The synergistic development of these two factors may have profound implications for employment. It is necessary to explore whether the synergy between digitalization and greening can promote or inhibit employment. The framework should also delve into the paths through which the synergy between digitalization and greening affects employment.

Previous studies have explored the impact on employment from the single perspective of the digital economy or green development, and there are two viewpoints of employment creation and employment substitution^{11–14}. However, against the backdrop of the synergistic development of digitalization and greening, few studies discuss the synergistic effect of these two on employment. Therefore, this paper examines 281 cities in China and explores the direct role, transmission mechanism, and spatial effects of these two factors on employment from both theoretical analysis and empirical testing. Finally, policy recommendations are proposed.

Unlike the existing research, the paper is characterized by the following aspects: First, we innovatively reveal the social effects of the synergistic development of digitalization and green. Second, focusing on the demand-supply side, this paper explores the driving mechanism of the synergistic effect on employment from multiple dimensions, including regional innovation and entrepreneurship and the effect of human capital investment. Finally, verification of the theoretical mechanism can provide corresponding policy insights for governments at all levels to explore the optimal path for achieving high-quality labor and full employment. It also offers empirical evidence with practical significance for setting up a digital China, promoting environmentally friendly development, and maintaining the sustainability of the economy and society.

Literature review

Coupling coordination of digitalization and greening

Although there have been relatively rich discussions about the digital economy and green development, few studies have discussed on their bidirectional relationship. Currently, the limited research that exists concentrates on the following three aspects. One stream of literature analyses the integration mechanism and implementation path of digitalization and greening from a theoretical perspective. Scholars have widely explored how digitalization empowers green development. For example, the application of digital technology accelerates the green economy and promotes energy efficiency improvements^{15,16}; subsequently, the integration of digitalization and greening has attracted attention from scholars. Their collision is an urgent and critical way to achieve sustainable and high-quality economic development¹⁷. Currently, scholars are researching on the conceptual connotations and mechanisms of digitalization and greening. They deeply explore the coupling relationship of digitalization or greening with industrialization¹⁸, the ecological environment¹⁹, the energy industry²⁰, green finance²¹, and the regional economy and society^{22,23}. Finally, it involves the measurement of the synergy between digitalization and greening. Building an index system according to their core concepts and using methods such as entropy weighting and the coupling coordination model are relatively common approaches^{19,21}.

Research on digitalization, greening, and employment

Research on digitalization, greening, and employment has focused on two main aspects: first, there are two viewpoints about the impact of digital development on employment. On the one hand, the core technologies brought about by digital development can attract high-skilled talents with more high-paying job opportunities^{24,25}. Furthermore, the rapid development of the internet possesses immense potential for job creation, specifically by generating new employment opportunities and mitigating labor misallocation^{11,26}. However, some work can be done by automation technology and artificial intelligence, posing significant challenges to labor employment^{12,27}. The second research stream discusses the impact of green development on employment. Strict environmental regulations may lead to increased costs for enterprises, reducing their output and thus diminishing the demand for labor^{13,28,29}. New environmental regulations accelerate technological upgrading in enterprises, enhance labor productivity, and consequently reduce the demand for labor¹³. However, many studies have found that policies related to green development promote employment growth. Moreover, relevant research has revealed that it can encourage the inflow of labor into cities and have a positive effect on employment by increasing output levels and promoting industrial innovation^{14,30}.

The aforementioned studies have expanded the content on factors affecting employment from the perspectives of digitalization or green transformation. However, studies on the synergy between digitalization and greening and its impact on employment still need to be conducted. In response, the mechanisms of the synergistic development of digitalization and greening were first clarified, and then their synergistic level was measured. On this basis, the direct role, transmission mechanisms, and spatial effects of this synergetic development on employment are explored.

Theoretical analysis and research hypotheses Synergistic mechanisms of digitalization and greening

Digitalization and greening are important features of economic and social development⁵, and They have a deep coupling and coordination relationship. The synergy theory emphasizes that the two systems of digitalization and greening eventually evolve from disorder to order through internal transformation and synergy, i.e., the synergy between the subsystems is the intrinsic driving force of the system's development³¹; therefore, referring to Zhou and Qiao³², the paper reveals the integration mechanism of the two systems from the sub-dimensions. It is important to explore the social effects generated by the synergy of digitalization and greening (Fig. 1).

On the one hand, digitalization empowers green development. Urban digitalization promotes synergistic development through the empowerment of digital infrastructure, the application of digital technologies, and the support of local governments.

First, digital infrastructure is not only a vital means of energy conservation and emission reduction but also empowers various industries to achieve green development goals^{33,34}, accelerating the green transformation of the economy and society. So the digital infrastructure empowerment mechanism is proposed. Second, advances in digital technology drive the upgrading of digital industrialization³⁵. As pivotal means and tools, digital technologies are extensively applied in driving the upgrading of traditional industries and promoting green production and lifestyles^{36,37}, thereby accelerating the empowerment of green development by data elements and digital technology applications. Consequently, a mechanism for digital technology application empowerment is proposed. Last, industrial digitalization represents an effective way to enhance resource utilization efficiency and propel the transformation and upgrading of traditional industries³⁸. However, it needs rational policy guidance and financial support from local governments. For example, green finance can guide funding toward emission-reduction enterprises and projects, encouraging firms to adjust and optimize their industrial structures, and thereby promoting environmentally friendly development³⁹. So the local government support mechanism is proposed.

On the other hand, greening, with green production as the key means, green living as the developmental goal, and green ecology as an important foundation, integrates the environmentally friendly concept and new technologies into the entire process of production, living, and ecology to promote the industrial upgrading, changes in lifestyle, and ecological optimization constraints^{40,41}. These will help the synergistic development of digitalization and greening.

First, the essence of green production is to construct a clean and efficient energy system within the production process and reduce the generation and emission of pollutants. It promotes the accelerated upgrading of traditional industries and the rapid emergence and expansion of new types. This, in turn, creates a greater demand for the deep integration of digital technology with enterprise production technology, as well as their extensive application throughout the entire production process, to optimize production and improve the efficiency of each production link. Therefore, the pulling mechanism for industrial transformation is proposed. Second, by raising awareness among the public of green living, they begin to actively practice environmentally friendly behaviors, leading to a shift toward a green lifestyle. Additionally, with the widespread use of digital technology, digital applications in scenarios such as green consumption, green travel, and green living have become more prevalent in daily life^{42,43}. This further necessitates more accurate dissemination of green concepts in digital application scenarios. Therefore, a lifestyle change-pulling mechanism is proposed. Third, a series of urban ecological optimization and development constraints, including scientific protection of the ecological environment, systematic governance of ecological issues, and effective management of ecological assets, drive the transformation and progress of digital technology. Moreover, the optimization of the urban ecosystem provides a high-quality environment for digital technology, facilitating the deep integration of digitalization and greening. Hence, an ecosystem optimization pulling mechanism is proposed.

