frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 06 November 2024
DOI 10.3389/fsufs.2024.1446410

OPEN ACCESS

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RECEIVED 09 June 2024
ACCEPTED 26 September 2024
PUBLISHED 06 November 2024

CITATION
Tian J, Liu C and Ma G (2024) The role of the digital economy on the coordinated development of green agriculture and food security: evidence from China. *Front. Sustain. Food Syst.* 8:1446410. doi: 10.3389/fsufs.2024.1446410

The role of the digital economy on the coordinated development of green agriculture and food security: evidence from China

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Promoting the coordinated development of green agriculture and food security is important for global sustainable development, and digital economy is a potential path to realizing this goal. Using panel data of 30 provinces (municipalities directly under the central government and autonomous regions) in China from 2014 to 2021, this study applies the entropy weight method and the coupling coordination degree model to measure the development of the digital economy and the coordination of green agriculture and food security. Moreover, the study constructs fixed-effects and spatial spillover effect models to determine the effect of the digital economy on the coordination of green agriculture and food security. We find a positive development trend between digital economy and coordination development in China, with no evident polarization phenomenon. The digital economy can effectively promote the coordinated development of green agriculture and food security, and has positive spatial spillover effects. Our findings expand the research related to the digital economy, and contribute to the promotion of sustainable agricultural development and food security.

KEYWORDS

digital economy (DE), green agriculture, food security, coupling coordination model (CCM), spatial Durbin model (SDM)

1 Introduction

Global economic development is facing challenges such as climate change and ecological deterioration (Mikhaylov et al., 2020; Zhang et al., 2022; Xin et al., 2023). In response, green industrial innovation to address these challenges is rapidly developing worldwide (Wang B. et al., 2023). Many countries are implementing measures to accelerate green technological innovation and promote green, green, and sustainable development. For the European Union, promoting green transformation is one of the core elements of its economic recovery plan.[1] Singapore has implemented a green development blueprint to promote sustainable living and green economic development.[2] Saudi Arabia launched

1 http://eu.mofcom.gov.cn/article/sqfb/202207/20220703323912.shtml

2 https://www.greenplan.gov.sg/

the Green Saudi Initiative to enhance environmental protection.[3] China advocates the development concept of "green water and green mountains are golden silver mountains" to promote green economic development.[4] Agriculture is a major contributor to economic development in most developing countries, and green agricultural development is crucial for advancing the sustainable development of the global economy. Green agriculture refers to the promotion of agricultural economic development, considering resource conservation and ecological environmental protection to advance sustainable agricultural development. In addition, achieving global food security is a growing challenge at the international policy level (Campi et al., 2021). In 2009, the United Nations Food and Agriculture Organization (FAO) asserted that food security in its multiple meanings includes adequate food supply, access, stability, and use (FAO, 2009). In this context, accurately assessing and addressing the relationship between agricultural green and green development and food security is essential for advancing national economic sustainable development and food security.

With the continuous development and application of block chain, cloud computing, big data, and other contemporary science and technology (Su et al., 2020), the digital economy is an important engine for promoting high-quality economic growth (Zhang et al., 2022; Wang B. et al., 2023; Wang Q. et al., 2023; Wang Y. et al., 2023). The digital economy refers to a series of economic activities to improve production efficiency and optimize the economic structure that are specifically manifested in digital information and knowledge as the factors of production, advanced networking as an important carrier, and efficient use of information and communications technology as the core driving force (Wang B. et al., 2023; Wang Q. et al., 2023; Wang Y. et al., 2023). In recent years, the digital economy has rapidly developed around the world. The Global Digital Economy Development Index reveals that the average global digital economy value increased from 45.33 in 2013 to 57.01 in 2021.[5] The rapidly developing digital economy promotes regional economic growth and green, sustainable development. As the largest developing country and largest agricultural producer in the world, what is the current status of the digital economy and green agricultural development in coordination with food security in China? Furthermore, what is the impact of the rapidly expanding digital economy on the coordination development of green agricultural development and food security? Are spatial spillover effects evident? Addressing these questions will help to advance the role of China's digital economy in promoting the coordination development of green agricultural development and food security and serve as a reference for other developing countries.

The contributions of this paper are as follows. First, the coordination development of green agriculture and food security are combined in the same framework. The study uses the entropy weight method and the coupling coordination degree model to measure the current status of coordination development of green agriculture and food security. Second, in the context of the rapid development of the digital economy, the study constructs a fixed-effects model to empirically analyze the impact of the digital economy on the coordinated development of green agriculture and food security, in addition to examining regional heterogeneity. Third, considering potential spatial interaction, we construct a spatial Durbin model to explore the spatial spillover effects of the digital economy on the coordinated development of green agriculture and food security in China. These approaches expand the research to provide more comprehensive insights.

The remainder of this paper is structured as follows. Section 2 reviews the related literature on the concerned issue and theoretical analysis. Section 3 introduces the estimation models variables and data sources. Section 4 presents and analyzes the baseline results. Section 5 discusses the results, and Section 6 summarizes the main conclusions and proposes related policy recommendations.

2 Literature review and theoretical analysis

2.1 Literature review

Achieving carbon emissions reduction and green transformation in agriculture is crucial for advancing global sustainable development (Liu and Ren, 2023). Previous research related to green agricultural development has primarily focused on carbon emissions (Guo and Zhang, 2023; Raihan, 2023; Rong et al., 2023), agricultural green efficiency (Deng et al., 2023; Sun et al., 2023; Shi et al., 2024), and agricultural carbon footprint (Liu Z. et al., 2023). The issue of food security is at the top of the world's agenda. Existing studies on food security have focused on quantifying food security and its influencing factors. Most scholars have quantified food security in terms of availability, accessibility, utilization, and stability (Adem et al., 2023; O'Connell et al., 2023). Regarding the influencing factors of food security, macro level studies have primarily included climate change (Hadley et al., 2023; Lee et al., 2024), agricultural trade (Aragie et al., 2023), and agricultural entrepreneurship (Kazungu and Kumburu, 2023), and micro level studies have primarily included household resources (Karnik and Peterson, 2023; Olumba et al., 2023), food price shocks (Yovo and Gnedeka, 2023), and related concerns. Previous research has established the foundation for coordinating the development of green agriculture and food security.

The digital economy is an important driver of green economic development (Li Y. et al., 2023; Wang Q. et al., 2023). Existing research on the digital economy has focused on three aspects. First, defining the concept of digital economy, which was initially defined as activities within entrepreneurial clusters (Papaioannou et al., 2009; Chijindu Iheanacho Okpalaoka, 2023). Over time, the digital economy has been given a new connotation as an innovation ecosystem (Nambisan and Baron, 2013; Chijindu Iheanacho Okpalaoka, 2023). Advancing the digital economy is a business model for digital products and services and a new form of economic development (Chijindu Iheanacho Okpalaoka, 2023; Uddin, 2023; Wang B. et al., 2023; Wang Q. et al., 2023; Wang Y. et al., 2023). Second, quantifying digital economy development. In existing research, scholars have predominantly measured the digital economy by constructing indicator evaluation systems and

3 https://www.greeninitiatives.gov.sa/#:~:text=Climate%20action,%20energy%20security%20and%20economic%20prosperity%20must

4 https://www.gov.cn/xinwen/2022-10/25/content_5721685.htm

5 Source: China Academy of Information and Communication Research http://www.caict.ac.cn/kxyj/qwfb/bps/202207/t20220708_405627.htm.

adopting the entropy weighting methods. Zhang and Li (2023) constructed a set of digital economy development measurement systems from the perspectives of digital industrialization and industrial digitization based on input–output data. Lyu et al. (2023) measured digital economy development in China from four dimensions, including the digital economy development carrier, digital industrialization, industrial digitization, and the digital economy development environment. Third, the economic effects of the digital economy. At the macro level, digital economy development can alleviate energy poverty (Lyu et al., 2023; Wang B. et al., 2023; Wang Y. et al., 2023), promote green economic development (Li S. et al., 2023; Wang Q. et al., 2023; Li Y. et al., 2023), and increase green total factor productivity (Deng et al., 2022; Chen et al., 2023). At the micro level, digital economy development can promote enterprises' breakthrough innovation (Liu J. et al., 2023; Wu et al., 2023) and enhance consumption (He et al., 2022).

Additionally, scholars have explored the effects of the digital economy on green agricultural development and its implications for food security. First, existing studies on the impact of the digital economy on green agricultural development primarily focus on three key aspects: (1) Reducing the intensity of agricultural carbon emissions. Jin et al. (2024) found that while the development of the digital economy can effectively lower agricultural carbon emissions, and the effect is nonlinear. Similarly, Zhao et al. (2023) discovered that agricultural digitization in China can reduce the intensity of agricultural carbon emissions by enhancing agricultural technology inputs, human capital, and the rate of urbanization. (2) Encourage the adoption of ecological agricultural technology among farmers. Yang et al. (2024) found that the digital economy can effectively encourage farmers to adopt agroecological technologies through digital production, digital marketing, and digital finance. (3) Enhancing green total factor productivity in agriculture. Lu et al. (2024) finds that rural digitization can effectively boost total factor productivity in agriculture, with the effect growing as the level of rural digitization increases. Meanwhile, Jiang et al. (2024) finds that digital finance can enhance agricultural green total factor productivity through digital rural development. Second, existing research on the digital economy on food security focuses on the following three aspects: (1) Efficiency in food production. Based on data from 600 wheat growers in rural Pakistan, Ahmad et al. (2024) utilized the stochastic frontier approach and propensity-matched score method to investigate the impact of Internet technology adoption on the technical efficiency of food production, finding that Internet use positively affects technical efficiency. Similarly, Chandio et al. (2023) found that Internet use significantly improved rice production in China. (2) Reducing food waste. Annosi et al. (2021) found that applying digital technology in the food supply chain can significantly reduce food waste. (3) Food security. Ferguson et al. (2023) found that digital agricultural technologies can ensure food security for smallholder farmers and their communities in Orissa, India, especially in the context of the COVID-19 pandemic. Meanwhile, Lee et al. (2023) found that the development of the digital economy can effectively ensure food security in China.

In summary, previous research has conducted meaningful inquiries into green agricultural development, food security, and the digital economy; however, room remains for further exploration. First, while promoting green sustainable development in agricultural production, it is equally important to guarantee national food security. Weighing the relationship between the green agricultural development and food security is worthy of further exploration. The digital economy is an important engine for contemporary green economic development, and its impact on the coordinated development of green agriculture and food security has not yet been investigated. Second, regarding spatial interaction, examining whether the impact of the digital economy on the coordinated development of green agriculture and food security has spatial spillover effects is an important pursuit.

2.2 Theoretical analysis

The digital economy is a new aspect of the economy that uses digital information and knowledge as factors of production, which can drive the coordinated development of green agriculture and food security by optimizing factor allocation, improving agricultural production methods and promoting agricultural technological innovation.

First, the digital economy can foster the coordinated development of green agriculture and food security by optimizing factor allocation. By integrating data with labor, land, and capital, the digital economy transforms the internal structure of traditional elements and enhances the integration of rural industries with the digital economy (Wu et al., 2024; Zhang and Qu, 2023). This not only boosts the contribution of traditional production factors like land and labor to agricultural output but also enhances agricultural total factor productivity and drives the transformation and upgrading of the agricultural industrial structure (Shen and Wang, 2024). Additionally, the use of big data, blockchain, and cloud computing in agricultural production can effectively address information asymmetry among factors (Liu Y. et al., 2023). This helps reduce the misallocation of agricultural resources, minimize unnecessary waste, achieve more efficient use of agricultural energy, and lower the intensity of agricultural carbon emissions.

Second, the digital economy can enable smart and precise agricultural production by enhancing production methods, thereby promoting the coordinated development of green agriculture and food security. On one hand, the advent of digital technologies like satellite remote sensing and smart agricultural machinery has made it possible to modernize agricultural production (George et al., 2024; Zhang et al., 2024). This, in turn, helps agricultural producers optimize production management (George et al., 2024) and enhance food production efficiency. On the other hand, as digital technology increasingly integrates into production, operation, management, and services in agriculture, the precision of agricultural practices continues to improve (Wang and Li, 2024). This reduces the environmental impact of fertilizers and pesticides and promotes the growth of green agriculture.

Third, the growth of the digital economy will drive technological innovation in agriculture (Lv and Chen, 2024), encourage the use of green high-tech solutions in the field (Li and Gao, 2024), and thus foster the balanced development of green agriculture and food security. On one hand, the development of the digital economy provides a network platform for disseminating agricultural green technology, breaks down technical barriers (Hao et al., 2023), fosters the exchange and collaboration of green agricultural technologies, enhances production efficiency, and supports sustainable agricultural development. On the other hand, the development of the digital economy removes time and space barriers, lowers the relative cost of technical factors (Rotz et al., 2019), broadens and deepens the diffusion of green technologies, significantly boosts the R&D and application of these technologies (Chen et al., 2024), and promotes the integrated advancement of green agriculture and food security.

Concerning spatial interaction, production factors such as capital, technology, and labor will flow between regions and a strong correlation exists between geographically similar regions. According to Tobler's (1970) first law of geography, the digital economy and coordinated development in each region are widely connected. A closer distance between regions elicits closer connections. Digital technology can overcome the spatiotemporal limitations of production factors (Chen and Yao, 2024; Ma et al., 2024) and enhance the correlation of agricultural production activities between regions. In addition, digital technology can have spatial spillover effects (Tao et al., 2024), and the technology in one region will have demonstration effects and increase the use of digital technology in neighboring regions, which subsequently improves the efficiency of agricultural production in neighboring regions and reduces agricultural carbon emissions. This study contends that the effect of the digital economy on the coordinated development of green agriculture and food security may have positive spatial spillover effects.

3 Methodology

3.1 Variables

3.1.1 Explained variable

Coordinated development of green agriculture and food security (COR) refers to the coordinated development of the two systems, which is calculated in this paper using a coupling coordination model. Among them, based on the definition of green agriculture and previous studies (Han et al., 2023; Shao et al., 2024), this paper constructs a comprehensive evaluation system to examine the development of green agriculture from four dimensions of resource conservation, environmental friendliness, ecological conservation, and economic growth. Then, this study constructs a comprehensive evaluation system of food security considering food supply security, food access security, food production stability, and food production sustainability according to previous studies (Hadley et al., 2023; Liu and Ren, 2023; Lee et al., 2024). Table 1 presents the specific evaluation system of green agriculture and food security.

3.1.2 Explanatory variable

Digital economy development (DED). As noted previously, the digital economy is a new form of economic development that is manifested in digital industrialization and industrial digitization. This study references previous research (Zhang and Li, 2023; Chen et al., 2024; Tao et al., 2024) and constructs a comprehensive evaluation system from the dimensions of digital industrialization and industrial digitization. Table 2 presents the comprehensive digital economy evaluation index.

3.1.3 Control variables

Based on previous studies (Deng et al., 2023; Lee et al., 2023; Jin et al., 2024; Yang et al., 2024), factors such as financial support for agriculture, the level of openness to the outside world, the structure of industry, urbanization level, and urban–rural income gap are known to have an impact on green agriculture and food security. Therefore, this study uses the following controls variables. Financial support for agriculture (Gov) is expressed as the ratio of government expenditure on agriculture, forestry, and water to general public budget expenditure. The level of openness to the outside world (Open) is expressed as the ratio of total import and export of goods to GDP. The structure of industry (Is) is expressed as the ratio of value added of primary industry to GDP. Urbanization level (Urb) is expressed as the ratio of the year-end population of cities and towns to the year-end population of the region. Urban–rural income gap (Gap) is expressed as the ratio of urban residents' per capita disposable income to the disposable income of rural residents.