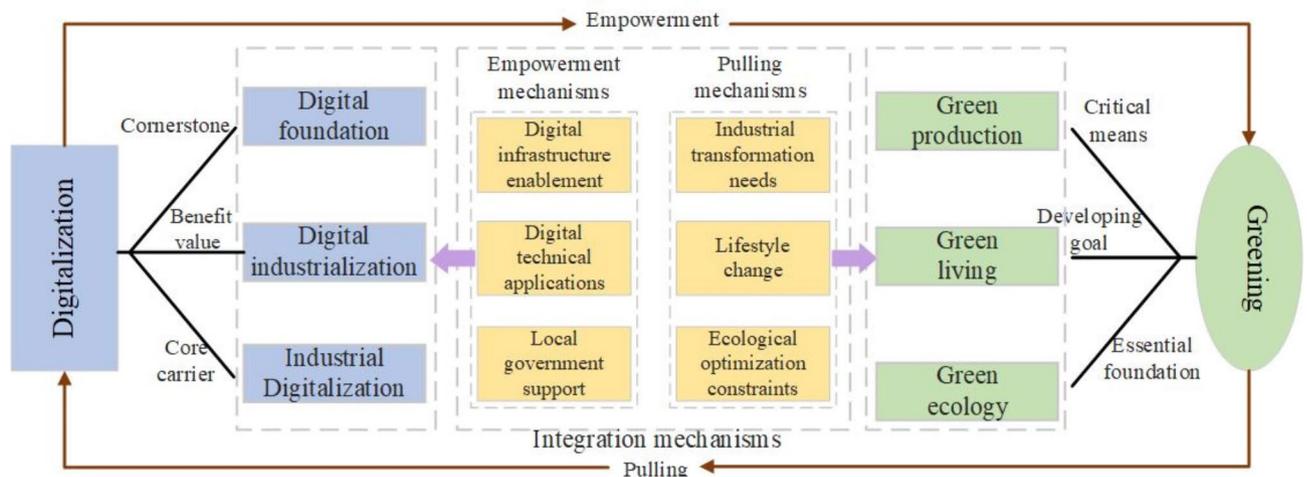


Fig. 1. Mechanisms of digitalization and greening synergy.

Direct impact of the synergy between digitalization and greening on employment

Research has shown that both digitalization and greening can affect employment to some extent^{14,25}. If digitalization and greening are deeply integrated, will they promote or hinder employment? In fact, against the backdrop of resource depletion and environmental degradation, finding a path for the synergy between greening and digitalization is key to achieving sustainability. Rapid digital development can inject vitality into the local green economy, promoting technological progress and the upgrading of industrial structures. And it also gives rise to the development of new industries such as software design and the service sector. This stimulates new demand and thereby generates new employment positions, job methods, and forms, thereby raising the demand for labor^{44,45}. Additionally, in the synergistic development of digitalization and greening, the extensive application of digital technology provides a platform for information dissemination and docking between the supply and demand of labor. It not only accurately matches labor demand, but also helps to reduce the problem of information asymmetry, lower the cost of labor searching for employment, and improve the matching efficiency of both sides, thus contributing to high-quality and full employment⁴⁶.

H1 The synergy between digitalization and greening is beneficial for improving the employment level.

Analysis of transmission mechanisms

To improve people's livelihoods and promote full employment, it is worth deeply exploring how the synergy between digitalization and greening promotes employment. This paper focuses on the demand and supply sides of labor, attempting to deconstruct the black box of mechanisms from multiple perspectives, including regional innovation and entrepreneurship and the effect of human capital investment (Fig. 2).

The synergy between digitalization and greening, regional innovation and entrepreneurship, and employment

For the demand side, the synergistic effect can facilitate regional innovation and entrepreneurship to support labor employment. During the process of promoting the synergistic effect, various intelligent and informational methods continuously influence residents' concepts of life and consumption patterns, thereby stimulating diverse consumer demands. The scale effect of demand formed by green consumption forces companies to provide corresponding products and services. This motivates entrepreneurs to engage in green ecopreneurship and innovation activities, thereby expanding the existing market and creating new markets⁴⁷. Moreover, digital development has overcome traditional spatial and temporal constraints and facilitates the free exchange of all types of information⁴⁸. This is conducive to promoting a more open and transparent trading market, improving information asymmetry, and reducing the problem of transaction costs. Convenient access to information resources and channels enhances people's awareness of innovation and entrepreneurship, and changes and innovations in the production and sales methods and operation modes of traditional industries increase the popularity of innovation and entrepreneurship. Previous studies have shown that stimulating regional innovation and entrepreneurship activities can promote economic growth and increase the demand for labor, thus providing labor with more employment opportunities^{49,50}. Therefore, the hypothesis 2 is proposed:

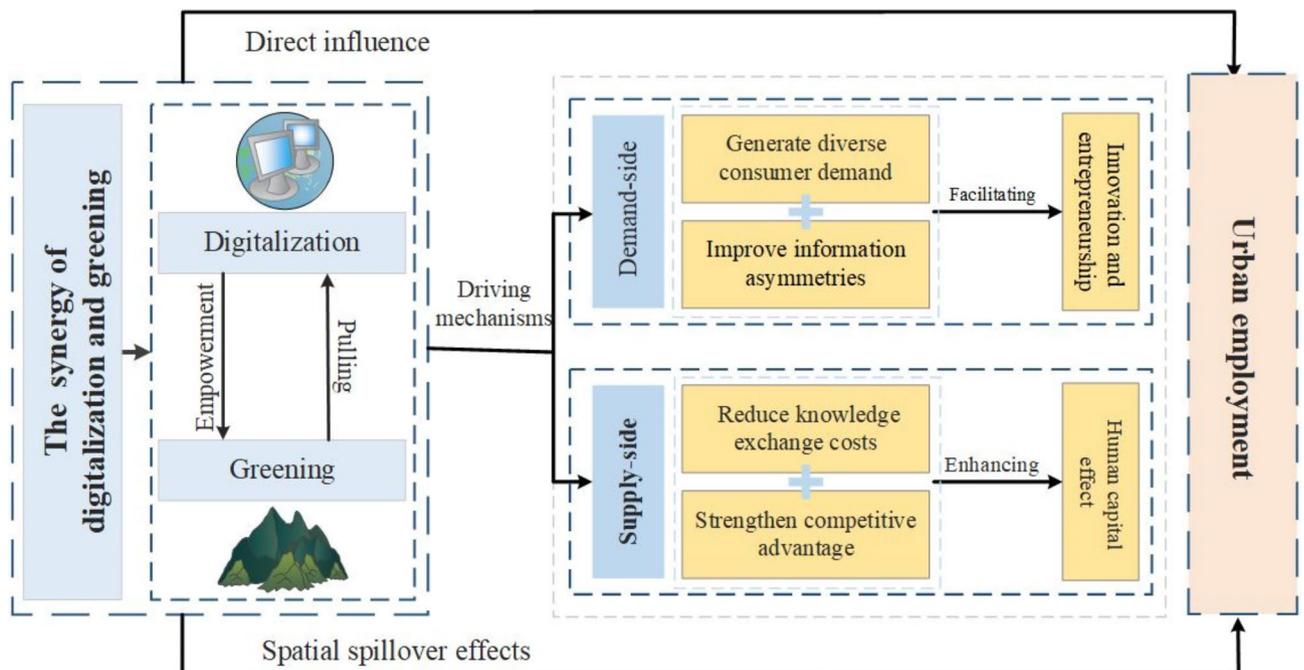


Fig. 2. Analysis of the mechanisms of the synergetic effect on employment.

H2 On the demand side, the synergistic effect promotes employment by facilitating regional innovation and entrepreneurship.

The synergy between digitalization and greening, human capital investment, and employment

From the supply side, the synergistic effect of these two factors can promote employment through the human capital investment effect. As the synergy between digitalization and greening continues to advance, many industries emerge from this process. They are characterized by being new in the field, having a high level of technological content, and being distinct in their scientific and technological features. This has led to a greater demand for highly skilled and proficient workers^{51,52}. If the labor force possesses a higher level of human capital, employees will correspondingly have stronger work skills and abilities, allowing them to be more competitive in the labor market, be eligible for more and higher-quality employment opportunities, and obtain higher salaries. Additionally, employees with high-level skills, even if unemployed, can quickly capture labor market information and secure new employment opportunities. The accumulation of highly skilled human capital also contributes to promoting green growth in cities⁵³. This, in turn, forces individuals to continuously learn and adapt to new technologies, such as mastering and applying new energy technologies and environmental monitoring technologies. Moreover, the rapid development of digitalization can overcome spatial limitations, thus promoting the accessibility of educational resources. This assists workers in quickly and accurately obtaining relevant learning resources, reducing the cost of labor education, and accelerating the acquisition of new skills and the accumulation of new knowledge⁵⁴. Based on the classic human capital theory, this helps workers acquire skills more quickly, enabling them to meet job requirements. Therefore, the hypothesis 3 is proposed:

H3 On the supply side, the synergistic effect can promote employment through enhancing the human capital effect.

Analysis of the spatial spillover effects of the synergy between digitalization and greening

It is widely acknowledged that social economic phenomena not only exhibit correlation over time but also show interdependence in space. The main characteristics of digital development, such as its wide coverage, strong permeability, integration, and sharing, make the regional economy and production links increasing⁵⁵, thus breaking the existing regional barriers of market segmentation and the free flow of factors. This also contributes to making the production and operation of various industries between regions interdependent and interpenetrating. Therefore, this study suggests that the synergy between digitalization and greening can help employment in both local and other regions. First, the synergy between digitalization and greening promotes employment by giving rise to new employment methods and business formats. However, it not only relies on increasing factor inputs locally but also benefits from industries in surrounding areas. It also helps expand the market scale of neighboring regions. Second, the successful experience of the synergy between digitalization and greening in promoting employment will serve as a demonstration effect for adjacent regions. In addition, stimulating other areas to imitate and learn will also encourage local governments to take action to support the further improvement of the synergistic effect, thereby achieving a multiplier effect on employment. Hence, the hypothesis 4 is proposed:

H4 There is a spatial spillover effect in the synergy between digitalization and greening; in other words, the synergetic effect can not only promote local employment but also stimulate employment in neighboring regions.

Methods and data

Research methods

Entropy weight method

As a means of objective weighting, the method measures weights based on the theory of information entropy; it is a more objective assessment method that effectively overcomes the shortcomings of subjective weighting methods⁵⁶. Generally, the smaller the information entropy of an indicator is, the greater the degree of variability in its values, and the more information it provides. Consequently, it has a greater role in comprehensive evaluations⁵⁷. The reverse is also true. Therefore, this method is used to measure the synergetic effect referring to Li et al.⁵⁶ and Zhu et al.⁵⁷.

(1) Determine the weight j :

$$W_j = \frac{d_j}{\sum_{j=1}^n d_j} = \frac{1 - e_j}{n - \sum_{j=1}^n e_j} \quad (1)$$

(2) Calculate the comprehensive score:

$$W_{ij} = \sum_{i=1}^n W_j \times y_{ij} \quad (2)$$

In Eqs. (1) and (2), y_{ij} represents the standardized indicator values, d_j is the coefficient of difference, W_j is the weight, and W_{ij} is the comprehensive score.

Coupling coordination model

The degree of coupling reveals the extent of interdependence and interaction between the two systems, whereas the coordination degree reflects the level of benign coupling of multiple systems. The synergetic development of digitalization and greening is calculated as follows^{57,58}:

$$C = 2 \times \left[\frac{U_D U_G}{(U_D + U_G)^2} \right]^{1/2} = 2 \times \frac{\sqrt{U_D U_G}}{U_D + U_G} \quad (3)$$

$$T = \alpha U_D + \beta U_G \quad (4)$$

$$D = (C \times T)^{1/2} \quad (5)$$

In Eq. (3) to (5), U_D and U_G present the levels of digital and green development, respectively; α and β are the weighting coefficients for each system. Considering the equal importance of both systems to the overall system, α and β are 1/2. C is the coupling degree of digitalization and greening, ranging from 0 to 1. In addition, a higher value indicates a weak degree of discreteness among the subsystems, suggesting a more perfected mechanism of mutual influence among the two subsystems. T is their comprehensive development level, while D is the synergetic development between digitalization and greening with a value ranging from 0 to 1.

Model construction

Benchmark model

To test the direct impact of the synergy between digitalization and greening on labor employment, the following benchmark regression model was set:

$$EMPL_{it} = \alpha_0 + \alpha_1 DSDG_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

In Eq. (6), i and t represent the city and year, respectively. $EMPL_{it}$ denotes the level of employment in city i in year t , whereas $DSDG_{it}$ represents the level of synergetic development of digitalization and greening in city i in year t . Additionally, the coefficients represent the degree of impact on employment. X is the set of control variables selected in this paper. We also control for the fixed effects of region (μ_i) and year (λ_t). ε is the random error term. Moreover, the standard errors are clustered at the urban level.

Furthermore, to verify Hypotheses 2 and 3, we attempt to deconstruct the mechanism of the synergetic effect on employment by directly regressing the mechanism variables on the core explanatory variable and constructing the following mechanism test model:

$$Med_{it} = \alpha_0 + \alpha_1 DSDG_{it} + \alpha_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (7)$$

where Med represents the mechanism variable, which is the regional innovation and entrepreneurship and the human capital investment effect. The meanings of the remaining variables are the same as those in Eq. (6).

Spatial econometric model

As previously analyzed, economic phenomena often exhibit a spatial correlation between different regions. To accurately reflect the spatial spillover effects of synergetic development, we further employ spatial econometric models for examination. These models include the spatial Durbin model (SDM), spatial autoregressive model (SAR), and spatial error model (SEM). The models are as follows:

$$SEM \begin{cases} EMPL_{it} = \alpha_0 + \alpha_1 DSDG_{it} + \beta_i X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \\ \varepsilon_{it} = \eta W \varepsilon_{it} + \nu_{it} \end{cases} \quad (8)$$

$$SAR \{ EMPL_{it} = \alpha_0 + \rho W EMPL_{it} + \alpha_1 DSDG_{it} + \beta_i X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (9)$$

$$SDM \begin{cases} EMPL_{it} = \alpha_0 + \rho W EMPL_{it} + \alpha_1 DSDG_{it} + \alpha_2 W DSDG_{it} + \beta_i X_{it} + \chi_i W X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \\ \varepsilon_{it} = \eta W \varepsilon_{it} + \nu_{it} \end{cases} \quad (10)$$

In Eqs. (8) and (10), W is the spatial weight matrix, which is employed as a 0–1 matrix in the benchmark regression. For robustness analysis, both the geographical distance and the economic geographical nested matrix are further utilized. And ρ is the coefficient of spatial spillover, ν is the random error vector, and η is the coefficient of the spatial interaction term.

Variable selection and explanation

Dependent variables

We apply the natural logarithm of the average annual number of all workers to measure the level of labor employment; in addition, the natural logarithm of employees in establishments at the end of the year is further utilized for robustness.

Core explanatory variables

We choose the level of synergetic development of digitalization and greening as the core explanatory variable in this study. This refers to an integrated system that covers digitalization and greening. Based on existing research results, an evaluation system for the synergy between digitalization and greening (Table 1) has been constructed.

System	Subsystem	Dimension	Index	Property
The synergetic development of digitalization and greening	The development of digitalization	Digital infrastructure B_1	Internet penetration rate X_1	+
			Mobile phone penetration rate X_2	+
			Fiber optic cable length X_3	+
			Per capita GDP X_4	+
		Digital industrialization B_2	Telecommunications business volume per capita X_5	+
			Per capita total post X_6	+
		Industrial digitalization B_3	Digital financial inclusion index X_7	+
			The proportion of secondary and tertiary industries' output value X_8	+
	The development of greening	Green production B_4	Centralized treatment rate of wastewater X_9	+
			Industrial wastewater discharge per unit of GDP X_{10}	-
			Industrial SO_2 emissions per unit of GDP X_{11}	-
		Green living B_5	Harmless treatment rate of domestic garbage X_{12}	+
			Number of public transport vehicles per 10^4 population X_{13}	+
			The ratio of residential land area to green space area X_{14}	-
			Per capita daily domestic water consumption X_{15}	-
		Green ecology B_6	Proportion of green space area X_{16}	+
			Per capita park green area X_{17}	+
			Green coverage rate in built-up area X_{18}	+

Table 1. The synergy between digitalization and greening.