3.2 Model

3.2.1 Entropy weighting method

The entropy weight method is a multi-indicator decision-making technique that provides a basis for evaluating multiple indicators, offering greater accuracy and adaptability. Therefore, this paper employs the entropy weight method to assess the development level of green agriculture and food security. The specific steps are as follows:

In the first step, the indicator data were standardized using the methods described in Equations 1, 2. And Equation 1 illustrates the method for calculating positive indicators, while Equation 2 illustrates the method for calculating negative indicators.

$$y_{ij} = \frac{x_{ij} - minx_{ij}}{\max x_{ij} - minx_{ij}} + 1 \tag{1}$$

$$y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - minx_{ij}} + 1 \tag{2}$$

where x_{it} represents the observed value of the j indicator in area i, $\max x_{ij}$ is the maximum observed value of indicator j in area i, $\min x_{ij}$ is the minimum observed value of indicator j in area i.

In the second step, the entropy value for each indicator is calculated, as shown in Equations 3, 4.

$$H_j = ln\frac{1}{n}\sum_{i=i}^{n} f_{ij} * lnf_{ij} \tag{3}$$

$$f_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}} \tag{4}$$

TABLE 1 Comprehensive evaluation index of green agriculture and food security.

Variable	Level 1 indicators	Level 2 indicators	Level 3 indicators	Symbol
Green agricultural development	Resource conservation	Cropland recovery index	Sown area (1,000 ha)/cultivated area (1,000 ha)	+
		Effective irrigation rate	Effective irrigated area (1,000 ha)/cultivated area (1,000 ha)	+
		Efficiency in the use of agricultural machinery	Total power of agricultural machinery (10,000 kW)/cultivated land (1,000 ha)	+
		Water efficiency in agriculture	Agricultural water consumption (100,000,000 m^3)/gross agricultural output (100,000,000 yuan)	+
	Environmental friendliness	Pesticide intensity	Pesticide application (10,000 tons)/crop sown area (1,000 ha)	−
		Fertilizer intensity	Fertilizer application (100,000,000 tons)/crop sown area (1,000 ha)	−
		Agricultural film use intensity	Agricultural plastic film use (10,000 tons)/area sown with crops (1,000 ha)	−
		Fuel consumption per unit of agricultural machinery	Diesel use (10,000 tons)/total power of agricultural machinery (10,000 kW)	−
	Ecological conservation	Forest coverage	Area covered by forests (1,000 ha)/provincial area (1,000 ha)	+
		Area of nature reserves	Area of nature reserves (1,000 ha)	+
		Agricultural natural disaster success rate	Area affected by natural disasters in agriculture (1,000 ha)/area caused by disasters (1,000 ha)	+
	Economic growth	Land output rate	Gross agricultural output value (100,000,000 yuan)/area sown with crops (1,000 ha)	+
		Farmers' income	Farmers' per capita disposable income (yuan/person)	+
		Grain yield per unit	Total grain output (10,000 tons)/area sown with crops (1,000 ha)	+
Food security	Food supply security	Food production base	Cultivated land area (1,000 ha)/provincial area (1,000 ha)	+
		Financial inputs for food production	Farmers' investment in fixed assets (100,000,000 dollars)	+
		Current status of agricultural modernization	Power of agricultural machinery (10,000 kW)/cultivated area (1,000 ha)	+
		Food production capacity	Total grain output (10,000 tons)/area sown with grain (1,000 hectares)	+
	Food access security	Food satisfaction	Total grain output (10,000 tons)/resident population (10,000 people)	+
		Food self-sufficiency rate	Total grain output (10,000 tons)/consumption of grain (10,000 tons)	+
	Food production stability	Food production fluctuation coefficient	$\frac{p-\overline{p}}{\overline{p}}$. Among them, p is grain yield and $\overline{p}$ is average grain yield	−
		Food disaster fluctuation coefficient	$\frac{a-\overline{a}}{\overline{a}}$. Among them, a is the ratio of the affected area to the sown area of crops, and $\overline{a}$ is the average of the ratio of the affected area to the sown area of crops	−
	Food production sustainability	Carbon emissions	$\sum_1^6 m_i{*}\alpha_i$. Among them, m_i is the amount of inputs, specifically including pesticides, fertilizers, agricultural film, the use of agricultural machinery, agricultural tillage, and irrigation. α_i is carbon emissions coefficients generated by the inputs, which are 0.8956 kg/kg, 4.9341 kg/kg, 5.18 kg/kg, 0.5927 kg/kg, 312.6 kg/km^2, and 20.476 kg/hm^2, respectively	−
		Surface source pollution	$\sum_1^3 n_i{*}\beta_i$. Among them, n_i is the amount of pesticide, fertilizer, and agricultural film inputs. β_i is the loss coefficient of pesticide, fertilizer, and agricultural film, which is 50%, 75%, and 10%, respectively	−

In the third step, the weight of each indicator is determined, as shown in Equation 5.

$$w_j = \frac{1 - H_j}{\sum_j 1 - H_j} \tag{5}$$

In the fourth step, the index value is calculated, as shown in Equation 6.

$$X_i = \sum_j w_j{*}y_{ij} \tag{6}$$

TABLE 2 Comprehensive of digital economy evaluation index.

Variable	Level 1 indicators	Level 2 indicators	Level 3 indicators	Symbol
Digital economy	Digital industrialization (DI)	Digital product manufacturing	Number of cell phone base stations (10,000)	+
			Operating income per electronic information manufacturing enterprise (100,000,000 yuan)	+
		Digital product service	Software product revenue (100,000,000 yuan)	+
			Total telecommunications business (100,000,000 yuan)	+
		Digital technology application	Number of internet domain names (10,000)	+
			Number of internet web pages (10,000)	+
			Revenue from IT services (100,000,000 yuan)	+
		Digital factor drivers	Number of internet broadband access ports (10,000)	+
	Industrial digitization (ID)	Digitization of agriculture	Share of administrative villages with internet broadband service (%)	+
			Rural broadband access users (10,000)	+
		Digitization of industry	Number of computers used by industrial enterprises per 100 people (set/hundred people)	+
		Digitization of services	Share of enterprises with e-commerce trading activities in total number of enterprises (%)	+
			E-commerce transaction volume (100,000,000 yuan)	+
			Digital inclusive finance index	+

3.2.2 Coupling coordination model

The Coupling coordination model is a mathematical tool used to evaluate the interaction and coordination between two or more systems. Its core function is to quantify the degree of coupling and coordination among these systems. This model offers several advantages: it quantifies the degree of coordination, helps identify and address issues of misalignment within the system, and ultimately facilitates more effective resource allocation and optimal management (Wang et al., 2017). Currently, it is applied across various fields, including but not limited to social sciences, economics, environmental sciences, and engineering. Considering that the coordinated development of green agriculture and food security represents the interaction between two systems, this study references previous research (Han et al., 2023; Liu and Ren, 2023) and uses the coupling coordination degree model to measure the degree of coordinated development of green agriculture and food security, which is calculated as follows, with the first step calculating coupling:

$$C = \left\{ \frac{G \times S}{\left(\frac{G+S}{2}\right)} \right\}^{\frac{1}{2}} \tag{7}$$

where C is the coupling degree, G is the levels of green agriculture,[6] and S is the level of food security.[7]

6 Calculated using the entropy weight method based on the comprehensive evaluation index of green agriculture shown in Table 1.

7 Calculated using the entropy weight method based on the comprehensive evaluation index of food security shown in Table 1.

The second step calculates the coupling coordination development index as follows:

$$T = \alpha \times G + \beta \times S \tag{8}$$

where T is the index of coupling coordination development, and α and β are the coefficients to be determined. Because green agriculture and food security are in the same significant position, this study references previous research (Liu and Ren, 2023) and assigns 0.5 as the value of both α and β.

The third step calculates the coupling coordination degree as follows:

$$COR = \sqrt{C \times T} \tag{9}$$

where COR is the degree of coupling coordination, quantifying the degree of coordinated development of green agriculture and food security.

3.2.3 Baseline regression model

To investigate the impact of the digital economy on green agriculture and food security coordinated development, we construct the following regression model:

$$COR_{it} = a_0 + a_1 DED_{it} + a_j Control_{it} + \mu_{it} + \varepsilon_{it} \tag{10}$$

where COR_{it} denotes the degree of coordinated development of green agriculture and food security in region i in year t, DED_{it} represents the level of development of the digital economy in region i in year t, $Control_{it}$ is a series of control variables, μ_i denotes regional fixed effects, and ε_{it} is a random error term.

3.2.4 Spatial spillover effects model

Considering the spatial interaction of production factors, local digital economy development also affects the coordination of green agriculture development and food security in neighboring regions. To explore this effect, this study constructs the following equation for regression analysis:

$$COR_{it} = \alpha + \rho \sum_{i=1,j\neq 1}^{n} w_{ij}COR_{it} + \beta_1 DED_{it} + \beta_2 Control_{it} + \theta \sum_{i=1,j\neq 1}^{n} w_{ij}\left(DED_{it} + Control_{it}\right) + \mu_i + \vartheta_t + \varepsilon_{it} \quad (11)$$

where COR_{it} denotes the degree of coordinated development of green agriculture and food security in region *i* in year *t*, DED_{it} represents the level of development of the digital economy in region *i* in year *t*, $Control_{it}$ is a series of control variables, w_{ij} is the adjacency (0–1) spatial weight matrix, μ_i denotes spatial fixed effects, ϑ_t represents time fixed effects, and ε_{it} denotes the random error term. Equation 11 reduces to a spatial lag model if the value of ρ is not 0 and the value of θ is 0. If the value of ρ is 0 and the value of θ is 0, Equation 11 reduces to a spatial error model.

3.3 Data sources and descriptive statistics

Based on the availability and timeliness of data, this study uses data from 30 provinces (municipalities directly under the central government and autonomous regions) in China from 2014 to 2021 for empirical analysis. The data in this study are obtained from the China Statistical Yearbook, the China Rural Statistical Yearbook, the China Population and Employment Statistical Yearbook, and the China Information Industry Yearbook. In addition, Linear interpolation is an effective tool for smoothing gaps in data and is commonly used to fill in missing values in statistical yearbooks. Thus, this study references previous research (Han et al., 2023; Wan et al., 2024) and uses linear interpolation to impute the missing values of individual variables. Table 3 presents the descriptive statistics of the variables.

4 Results and discussion

4.1 The dynamic evolution of digital economy and the coordinated development of green agriculture and food security

This study uses MATLAB2020b software and kernel density to investigate the dynamic evolution of digital economy and the coordinated development of green agriculture and food security, as shown in Figure 2. Figure 2A shows the dynamic evolution of the digital economy in China. The center of the kernel density curve gradually moves to the right, indicating that China's digital economy is growing rapidly. In terms of the wave peak, the width of the wave peak of the kernel density curve of digital economy in China gradually becomes narrower, indicating that the development level of digital economy in various regions is equalizing. Furthermore, the distribution of kernel density curve has been single peak, indicating no polarization in digital economy development in China. Figure 2B illustrates the dynamic evolution of green agriculture and food security coordination in China. The center position of the kernel density curve first moves slightly to the left and then to the right, indicating that the degree of green agriculture and food security coordination in China first declines, then rises; however, the overall coordinated development trend is positive. In terms of wave peaks, the kernel density curve gradually transitions from a broad peak to a sharp peak, indicating that differences are gradually narrowing in China, and the distribution of the kernel density curve has always been single-peaked. The findings suggest that the degree of coordinated development is balanced in all regions.

4.2 Baseline results

The results of F and Hausman tests confirm that the fixed-effects model is appropriate for the study's regression, and the baseline regression results are presented in Table 4. Column (1) demonstrates the effect of the digital economy on the coordinated development of green agriculture and food security. Column (2) demonstrates the effect of digital industrialization as a subdimension of the digital economy on the coordinated development of green agriculture and food security. Finally, Column (3) demonstrates the effect of industrial digitization as a subdimension of the digital economy on the coordinated development of green agriculture and food security.

According to the regression results, the digital economy coefficient in Column (1) is 1.523 ($p < 0.01$), indicating that a 1-unit increase in digital economy development results in 1.523 units of green agriculture and food security coordination, confirming that the digital economy can significantly promote coordinated development. The coefficient of digital industrialization in Column (2) is 1.119, and the coefficient of industrial digitization in Column (3) is 0.839, both of which pass the significance test. The results imply that a 1-unit increase in digital industrialization promotes the coordinated development of green agriculture and food security by 1.119 units. Furthermore, a 1-unit increase in industrial digitization promotes green agriculture and food security coordination by 0.839 units. In contrast, digital industrialization contributes more to the effect of the digital economy on coordinated development than industrial digitization.

4.3 Robustness tests

The baseline regression results confirm that the digital economy can significantly promote the coordinated development of green agriculture and food security. To ensure the robustness of the results, this study adopts three methods for robustness tests. The first is shrinkage treatment, in which the upper and lower 1% of the sample is reduced to exclude the influence of outliers on the regression results. The second uses the lagged period of digital economic development as an instrumental variable. The lagged period of digital economic development is highly correlated with digital economy development, which satisfies correlation. Furthermore, the lagged period of digital economic development

TABLE 3 Variable definitions and descriptive statistics.

Variable classification	Variable	Definition	Mean	Std.	Min	Max
Explained variable	Coordinated development of green agriculture and food security (COR)	Calculated using the coupling coordination model and the entropy weighting method	0.597	0.071	0.418	0.860
Explanatory variable	Digital economy development (DED)	Calculated using the entropy weighting method	0.364	0.115	0.149	0.795
Control variables	Financial support for agriculture (Gov)	Government expenditure on agriculture, forestry, and water (100,000,000 yuan)/general public budget expenditure (100,000,000 yuan)	0.609	0.174	0.268	1.297
	Trade openness (Open)	Total import and export of goods (100,000,000 yuan)/GDP (100,000,000 yuan)	0.231	0.245	0.004	1.216
	Industrial structure (Is)	Value added of primary industry (100,000,000 yuan)/GDP (100,000,000 yuan)	0.109	0.068	0.002	0.338
	Urbanization level (Urb)	Year-end population of cities and towns (10,000 people)/the year-end population of the region (10,000 people)	0.593	0.118	0.35	0.896
	Urban–rural income gap (Gap)	Per capita disposable income of urban residents (yuan/people)/per capita disposable income of rural residents (yuan/people)	2.52	0.355	1.842	3.474

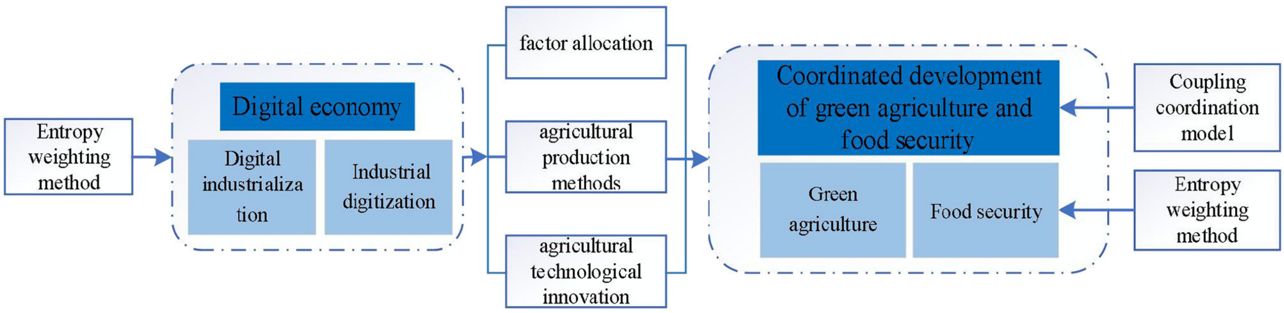

FIGURE 1
Methodological framework.