To promote digitalization for further development, it is important to synergize digital industrialization and industrial digitalization. Therefore, focusing on the foundation of digital transformation, benefit value, and core carriers, the digital development level is measured from the digital infrastructure, digital industrialization, and industrial digitalization aspects. Additionally, relevant studies are referenced to select corresponding secondary indicators^{59,60}. Urban green development, with green production as the key means, green living as the development goal, and green ecology as an important foundation, integrates green concepts into production, living, and ecology. Hence, we measure green development from the perspectives of green production, green living, and green ecology^{9,40}.

Control variables

Moreover, we refer to existing research to select several control variables that influence synergistic development and employment³⁰⁶¹. Specifically, (1) government intervention (gove) is measured by the ratio of local government budgetary expenditure to GDP; (2) infrastructure development (road) is measured by the natural logarithm of per capita road area; (3) the financial development level (fina) is measured by the ratio of year-end financial institution loans to regional GDP; (4) the wage level (wage) is represented by the natural logarithm of the average wage of urban employees; (5) city size (popu) is represented by the natural logarithm of the total urban population at the end of the year; and (6) openness to the outside world (open) is represented by the proportion of actual foreign investment in RMB to GDP.

Mediating variables

Furthermore, we select regional innovation (pate) and entrepreneurship (firm) and the human capital investment effect (huma) as mechanism variables to verify Hypotheses 2 and 3. Specifically, the number of patent applications per 10^4 people is utilized to measure regional innovation level, and regional entrepreneurship is estimated by the number of new businesses per hundred people in a city. To measure the human capital investment level, the natural logarithm of education expenditure per capita is applied to represent the level of human capital investment.

Data sources

The study uses panel data of 281 cities in China from 2011 to 2021 for examination. Due to the limited availability and integrity of the data, Hong Kong, Macau, Taiwan, and cities with incomplete statistical data or adjusted administrative divisions were excluded. Additionally, the employment data are from CSMAR, and the regional entrepreneurship data are obtained from the Qichacha database. The patent data are from the National Intellectual Property Administration. And these secondary indicators of digitalization and greening and other data are from the "China City Statistics Yearbook", the "China Urban Construction Statistics Yearbook", and the annual statistical yearbooks of each province (city). Finally, the missing data for individual years are filled using the moving average method. The descriptive statistics of the variables are presented in Table 2.

Results

Baseline regression results

The direct role of the synergy between digitalization and greening in employment is reported in Table 3. In detail, Columns (1) to (4) of Table 3 represent the effect with no control variables, with control variables fixed

VarType	VarName	Obs	Mean	SD	P5	Median	P95
Dependent variable	<i>EMPL</i>	3091	3.539	0.842	2.321	3.466	5.085
Explanatory variable	<i>DSDG</i>	3091	0.318	0.099	0.215	0.289	0.511
Control variable	<i>gove</i>	3091	0.201	0.096	0.098	0.177	0.393
	<i>fin</i>	3091	1.479	0.743	0.768	1.332	2.703
	<i>wage</i>	3091	10.953	0.349	10.378	10.962	11.497
	<i>popu</i>	3091	5.897	0.690	4.706	5.943	6.895
	<i>road</i>	3091	2.804	0.434	2.108	2.812	3.450
	<i>open</i>	3091	0.018	0.024	0.001	0.012	0.053
Mediating variable	<i>firm</i>	3091	1.321	1.257	0.402	1.005	3.263
	<i>pate</i>	3091	1.851	4.707	0.052	0.406	8.501
	<i>huma</i>	3091	7.284	0.471	6.603	7.232	8.141

Table 2. Descriptive statistics of the key variables.

	(1)	(2)	(3)	(4)
	<i>EMPL</i>	<i>EMPL</i>	<i>EMPL</i>	<i>EMPL</i>
<i>DSDG</i>	1.049***	3.095***	0.584***	1.116***
	(0.272)	(0.192)	(0.206)	(0.223)
<i>gove</i>		-0.855***	-0.233*	-0.587***
		(0.132)	(0.125)	(0.127)
<i>fin</i>		0.007	-0.025	-0.027
		(0.007)	(0.015)	(0.020)
<i>wage</i>		-0.210**	-0.061**	-0.331***
		(0.088)	(0.024)	(0.117)
<i>popu</i>		0.783***	0.672***	0.553***
		(0.034)	(0.143)	(0.120)
<i>road</i>		0.008	0.024	0.009
		(0.024)	(0.024)	(0.024)
<i>open</i>		0.568*	0.170	0.526**
		(0.306)	(0.215)	(0.230)
<i>_cons</i>	3.109***	0.177	0.079	3.399***
	(0.086)	(0.904)	(0.793)	(1.229)
<i>N</i>	3091	3091	3091	3091
<i>Control</i>	N	Y	Y	Y
<i>Year</i>	Y	Y	N	Y
<i>City</i>	Y	N	Y	Y
<i>R</i> ²	0.162	0.233	0.078	0.273

Table 3. Baseline regression results. * < 0.1, ** < 0.05, *** < 0.01 indicate significance at 10%, 5%, and 1% levels, respectively. Standard errors in parentheses. The following tables are the same.

only for the year, with control variables fixed only for the region, and with both control variables and time and year fixed, respectively. As demonstrated, the synergistic development has a significantly positive effect at the 1% level in all regressions. It shows that the synergetic role can enhance employment. The first hypothesis is preliminarily verified.

From the perspective of the selected control variables, government intervention is negatively significant at the 1% level, indicating that it may hinder employment; an increase in government spending may lead to wage increases in the public sector, which is beneficial for increasing wage level in the private sector; however, to provide this funding, the government may increase taxes, thereby reducing private sector investment and adversely affecting employment⁶².

The coefficient of financial development is -0.027, meaning that it may have a nonsignificant inhibitory effect on employment. The wage level is significantly negative at 1%, indicating that a rise in wages is detrimental to the promotion of employment levels. This may be because a higher wage level raises the cost of labor for enterprises, thus reducing the demand for labor.

The role of city size in employment is significant at the 1% level. Due to urban expansion, high-skilled talent is attracted to and concentrated within cities. Moreover, the urban expansion will also create more nonagricultural employment positions, thus boosting nonagricultural employment and ultimately promoting the level of labor

employment⁶³. The impact of infrastructure construction is positive but not significant because traditional infrastructure construction is beneficial for improving regional accessibility, but it cannot effectively reduce the cost of searching for labor information; thus, its role in promoting labor mobility and alleviating labor mismatch is limited. Opening up has a prominently positive effect at a 5% level, meaning that increasing the level of opening up is beneficial for improving labor employment. The higher the level of opening up is, the more diverse choices for entrepreneurship the labor market provides.

Robustness tests

To confirm that the synergistic effect indeed significantly contributes to urban employment, this paper validates the reliability of the baseline conclusion from multiple perspectives, including endogeneity tests, the replacement of variable measurement methods, the exclusion of cities with higher administrative levels, and so on.

Endogeneity tests

To alleviate potential endogeneity issues, tests from two aspects were conducted. First, inspired by the study of Zhu and Lan⁶⁴, this paper uses the spherical distance from each city to Hangzhou as an exogenous instrumental variable to mitigate endogeneity issues. Hangzhou is a leader in digital development, so the distance from Hangzhou is related to the level of digitalization, but it may have little effect on employment. Moreover, the use of digital technology can drive green innovation, thereby accelerating the synergy between local digitalization and greening. Therefore, the spherical distance satisfies the “strict exogeneity” and “strong correlation” criteria for instrumental variables.

Considering that the spherical distance does not vary with time, we use the interaction term of the inverse of the spherical distance and the lagged one-period development level of digital and greening synergy as an instrumental variable (IV) and re-estimate the model. In Table 4, the Kleibergen–Paap rk LM statistic is significant at the 1% level, indicating that there is no under-identification, and the Cragg–Donald Wald F statistic has a value greater than 16.38, confirming that there is no issue with weak instrument variables. The second-stage regression results are significantly positive at the 1% level and have a stronger role, which demonstrates that the basic conclusions remain unchanged after endogeneity issues are considered.