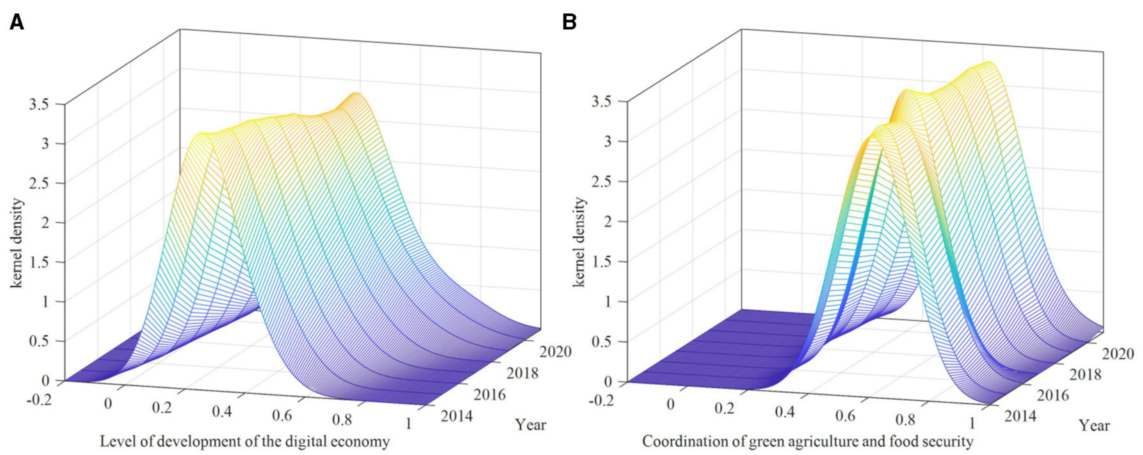

FIGURE 2
(A,B) Dynamic evolution of the digital economy and the coordination of green agriculture and food security.

cannot affect green agriculture and food security coordination through other ways than the digital economy. In addition, the lagged period of digital economic development is not correlated with the random error term, meeting exogeneity. In the third test, this study adds control variables. This study introduces farmers' education (Edu) as a control variable to the model for regression.

TABLE 4 Baseline regression results.

Variable	(1)	(2)	(3)
DED (Digital economy development)	1.523*** (43.69)		
DI (Digital industrialization)		1.119*** (12.44)	
ID (Industrial digitization)			0.839*** (23.72)
Gov (Financial support for agriculture)	−0.898*** (−50.12)	−0.613*** (−16.06)	−0.712*** (−27.83)
Open (Trade openness)	0.046*** (3.50)	−0.003 (−0.08)	−0.071*** (−3.45)
Is (Industrial structure)	0.373*** (3.25)	0.296 (1.06)	−0.007 (−0.04)
Urb (Urbanization level)	0.061** (2.20)	0.314*** (4.42)	−0.219*** (−4.64)
Gap (Urban–rural income gap)	−0.005 (−1.50)	0.004 (0.52)	−0.009 (−1.56)
Con_	0.515*** (17.96)	0.447*** (6.10)	0.781*** (16.80)
Country	Control	Control	Control
N	240	240	240
R^2	0.916	0.580	0.770

*, **, *** indicate 10%, 5%, and 1% significance levels, respectively. t or z values are in parentheses.

The results of the robustness test are presented in Table 5, revealing that the digital economy coefficients are all significantly positive. The findings indicate that the digital economy can effectively drive the coordinated development of green agriculture and food security, which is consistent with the benchmark regression results; therefore, the empirical results are robust.

4.4 Heterogeneity analysis

Because of differing geographic characteristics, the significance of agricultural production, and agricultural development patterns among regions of China, the following heterogeneity analysis is conducted to further explore the effect of the digital economy on the coordinated development of green agriculture and food security in different regions.

4.4.1 Heterogeneity of geographical characteristics

Digital economy development can be constrained by geographic features. In addition, its impact on the coordinated development of green agriculture and food security may subsequently differ in various regions. Therefore, this study divides the sample into mountainous-hilly areas and plains areas according to geographical features.[8] The regression results are presented in Table 6. The digital economy coefficient in Column (1) is 1.500 and passes the significance test, indicating that a 1-unit increase in digital economy development can promote the coordinated development of green agriculture and food security by 1.500 units in hilly areas. The digital economy coefficient in Column (2) is 1.545 ($p < 0.01$), indicating that a 1-unit increase in digital economy development can promote the coordinated development of green agriculture and food security by 1.545 units in plains areas.

In summary, the impact of the digital economy on the coordinated development of green agriculture and food security is greater in the plains than in hilly areas. The rationale for this is that digital economy development, technology, and facilities in mountainous-hilly areas is relatively lagging compared with that in plains areas, which slows digital economy development.

4.4.2 Heterogeneity of agricultural production

Considering the different emphasis on agricultural production between large agricultural provinces and nonagricultural provinces, differences are expected in the impact of the digital economy on the coordinated development of green agriculture and food security. Therefore, this study divides the sample into agricultural and nonagricultural provinces according to functional areas, and the results are shown in Table 6. The digital economy coefficient in Column (3) is 1.601, passing the significance test. A 1-unit increase in the digital economy can promote coordinated development of green agriculture and food security by 1.601 units in large agricultural provinces. The digital economy coefficient in Column (4) is 1.579 ($p < 0.01$), indicating that a 1-unit increase in the digital economy can promote coordinated development of green agriculture and food security by 1.579 units in nonagricultural provinces. Therefore, the impact of the digital economy on the coordinated development of green agriculture and food security is greater in large agricultural provinces than nonagricultural provinces. This is attributable to the fact that large agricultural provinces prioritize agricultural production and have greater advantages in realizing large-scale agricultural management and adopting green production technology.

4.4.3 Heterogeneity of functional areas

Main grain producing areas are better equipped for scale operation and green technology adoption than the main nongrain

8 This study categorizes provinces where the combined area of mountains and hills exceeds 70% as mountainous-hilly areas, and remaining areas are categorized as plains.

TABLE 5 Robustness test.

Variable	(1) Shrinkage treatment	(2) Introducing instrumental variables	(3) Adding control variables
DED (Digital economy development)	1.493*** (40.72)	1.458*** (34.02)	1.523*** (43.60)
Gov (Financial support for agriculture)	−0.874*** (−46.51)	−0.891*** (−33.26)	−0.898*** (−50.01)
Open (Trade openness)	0.095*** (6.68)	0.004 (0.28)	0.048*** (3.52)
Is (Industrial structure)	0.339*** (2.74)	−0.010 (−0.37)	0.374*** (3.25)
Urb (Urbanization level)	0.074** (2.56)	0.031 (1.54)	0.051 (1.56)
Gap (Urban–rural income gap)	−0.005 (−1.41)	−0.001 (−0.17)	−0.005 (−1.53)
Edu (The level of education of farmers)			0.004 (0.56)
Con_	0.495*** (16.22)	0.593*** (37.91)	0.491*** (9.35)
N	240	210	240
R^2	0.903	0.952	0.916

*, **, *** indicate 10%, 5%, and 1% significance levels, respectively. t or z values are in parentheses.

TABLE 6 Results of heterogeneity analysis.

Variable	Heterogeneity of geographical characteristics		Heterogeneity of agricultural production		Heterogeneity of functional areas	
	(1) Mountainous-hilly areas	(2) Plains areas	(3) Agricultural provinces	(4) Nonagricultural provinces	(5) Main grain producing areas	(6) Nonmain grain producing areas
DED (Digital economy development)	1.500*** (26.28)	1.545*** (32.55)	1.601*** (30.89)	1.579*** (29.20)	1.564*** (29.77)	1.561*** (29.03)
Gov (Financial support for agriculture)	−0.901*** (−24.44)	−0.904*** (−40.83)	−1.005*** (−29.86)	−0.893*** (−38.57)	−0.972*** (−28.25)	−0.895*** (−37.87)
Open (Trade openness)	0.008 (0.26)	0.054*** (3.37)	−0.022 (−0.51)	0.068*** (3.91)	0.007 (0.16)	0.058*** (3.34)
Is (Industrial structure)	0.241 (1.01)	0.385*** (2.76)	0.019 (0.12)	0.336** (1.99)	0.041 (0.27)	0.440** (2.62)
Urb (Urbanization level)	0.045 (1.07)	0.060 (1.58)	0.018 (0.47)	0.066 (1.66)	0.026 (0.69)	0.069* (1.71)
Gap (Urban–rural income gap)	−0.002 (−0.30)	−0.006 (−1.29)	−0.009** (−2.09)	−0.004 (−0.83)	−0.008*(−1.92)	−0.004 (−0.67)
Con_	0.548*** (10.58)	0.512*** (13.37)	0.638*** (13.62)	0.484*** (12.57)	0.617*** (13.61)	0.480*** (12.08)
Country	Yes	Yes	Yes	Yes	Yes	Yes
N	80	160	112	128	104	136
R^2	0.905	0.918	0.901	0.931	0.899	0.925

*, **, *** indicate 10%, 5%, and 1% significance levels, respectively. t or z values are in parentheses.

producing areas (Lee et al., 2024). Therefore, the effect of the digital economy on the coordinated development of green agriculture and food security will be impacted by changes in agricultural functional areas. This study divides the sample into grain and nongrain producing areas, presenting the regression results in Table 6. The digital economy coefficient in Column (5) is 1.564, passing the significance test. A 1-unit increase in the digital economy promotes the coordinated development of green agriculture and food security by 1.564 units in main grain producing areas. The digital economy coefficient in Column (6) is 1.561 ($p < 0.01$), indicating that a 1-unit increase in the digital economy can promote the coordinated development of green agriculture and food security by 1.561 units in nonmain grain producing areas. Therefore, the impact of the digital economy on the coordinated development of green agriculture and food security is greater in main grain producing areas than nonmain grain producing areas. The rationale for this is that mousere conditions for large-scale operation exist in main grain producing areas, and the cost of agricultural digital transformation and agricultural green production is lower.

4.5 Analysis of spatial spillover effects

4.5.1 Spatial autocorrelation

This study next uses a spatial econometric model to test the spatial spillover effect of the digital economy on the coordinated development of green agriculture and food security. Before conducting spatial regression, it is necessary to test whether spatial dependence exists in the data by performing a spatial autocorrelation test. This study uses the global Moran's index

TABLE 7 Global Moran's *I*.

Year	Digital economy			Coordinated development of green agriculture and food security		
	I-value	*z*-value	*p*-value	*I*-value	*z*-value	*p*-value
2014	0.150	1.656	0.049	0.276	2.848	0.002
2015	0.261	2.655	0.004	0.305	3.121	0.001
2016	0.393	3.857	0.000	0.238	2.511	0.006
2017	0.103	1.252	0.105	0.228	2.415	0.008
2018	0.237	2.456	0.007	0.210	2.257	0.012
2019	0.294	3.005	0.001	0.202	2.189	0.014
2020	0.114	1.354	0.088	0.158	1.791	0.037
2021	0.145	1.689	0.046	0.148	1.699	0.045

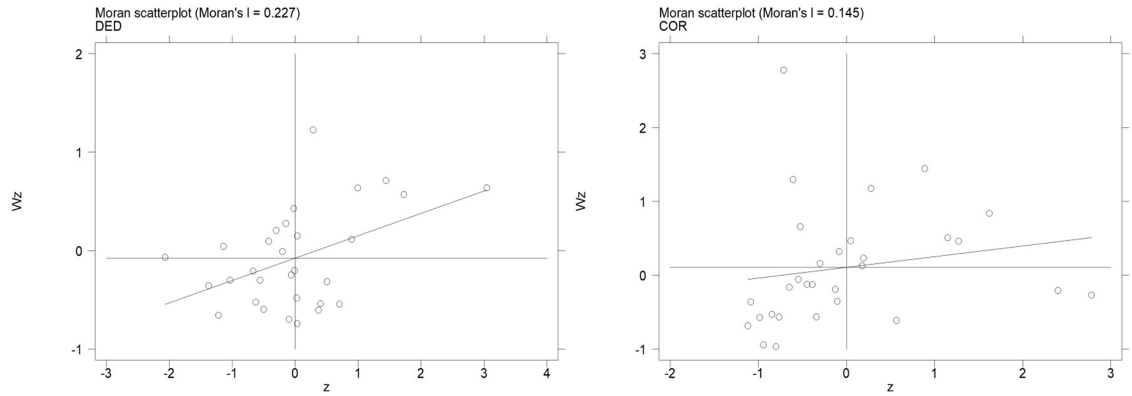

FIGURE 3
Localized Moran's *I* map of the digital economy and the harmonization of green and green agriculture with food security in 2020.

(Moran's *I*) to test the spatial correlation of digital economy and the coordinated development of green agriculture and food security, presenting the results in Table 7. The global Moran's I of the digital economy is >0 in all years, passing the significance test (except in 2017). This indicates a positive spatial coefficient correlation for the digital economy as a whole. The values of global Moran's *I* of the coordinated development of green agriculture and food security are all >0 in all years and significant at the 1% level. This indicates a positive spatial coefficient correlation between the coordinated development of green agriculture and food security overall. The local Moran's *I* plot of digital economy and coordinated development of green agriculture and food security in 2021 are illustrated in Figure 3, and the slope of the straight line is positive, indicating significant spatial autocorrelation in digital economy and coordinated development of green agriculture and food security.

4.5.2 Spatial Durbin model regression results

To determine the specific form of the spatial regression model, this study applies Wald and LR tests, presenting the results in Table 8. According to the test results, the *p*-values of the tests are <0.05, indicating that it is more appropriate to select the spatial Durbin model for regression estimation. In addition, the chi-square value of Hausman test is 75.31 and *p*-value is 0.0000. Therefore, the spatial Durbin model with fixed effects is selected for estimation.

TABLE 8 Results of Wald and LR tests.

Test	Spatial lag model	Spatial error model
Wald test	28.49** (0.0001)	28.10*** (0.0001)
LR test	18.01*** (0.0062)	15.78** (0.0150)

*, **, *** indicate 10%, 5%, and 1% significance levels, respectively. t or z values are in parentheses.

Based on the above analysis, this study uses the spatial Durbin model with fixed effects for the regression estimation, presenting the results in Table 9. From the perspective of the core explanatory variables, the coefficient of digital economy is positive and significant at the 1% level, indicating that digital economy development can effectively promote the coordinated development of green agriculture and food security. Furthermore, the spatial lagged coefficient of digital economy is positive and passes the significance test, demonstrating that the digital economy has a positive spatial spillover effect on the coordinated development of green agriculture and food security. In other words,

TABLE 9 Results of spatial Durbin model regression.