Second, this paper also follows the practice commonly used in the field of using lagged endogenous explanatory variables as instrumental variables⁶⁵. Considering the time lag of the integration of digitalization and greening, we use the lagged two -period synergistic effect(L2DSDG) as an instrumental variable to test robustness. The results are in the last two columns of Table 4.

Alternative measurement of variables

(1) Replacement of the measurement method for the dependent variable

Using the natural logarithm of employed personnel at the end of the year to characterize employment, we substituted it into the benchmark equation for regression. As shown in the first two columns of Table 5, after its measurement is changed, the results are significantly positive at least at the 5% level. The basic conclusions are still robust.

	(1) DSDG	(2) EMPL	(3) DSDG	(4) EMPL
IV	0.131*** (0.019)			
DSDG		2.759*** (0.746)		
L2DSDG			0.294*** (0.045)	
DSDG				2.425** (1.072)
_cons	0.613*** (0.111)		0.623*** (0.106)	
Year	Y	Y	Y	Y
City	Y	Y	Y	Y
N	2800	2800	2529	2529
Control	Y	Y	Y	Y
R ²	0.539	0.221	0.520	0.205
Kleibergen–Paap rk LM statistic	37.720***		21.257***	
Cragg–Donald Wald F statistic	270.842		150.500	
Stock–Yogo	[16.380]			

Table 4. Endogeneity test results. Spherical distance is as an instrumental variable in columns (1) and (2), and explanatory variables lagged by two periods is as instrumental variables in columns (3) and (4).

	(1)	(2)	(3)	(4)
<i>DSDG</i>	0.688**	0.798***		
	(0.277)	(0.244)		
<i>SsDSDG</i>			0.671***	0.641***
			(0.149)	(0.139)
<i>_cons</i>	3.292***	1.394	3.123**	3.850***
	(0.088)	(0.898)	(0.070)	(1.261)
<i>N</i>	3091	3091	3091	3091
<i>Control</i>	N	Y	N	Y
<i>Year</i>	Y	Y	Y	Y
<i>City</i>	Y	Y	Y	Y
<i>R</i> ²	0.152	0.221	0.158	0.267

Table 5. Alternative measurement of variables for robustness tests. , , Columns (1) and (2) stand for changing the measurement of the dependent variable, while the last two are changing the measurement of the explanatory variable.

	(1)	(2)	(3)
<i>DSDG</i>	1.113***	1.116***	1.041***
	(0.270)	(0.252)	(0.288)
<i>_cons</i>	3.449***	3.399*	2.803**
	(1.290)	(1.697)	(1.364)
<i>N</i>	2695	3091	2529
<i>Control</i>	Y	Y	Y
<i>Year</i>	Y	Y	Y
<i>City</i>	Y	Y	Y
<i>R</i> ²	0.268	0.273	0.265

Table 6. Other results for robustness tests. Column (1) to (3) is the robustness test for removing cities with higher administrative levels, changing the clustering method, and excluding the impact of the pandemic, respectively.

(2) Rescaling the level of the synergistic effect

Furthermore, we refer to Wu et al.⁶⁶ and apply the permutation polygon diagram indicator method to rescore the level of synergistic development. The results are in the last two columns of Table 5. After the measurement method is changed, the promotional effect on employment is significantly positive at the 1% level, regardless of whether the control variables are considered. It verifies that the basic conclusions are reliable.

Elimination of cities with higher administrative ranks

The synergistic development of digitalization and greening may be influenced by the administrative rankings of cities; therefore, this study excludes municipalities directly under the central government, provincial capitals, and separately listed cities and re-estimates the model. As shown in Column (1) of Table 6, after excluding these samples, the synergistic effect on employment has no obvious difference from that of the benchmark regressions. This means that the main conclusions are robust.

Adjustment of the clustering method

The general practice of clustering standard errors at the city level under consideration was applied in the above tests. However, this method may overlook the strong policy and economic relationships between the synergistic effect and labor employment in the same province. To solve this issue, this paper adjusts the standard errors to the provincial level and reports the results in Column (2) of Table 6 as a robustness check. The results after adjusting the clustering method are robust. This indicates that there may be a policy and economic relationship between cities within the same province, but it does not cause a substantial change in the main results. In short, the baseline conclusion is credible.

Exclusion of the impact of the pandemic

A vast amount of existing research has shown that the COVID-19 pandemic, which erupted in early 2020, has profoundly shocked green development and the digital economy as well as labor employment across different regions and industries. Therefore, to exclude the impact of the pandemic shock, this paper excludes samples from 2020 to 2021 and re-runs the test. Column (3) in Table 6 indicates that the impact of the synergistic

development of digitalization and greening on employment remains positive at a 1% level. This further suggests that the baseline conclusion is reliable.

Mechanism test

The above results indicate that the synergistic effect markedly promotes employment, even after several robustness tests. To further validate Hypotheses 2 and 3, we use the number of patent applications per 10^4 people to measure the regional innovation level, while the entrepreneurship is represented by the number of newly established enterprises per hundred people in a city. Moreover, the human capital investment effect is measured by the natural logarithm of education expenditure per capita, and the results are shown in Table 7.

Regional innovation and entrepreneurship

The first two columns in Table 7 represent the results of the synergy between digitalization and greening affecting labor employment by stimulating regional innovation and entrepreneurship. After considering the control variables and fixed time and regional effects, the coefficients are significantly positive at least at the 5% level. The finding demonstrates that the synergistic effect can promote regional innovation and encourage entrepreneurship. It can further encourage companies to expand their production scale, thereby providing more employment opportunities and improving their employment absorption capacity⁵⁰. This result also validates the existence of the mechanisms, i.e., Hypothesis 2 is established.

Human capital investment effect

Column (3) of Table 7 shows the estimated results of the human capital investment effect as an influencing mechanism. The synergistic effect can significantly promote improvements in human capital levels. Green development directly or indirectly creates many employment opportunities, including those related to pollution treatment and clean equipment production. This requires the labor force to possess certain knowledge of and skills related to new energy technologies and energy emission reduction. Moreover, the further acceleration of digital infrastructure development, such as broadband and 5G, can not only help reduce the cost of knowledge exchange but also increase the efficiency of knowledge dissemination. This allows the labor force to quickly acquire new knowledge and skills with relatively low thresholds and costs, thereby continuously promoting human capital accumulation. According to classic human capital theory, high-quality labor is the main body of an effective labor supply in the labor market and human capital accumulation enables workers to acquire heterogeneous skills, which help them find suitable jobs in the labor market more quickly. The above analysis shows that the synergistic effect can promote employment by enhancing the human capital investment effect. Therefore, Hypothesis 3 is verified.

Heterogeneity analysis

Heterogeneity of the employment structure

To further analyze their heterogeneous influence on employment structures, this paper examines it at the industry level. Specifically, the proportion of employment in the primary, secondary, and tertiary industries is adopted as the dependent variable to rerun the regression. In Table 8, the synergy between digitalization and greening promotes employment in all three industries but only has a significant role in the tertiary industry. In the process of labor migration from the primary and secondary sectors to the tertiary sector, the employment-absorbing capacity of the tertiary sector is increasing. This may be because the synergy between the two factors plays a more prominent role in driving services such as logistics, finance, and information technology, which has improved labor productivity in these sectors, thus having the most obvious promotional effect on the tertiary industry. Owing to the limited integration of the other two industries with digital and green development, the promotional effect on labor employment is not significant.

Regional heterogeneity analysis

In general, Chinese geographical differences contribute to unbalanced and inadequate regional development. Owing to significant variations in the development stage, economic development, and institutional environment among different regions, there may be notable differences in the synergistic effect on employment across regions.

	(1) <i>pate</i>	(2) <i>firm</i>	(3) <i>huma</i>
<i>DSDG</i>	12.127**	5.094***	0.819***
	(5.222)	(1.235)	(0.170)
<i>_cons</i>	11.410	-9.741**	5.571***
	(10.945)	(4.093)	(0.954)
<i>N</i>	3091	3091	3091
<i>Control</i>	Y	Y	Y
<i>Year</i>	Y	Y	Y
<i>City</i>	Y	Y	Y
<i>R</i> ²	0.152	0.339	0.819

Table 7. Results for mechanism analysis.

	(1)	(2)	(3)
<i>DSDG</i>	0.016	0.009	0.165**
	(0.033)	(0.127)	(0.071)
<i>_cons</i>	0.159***	0.900***	0.214
	(0.051)	(0.335)	(0.188)
<i>N</i>	3091	3091	3091
<i>Control</i>	Y	Y	Y
<i>Year</i>	Y	Y	Y
<i>City</i>	Y	Y	Y
<i>R</i> ²	0.152	0.220	0.200

Table 8. Results for employment structure heterogeneity. Column (1) to (3) stands for employment in the primary, secondary, and tertiary industry.

	(1)	(2)	(3)	(4)	(5)
	Eastern	Central	Western	High group	Low group
<i>DSDG</i>	0.917**	1.381***	0.379	1.227***	0.515*
	(0.357)	(0.294)	(0.398)	(0.284)	(0.284)
<i>_cons</i>	2.797	4.323***	3.568*	3.720	4.248***
	(3.952)	(1.555)	(1.851)	(2.330)	(1.635)
<i>N</i>	1100	1100	891	1650	1441
<i>Control</i>	Y	Y	Y	Y	Y
<i>Year</i>	Y	Y	Y	Y	Y
<i>City</i>	Y	Y	Y	Y	Y
<i>R</i> ²	0.400	0.360	0.200	0.313	0.249

Table 9. Results for regional heterogeneity and heterogeneity analysis in government preferences for innovation.

Therefore, the sample is divided into eastern, central, and western groups, and a grouped regression is conducted, as shown in Table 9.

The results reveal that the synergistic effect on employment follows a pattern of central > eastern > western, and it is significant at least at the 5% level in the eastern and central regions. The reason may be that the digital economy and green development of the eastern regions occurred relatively early and are larger in scale, and new employment forms and methods are generated by their deep synergy, which already benefits the local labor force; hence, the marginal utility of the synergistic effect driving employment is smaller. Luckily, benefiting from the central rise strategy and the continuous influx of innovative talent and technologies from the eastern regions, the synergistic effect in the central region has the most obvious promotional effect on employment⁶⁷. In the Western region, however, due to relatively backward development, digitalization is still at its initial stage; thus, the integration level with green development is not high, and the promotional effect is not obvious.

Heterogeneity in government preferences for innovation

The analysis of the above suggests that the synergistic effect can promote employment by facilitating regional innovation and entrepreneurship. However, neither innovation nor entrepreneurship can be separated from the support of local governments. For example, in the commercialization of research findings, as well as the cultivation of innovative and entrepreneurial talent, governments can support corporate financing through various means, thus taking maximum advantage of local governments and guiding their role in innovation and entrepreneurship^{68,69}.

Therefore, the government's preference for innovation measured by the proportion of scientific and technological expenditure to GDP is incorporated to represent the participation of local governments in the process of urban innovation and entrepreneurship. In addition, groups are divided based on annual median of government innovation preference, with those above the median being classified into the high-preference group and those below the median being the low-preference group. As shown in Columns (4) and (5) in Table 9, the synergy between digitalization and greening has a noteworthy promotional influence on employment in both the high- and low-preference groups, but the effect is more significant and stronger in the high-preference group.

Further research: analysis of the spatial spillover effects of the synergy between digitalization and greening

To validate the spatial spillover effect of Hypothesis 4 mentioned earlier, which suggests that the synergistic effect benefits the promotion of employment both in local and neighboring regions, the spatial econometric model is further employed.

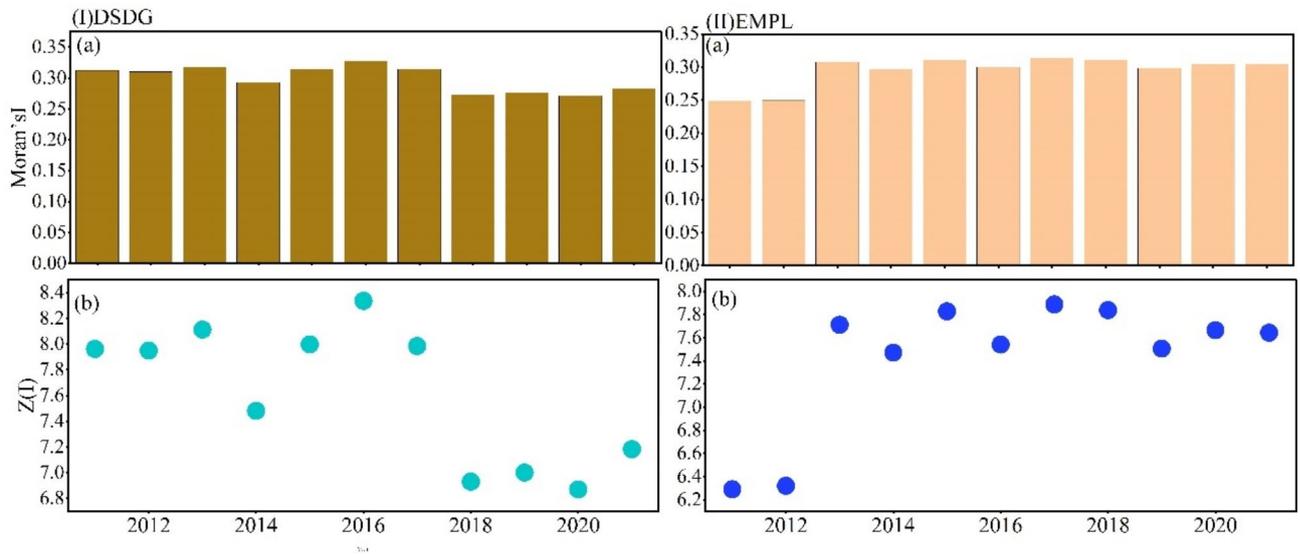


Fig. 3. Global spatial distribution of DSDG and EMPL, (a) is Moran's I value, (b) is the Z-value.

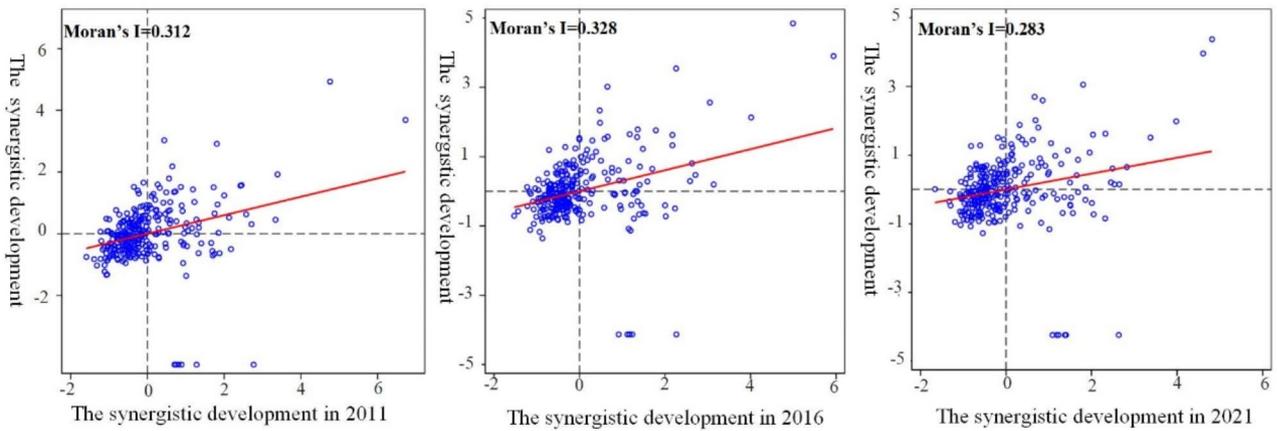


Fig. 4. Moran's I scatter plot for the synergistic development in 2011, 2016, and 2021.