Variable	COR
DED (Digital economy development)	1.393*** (32.68)
Gov (Financial support for agriculture)	−0.905*** (−53.89)
Open (Trade openness)	0.031** (2.38)
Is (Industrial structure)	0.525*** (4.76)
Urb (Urbanization level)	0.165** (2.25)
Gap (Urban–rural income gap)	−0.007** (−2.34)
W × DED (Digital economy development)	0.255* (1.75)
W × Gov (Financial support for agriculture)	−0.061 (−0.73)
W × Open (Trade openness)	0.040* (1.72)
W × Is (Industrial structure)	−0.280 (−1.62)
W × Urb (Urbanization level)	−0.115 (−1.49)
W × Gap (Urban–rural income gap)	−0.004 (−0.73)
Country	Control
Year	Control
N	240
R^2	0.9365

*, **, *** indicate 10%, 5%, and 1% significance levels, respectively. t or z values are in parentheses.

local digital economy development can effectively promote the coordinated development of green agriculture and food security in neighboring areas. In addition, the coefficients of openness to the outside world, industrial structure, and urbanization are all positive and pass the significance test, indicating positive effects on the coordinated development of green agriculture and food security. The coefficient of financial support for agriculture is significantly negative, indicating that the impact of financial support for agriculture on green agriculture and food security coordination is negative. The rationale for this may be that financial support for agriculture has deviations and does not have an influence. Therefore, the government should establish and enhance the supervision mechanism, increase transparency and public participation in agricultural financial support, and ensure the precision of these financial resources.

4.5.3 Decomposition of spatial spillover effects

To further explore total, direct, and indirect effects, this study uses the partial differential method to decompose the spatial spillover effect of the digital economy on the coordinated development of green agriculture and food security, presenting the results in Table 10. According to the total effect, the coefficient of the digital economy is positive and highly significant, showing that the digital economy can promote green agriculture and food security coordination. Regarding the direct effect, the coefficient of the level of the digital economy is positive and significant, indicating that the digital economy can effectively promote the local green agriculture and food security coordination. In terms of the indirect effect, the coefficient of the digital economy is positive and significant, showing that digital economy development can effectively promote green agriculture and food security coordination in neighboring regions; however, the indirect effect is smaller than the direct effect.

5 Discussion

The digital economy, green agriculture, and food security are popular Research Topics. However, in the context of global economic development facing challenges of climate warming and ecological environment deterioration, it is particularly important to promote the coordinated development of green agriculture and food security.

Focusing on how the digital economy affects the coordinated development of green agriculture and food security, we measure the development of digital economy, green agriculture and food security through the entropy weight method, and apply the Coupling coordination model to measure the coordinated development level of green agriculture and food security, which is similar to the existing related research in research methods (Han et al., 2023; Liu and Ren, 2023; Shao et al., 2024; Tao et al., 2024). Our research found that the digital economy can effectively enhance the coordinated development of low-carbon agriculture and food security by optimizing factor allocation efficiency (Hao et al., 2023; Liu and Hao, 2023), improving agricultural production methods (Yang et al., 2024; Lu et al., 2024), and fostering agricultural technology innovation (Hao et al., 2023; Li and Gao, 2024; Lv and Chen, 2024). This conclusion aligns with existing studies on how the digital economy promotes low-carbon development and ensures food security (Deng et al., 2023; Shi et al., 2024), but there are some differences. Compared to previous studies, this research not only examines the individual impact of the digital economy on green agriculture and food security but also integrates these elements into a unified framework. It provides an in-depth analysis of how the digital economy affects the coordinated development of green agriculture and food security, specifically through the lens of spatial spillover effects. Our findings can still offer valuable insights for countries with similar agricultural practices, such as India, to help ensure food security and promote sustainable agricultural development.

But, this study also has the following limitations. First, this study analyzes the impact of the digital economy on the coordinated development of green agriculture and food security solely from the perspective of spatial effects. Future research should build on this foundation to explore the mechanisms underlying the digital economy's influence on the coordinated development of green agriculture and food security in greater depth. Second, this study only examined the effect of China's overall digital economy on the coordinated development of green agriculture and food security. Future research should build on this foundation to further investigate the nonlinear aspects of this impact and derive more policy-oriented conclusions. Third, due to data limitations, this study only examined the impact of the digital economy on the coordinated development of green agriculture and food security at the provincial level in China. Future research should collect county-level data through field surveys and other methods to further explore the impact of the digital economy on green agriculture and food security in different counties.

TABLE 10 Decomposition of effects.

Variable	Total effect	Direct effect	Indirect effect
DED (Digital economy development)	1.550*** (32.78)	1.392*** (31.77)	0.157*** (2.75)
Gov (Financial support for agriculture)	−0.909*** (−32.76)	−0.906*** (−53.23)	−0.003 (−0.11)
Open (Trade openness)	0.069*** (3.47)	0.032** (2.53)	0.036* (1.68)
Is (Industrial structure)	0.227 (1.34)	0.530*** (4.83)	−0.303* (−1.80)
Urb (Urbanization level)	0.047* (1.86)	0.166** (2.35)	−0.119 (−1.60)
Gap (Urban–rural income gap)	−0.010 (−1.40)	−0.007** (−2.35)	−0.003 (−0.53)

*, **, *** indicate 10%, 5%, and 1% significance levels, respectively. t or z values are in parentheses.

6 Conclusion and recommendations

Based on the above analysis, we draw three relevant conclusions. First, the development trend of digital economy and coordinated development of green agriculture and food security in China is positive, with no polarization phenomenon. Second, the digital economy can effectively promote the coordinated green agriculture and food security development, with notable heterogeneity. The positive effect of the digital economy on the coordinated development is larger in plains areas, agricultural provinces, and main grain producing areas. Third, digital economy development exhibits positive spatial spillover effects on the coordinated green agriculture and food security development. In other words, digital economy development promotes the coordinated development of green agriculture and food security in a region as well as neighboring regions. This study proposes the following relevant policy implications.

First, the development of rural digital economy should be promoted. We have shown that the digital economy can significantly enhance the coordinated green agriculture and food security development. On the one hand, infrastructure is crucial for economic development. More efforts should be directed toward advancing digital rural infrastructure, such as speeding up the deployment of 5G networks in rural areas and broadening network coverage in these regions. On the other hand, policy support should be formulated to vigorously promote the development of the Internet of Things, improve the integration of digital technology and traditional technology facilities, accelerate the digital transformation of traditional infrastructure, and promote agricultural business entities to use digital technology to promote the coordinated development of green agriculture and food security.

Second, we should support the adoption of technology by agricultural business entities. Research shows that digital economy can promote the coordinated development of green agriculture and food security through technological innovation in agriculture. On the one hand, the government should provide financial incentives and subsidies, not only providing grants, low-interest loans or tax breaks for farmers and agricultural enterprises to purchase digital technology and software, but also developing subsidy programs for the purchase of advanced equipment such as drones, automated machinery and precision farming tools. On the other hand, a group of high-quality digital agricultural talents should be cultivated to promote the research and development and application of agricultural digital technology, and promote agricultural technology innovation, so as to realize the coordinated development of green and low-carbon agriculture and food security.

Third, evaluation and monitoring systems should be established. On the one hand, indicators and benchmarks should be developed to assess the effectiveness of digital initiatives in improving green agriculture and food security. On the other hand, there should also be regular monitoring and review, creating a system of regular review and feedback to refine policies and ensure that they respond to changing challenges and opportunities.

Fourth, promoting coordinated regional development of the digital economy. We have shown that the digital economy has positive spatial spillover effects on the balanced development of green agriculture and food security. The government should encourage inter-regional exchanges and cooperation, establish unified policies for digital economy development, and facilitate the movement of capital, technology, and other production factors between regions. By promoting the coordinated development of the digital economy across regions.