Spatial correlation test

1. Global autocorrelation test

Before spatial effects, spatial correlation is first tested with Moran's I index. As presented in Fig. 3, the index for the synergy between digitalization and greening and labor employment over the years has been positive and significant at the 1% level. Both variables exhibit a positive spatial correlation. This finding indicates that there is a characteristic of mutual influence between the synergistic development among cities and employment.

2. Local autocorrelation test

The above test can reflect only the spatial correlation of the synergy and employment within the entire region; however, it cannot reveal the spatial correlation within each subregion. Therefore, this paper further tests the local correlation between the synergistic effect and employment to distinguish between the spatial relationships with high and low values in the region and its neighboring regions. The curve of Moran's I scatter plot (Figs. 4 and 5) reveals that the synergy and employment in China are mainly in the first and third quadrants, which again manifests a spatial association and has the characteristics of "high-high" and "low-low" types.

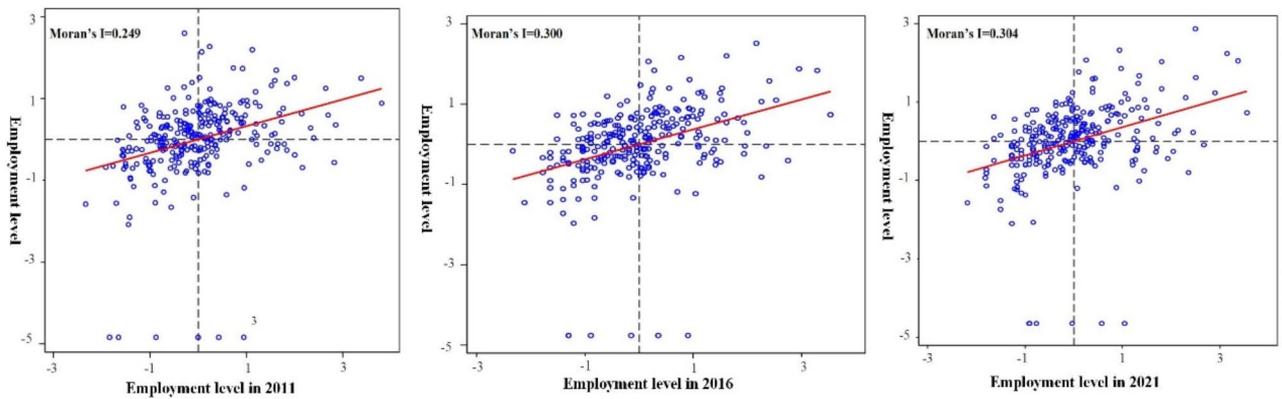


Fig. 5. Moran's I scatter plot for the employment in 2011, 2016, and 2021.

	(1) SEM	(2) SAR	(3) SDM
DSDG	0.954*** (0.133)	0.970*** (0.128)	0.871*** (0.131)
WSDSG			0.165 (0.231)
Direct effect		1.006*** (0.135)	0.909*** (0.134)
Indirect effect		0.507*** (0.075)	0.598** (0.290)
Total effect		1.512*** (0.203)	1.507*** (0.323)
ρ or λ	0.364*** (0.022)	0.361*** (0.020)	0.324*** (0.021)
N	3091	3091	3091
Control	Y	Y	Y
FE	Y	Y	Y
R ²	0.615	0.550	0.316

Table 10. Estimation results for spatial effects and its decomposition.

Spatial spillover effects analysis

1. Model identification

Next, this paper examines which model should be adopted through identification and judgment. Specifically, Stata16 is employed to conduct LM tests and robust LM tests on panel data, which yield results of spatial error and spatial lag LM values of 768.941 and 130.395, respectively, with both P values being 0.000. The robust LM values are 645.067 and 6.522, respectively, and all pass the significance test at 5% or higher. Consequently, the null hypothesis is rejected, indicating that both spatial lag and spatial error effects are present. However, the LR test results have a low level of significance, suggesting that SDM may degenerate into the other two models. Therefore, we choose to use these three models separately to estimate the spatial spillover effects of the synergy; moreover, considering the spatio-temporal heterogeneity, the study adopts a spatio-temporal double-fixed model.

2. Spatial effects and their decomposition

Furthermore, considering that both the spatial Lag and spatial Durbin models contain spatial interaction terms, to improve the precision of estimation, partial differential equations were adopted to decompose the spatial effects of the synergy on employment into spatial direct, spatial indirect (i.e., spatial spillover effects), and spatial total effects. The results of the three models under the 0–1 matrix are presented in Table 10. Regardless of the model applied, the role of synergy is positive. Local synergy can promote improvements in employment in the region.

After decomposing the total effect of the synergy on employment into direct and indirect effects (Table 10), under both models, the direct effect on employment is significantly positive at the 1% level, showing that the local synergy significantly improves employment. Although the indirect effect of the synergy is not as strong as the direct effect, it is also significantly positive. It shows that the synergistic effect in neighboring regions also significantly promotes local employment through spatial interaction. Hence, Hypothesis 4 of the study is verified.

Robustness check for spatial spillover effects

To guarantee the reliability of the spatial conclusions, we further re-estimate the regression by replacing the initial 0–1 matrix with a geographical distance and an economic geographical nestedness matrix. Specifically, after replacing the matrices, the coefficients of the synergistic development of digitalization and greening on employment change slightly, with the significance remaining unchanged (Table 11). This further verifies the basic conclusion. Moreover, decomposing the total effect, regardless of whether the model is the SAR or the SDM, after matrix replacement, the indirect effect is stronger than that of the 0–1 matrix. In conclusion, under any model, the synergistic development of digitalization and greening not only raises labor employment levels in a region but also plays a role in neighboring areas.

Discussion

Research comparison

This study has similarities and unique aspects with previous studies. First, we measure digitalization from the digital infrastructure, digital industrialization, and industrial digitalization, with reference to Zhang et al.⁵⁹ and Wu et al.⁶⁰. Similarly, this paper attempts to measure green development from green production, green life, and green ecology, and it is in line with the studies of Tian et al.⁴⁰ and Li et al.⁹. In addition, the entropy weighting method and the coupling coordination model that we apply are widely used in measuring comprehensive and coordinated development. Second, existing studies have explored mostly the possible impacts of digital development or green transitions on employment, and both job substitution and job creation exist^{12,13,25,46}. However, based on sorting out the development mechanism of the synergy between digitalization and greening, this study explores whether and what kind of impact the synergy between the two will have on employment. This is the greatest difference from existing studies. Moreover, the conclusions drawn from the sample period and sample examined in the study further enrich the relevant research on job creation. Third, the mechanism of regional innovation and entrepreneurship and human capital explored in this study is also basically similar to that explored in existing studies; for example, Wang et al.²⁶ argued that entrepreneurship is a mediator of broadband acceleration for employment. In short, we further enrich the existing theory and practice while remaining consistent with the references.

Limitations and prospects

Although this study strongly affects the issues explored, some limitations still exist. First, digital development is measured mainly from digital infrastructure, digital industrialization, and industrial digitalization, and this method of measurement may overlook other factors, such as indicators of digital transformation in daily life. Second, owing to the lag in updating authoritative data on carbon emissions and considering the completeness of the study sample, we do not include carbon emissions in green development in the current study. In future

	SEM		SAR		SDM	
	(1)	(2)	(3)	(4)	(5)	(6)
<i>DSDG</i>	0.936***	0.975***	0.952***	0.950***	0.751***	0.836***
	(0.134)	(0.132)	(0.130)	(0.132)	(0.133)	(0.133)
<i>WSDSG</i>					5.736**	3.275**
					(1.543)	(1.302)
<i>Direct effect</i>			0.992***	0.962***	0.896***	0.856***
			(0.138)	(0.137)	(0.144)	(0.136)
<i>Indirect effect</i>			9.528**	1.798***	38.764**	5.876***
			(3.904)	(0.465)	(17.623)	(2.025)
<i>Total effect</i>			10.519***	2.760***	39.659**	6.732***
			(3.958)	(0.537)	(17.670)	(2.022)
ρ or λ	0.896***	0.741***	0.901***	0.648***	0.826***	0.398***
	(0.030)	(0.049)	(0.029)	(0.054)	(0.049)	(0.085)
<i>N</i>	3091	3091	3091	3091	3091	3091
<i>Control</i>	Y	Y	Y	Y	Y	Y
<i>FE</i>	Y	Y	Y	Y	Y	Y
<i>R</i> ²	0.598	0.591	0.090	0.419	0.253	0.456

Table 11. Robustness estimation results for spatial spillover effects. (1), (3), and (5) represent using the geographical distance, while the rest are applying the economic geography nestedness matrix, respectively.

research, we will reconsider the measurement indicators of digitalization and greening and scientifically measure the synergistic development of digitalization and greening. We will further explore its potential impact on employment and attempt to extend this research to other areas.

Conclusions and policy implications

Conclusions

Employment serves as a barometer of the economy and a stabilizer of society; thus, stabilizing employment has vital practical significance for high-quality economic development. With data from 281 cities in China from 2011 to 2021, this paper empirically examines the synergistic effect of digitalization and greening on employment. In conclusion, four findings are drawn as follows:

First, synergy indeed plays a crucial role in promoting labor employment, and this result remains valid after numerous robustness tests are conducted. Moreover, it is essential for promoting full employment of labor, and finally facilitating economic development at a high level. From a practical perspective, as the digital economy drives the transformation toward a green economy, numerous firms with high levels of pollution and energy consumption inevitably face issues such as changing production methods and innovating production technologies, which impact labor employment. Theoretically, the synergy between digitalization and greening is a new impetus for setting up a digital China and a beautiful China, which are crucial for the sustainability of the economy and society. Unfortunately, the pathways of their impacts are seldom explored. Therefore, we explore the social effects of the synergy between digitalization and greening from the perspective of labor employment. The study further supplements and expands the research on the digital economy, green development, and employment. In addition, this research offers a practical basis for promoting higher standards of living for people.

Second, path analysis indicates that synergistic development has an impact on labor employment through two pathways: stimulating regional innovation and entrepreneurship and enhancing the human capital investment effect. For the demand side, the synergistic development of digitalization and greening not only inspires diverse consumer demands but also creates a demand scale effect from green consumption, which forces companies to provide corresponding products and services and stimulates innovative and entrepreneurial activities. On the supply side, as the synergistic development of digitalization and greening advances, emerging industries thereby increase demand for employees with high skill levels and high innovative capabilities. This encourages employees to value their educational investment, further enhances the acquisition of new skills, and finally strengthens their competitive advantage when they try to find a job. Additionally, the rapid development of digitalization can overcome spatial limitations, helping workers quickly and accurately access relevant learning resources and accelerating the mastery of new skills and knowledge accumulation, thus improving the employment quality of laborers to meet job requirements.

Third, the analysis of heterogeneity reveals that the synergy has a different effect on employment in different employment structures, different regions, and varying government innovation preferences. In terms of employment structure heterogeneity, the synergistic effect more significantly promotes labor employment in the tertiary industry, while it has no significant impact on the primary or secondary industries; regionally, the synergistic effect on the three regions shows a pattern of central > eastern > western; in terms of government innovation preferences, the synergistic effect can promote employment in both the high- and low-preference groups, but its effect is more pronounced in the high-preference group, indicating that government involvement in innovation and entrepreneurship is conducive to promoting the employment-creating effects of synergistic development.

Fourth, further discussion implies that synergistic development has a significant spatial spillover effect. The synergistic effect not only promotes labor employment within a region but also has a beneficial effect on neighboring areas. On the one hand, with the features of broad coverage, strong penetration, and integration and sharing, the process of synergy can compress the temporal and spatial distances of information transmission, as well as break down the existing regional barriers to market segmentation and the free flow of factors, thereby fostering interdependence and interpenetration among industries and businesses across regions. On the other hand, the successful experience of promoting labor employment through synergistic development will create a demonstration effect on adjacent areas. While inspiring other regions to imitate and learn, it also encourages local governments to take action to support the further improvement of the synergistic effect level, thereby realizing a multiplier effect on employment.

Policy implications

In conclusion, to promote the full employment creation effect of synergistic development and ultimately achieve full and high-quality employment, the four policy implications are proposed.

First, the inherent mechanism of the synergistic development of digitalization and greening should be accurately understood, and their synergistic transformation should be vigorously promoted. Based on the overall framework of empowering green development with digitalization and pulling digital transformation with green development, local governments should take action to strengthen the promotion of the synergistic development of digitalization and greening. Relevant government departments should pay attention to improving the support mechanisms for synergistic development. They can contribute to promoting comprehensive pilot policies for synergistic transformation toward digitalization and greening and formulating reproducible paths and models, thus releasing the maximum benefits of new productivity to lead the labor employment market; meanwhile, supervision and training should be used to increase awareness and a sense of responsibility for synergistic transformation in key sectors and industries. These measures will encourage enterprises to innovate in the application of digital and green technologies in their production and operation processes, ultimately promoting the integration of digital technology with traditional industries.

Second, strengthening the role of innovation and entrepreneurship in driving employment achieves a high degree of alignment between industry demand and educational supply, thereby amplifying the multiplier effect on employment. First, in the process of promoting digital transformation and green development, providing policy support for the digital and green collaborative transformation of traditional enterprises is important. Moreover, local governments should provide the best services for entrepreneurial and innovative activities to unleash the vitality of various market players and the creative potential of the people to a greater extent. This helps increase the level of innovation and entrepreneurship in the region, thereby enhancing the absorptive capacity of the labor market. The internet can then be used to break down regional barriers, disseminate knowledge across spaces with lower cost but higher efficiency, and strengthen the cultivation of high human capital and highly innovative talent, thereby accelerating the accumulation of human capital and improving the quality of the labor supply.

Third, location-specific strategies for synergy should be formulated to maximize the potential for employment creation. Heterogeneity analysis reveals that the employment creation effects of synergistic development vary due to differences in employment structures, regional characteristics, and other factors. Therefore, in the process of promoting the synergistic effect to enhance labor employment, it is necessary to provide differentiated funding and technical support based on characteristics such as types of employment structures and levels of regional development. This approach aims to avoid the implementation of one-size-fits-all policies that could lead to resource wastage, increased costs, and other unfavorable situations.

Finally, a national perspective should be adopted, and regional spatial restructuring should be strengthened to fully leverage the spatial spillover effects of the synergy between digitalization and greening. The synergistic development of Chinese cities and labor employment both exhibit significant spatial correlation. Local governments should abandon the localism mindset and actively break down barriers to regional communication. They should embrace a win-win cooperation philosophy, strengthen economic ties, and communicate with neighboring regions. These contribute to enhancing the radiation range and influence of the employment creation effects of synergistic development, which further increases the spatial contribution force of such collaboration. Local governments should also further provide support for the synergistic transformation of digitalization and greening. It is necessary not only to expand the coverage of synergistic development but also to reshape the spatial layout according to regional industrial characteristics and advantages. Specifically, this can be achieved through the allocation of factor resources, adjusting regional functions, and other means. In addition, by strengthening the economic connection between core cities and other cities, local governments can promote the spatial spillover effects of their synergistic development and foster stable growth in local and neighboring employment.

Data availability

Data will be made available on request from the corresponding author (gejiexiao@stu.gxnu.edu.cn).

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Author contributions

Q. L. was responsible for conceptualization, investigation, software methodology, formal analysis, funding acquisition, revising draft. J. G. undertook the primary responsibility for writing—original draft, visualization, writing—review & editing. H. F. was mainly responsible for formal analysis and visualization.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to J.G.

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