In summary, our study has both theoretical and practical implications for achieving agricultural sustainability and safeguarding food security. However, since the research focuses on China, the results may vary with different data sets and contexts. It is necessary for further research to determine whether our conclusions are applicable to other countries. Additionally, the policy recommendations in this paper are tailored to China's specific situation and are more suitable for scenarios where the government plays a leading role. They may not be relevant in other contexts with more liberal approaches of the digital economy, green agriculture and food security.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JT: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. CL: Writing – review & editing, Supervision, Project administration, Funding acquisition. GM: Project administration, Resources, Supervision, Investigation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the National Social Science Foundation of China (grant number 22BGL175).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Adem, M., Cochrane, L., Miceikiene, A., Skominas, R., and Azadi, H. (2023). The dynamics of multidimensional food security in rural Ethiopia. *Glob. Food Secur.* 39:100725. doi: 10.1016/j.gfs.2023.100725

Ahmad, B., Zhao, Z., Xing, J., Gultaj, H., Khan, N., and Yan, Y. (2024). Exploring the influence of internet technology adoption on the technical efficiency of food production: insight from wheat farmers. *Front. Sustain. Food Syst.* 8:1385935. doi: 10.3389/fsufs.2024.1385935

Annosi, M. C., Brunetta, F., Bimbo, F., and Kostoula, M. (2021). Digitalization within food supply chains to prevent food waste. Drivers, barriers and collaboration practices. *Ind. Mark. Manag.* 93, 208–220. doi: 10.1016/j.indmarman.2021.01.005

Aragie, E., Balié, J., Morales, C., and Pauw, K. (2023). Synergies and trade-offs between agricultural export promotion and food security: evidence from African economies. *World Dev.* 172:106368. doi: 10.1016/j.worlddev.2023.106368

Campi, M., Dueñas, M., and Fagiolo, G. (2021). Specialization in food production affects global food security and food systems sustainability. *World Dev.* 141:105411. doi: 10.1016/j.worlddev.2021.105411

Chandio, A. A., Gokmenoglu, K. K., Khan, I., and Jiang, Y. (2023). Does internet technology usage improve food production? Recent evidence from major rice-producing provinces of China. *Comput. Electr. Agric.* 211:108053. doi: 10.1016/j.compag.2023.108053

Chen, C., Ye, F., Xiao, H., Xie, W., Liu, B., and Wang, L. (2023). The digital economy, spatial spillovers and forestry green total factor productivity. *J. Clean. Prod.* 405:136890. doi: 10.1016/j.jclepro.2023.136890

Chen, W., and Yao, L. (2024). The impact of digital economy on carbon total factor productivity: a spatial analysis of major urban agglomerations in China. *J. Environ. Manag.* 351:119765. doi: 10.1016/j.jenvman.2023.119765

Chen, Z., Li, X., Zhang, J., and Xia, X. (2024). Does digital finance alleviate household consumption inequality? Evidence from China. *Fin. Res. Lett.* 60:104844. doi: 10.1016/j.frl.2023.104844

Chijindu Iheanacho Okpalaoka (2023). Research on the digital economy: developing trends and future directions. *Technol. Forecast. Soc. Change* 193:122635. doi: 10.1016/j.techfore.2023.122635

Deng, H., Bai, G., Shen, Z., and Xia, L. (2022). Digital economy and its spatial effect on green productivity gains in manufacturing: evidence from China. *J. Clean. Prod.* 378:134539. doi: 10.1016/j.jclepro.2022.134539

Deng, H., Zheng, W., Shen, Z., and Štreimikiene, D. (2023). Does fiscal expenditure promote green agricultural productivity gains: an investigation on corn production. *Appl. Energy* 334:120666. doi: 10.1016/j.apenergy.2023.120666

FAO (2009). *Declaration of World Summit on Food Security*. Rome: Food and Agriculture Organization (FAO).

Ferguson, R., Mishra, S., Qureshi, S., Injac, L., Talukder, B., and Orbinski, J. (2023). Digital technologies and food security during crisis: COVID-19 experiences from smallholder farmers in Odisha, India. *Front. Sustain. Food Syst.* 7:1150197. doi: 10.3389/fsufs.2023.1150197

George, P., Arduini, S., Uyar, H., Psiroukis, V., Kasimati, A., and Fountas, S. (2024). Economic and environmental benefits of digital agricultural technologies in crop production: a review. *Smart Agric. Technol.* 8:100441. doi: 10.1016/j.atech.2024.100441

Guo, Z., and Zhang, X. (2023). Carbon reduction effect of agricultural green production technology: a new evidence from China. *Sci. Total Environ.* 874:162483. doi: 10.1016/j.scitotenv.2023.162483

Hadley, K., Talbott, J., Reddy, S., and Wheat, S. (2023). Impacts of climate change on food security and resulting perinatal health impacts. *Semin. Perinatol.* 47:151842. doi: 10.1016/j.semperi.2023.151842

Han, X., Wang, Y., Yu, W., and Xia, X. (2023). Coupling and coordination between green finance and agricultural green development: evidence from China. *Fin. Res. Lett.* 58:104221. doi: 10.1016/j.frl.2023.104221

Hao, X., Li, Y., Ren, S., Wu, H., and Hao, Y. (2023). The role of digitalization on green economic growth: Does industrial structure optimization and green innovation matter? *J. Environ. Manag.* 325:116504. doi: 10.1016/j.jenvman.2022.116504

He, Y., Li, K., and Wang, Y. (2022). Crossing the digital divide: the impact of the digital economy on elderly individuals' consumption upgrade in China. *Technol. Soc.* 71:102141. doi: 10.1016/j.techsoc.2022.102141

Jiang, Y., Han, G., and Yu, D. (2024). Digital finance and agricultural green total factor productivity: the mediating role of digital village development. *Fin. Res. Lett.* 67:105948. doi: 10.1016/j.frl.2024.105948

Jin, M., Feng, Y., Wang, S., Chen, N., and Cao, F. (2024). Can the development of the rural digital economy reduce agricultural carbon emissions? A spatiotemporal empirical study based on China's provinces. *Sci. Total Environ.* 939:173437. doi: 10.1016/j.scitotenv.2024.173437

Karnik, H., and Peterson, H. H. (2023). Food security among low-income immigrant households and the role of social capital: a case study of Somali-American households in the Midwestern United States. *Food Policy* 117:102456. doi: 10.1016/j.foodpol.2023.102456

Kazungu, I., and Kumburu, N. P. (2023). Agripreneurship as a panacea for food security in Tanzania: a systematic review. *Heliyon* 9:e13305. doi: 10.1016/j.heliyon.2023.e13305

Lee, C.-C., Zeng, M., and Luo, K. (2023). Food security and digital economy in China: a pathway towards sustainable development. *Econ. Analysis Policy* 78, 1106–1125. doi: 10.1016/j.eap.2023.05.003

Lee, C.-C., Zeng, M., and Luo, K. (2024). How does climate change affect food security? Evidence from China. *Environ. Impact Assess. Rev.* 104:107324. doi: 10.1016/j.eiar.2023.107324

Li, B., and Gao, Y. (2024). Impact and transmission mechanism of digital economy on agricultural energy carbon emission reduction. *Int. Rev. Econ. Fin.* 95:103457. doi: 10.1016/j.iref.2024.103457

Li, S., Chang, G., and Zunong, R. (2023). Does regional digital economy development influence green investment? *Innov. Green Dev.* 2:100053. doi: 10.1016/j.igd.2023.100053

Li, Y., Li, N., and Li, Z. (2023). Evolution of carbon emissions in China's digital economy: an empirical analysis from an entire industry chain perspective. *J. Clean. Prod.* 414:137419. doi: 10.1016/j.jclepro.2023.137419

Liu, J., Chen, Y., and Liang, F. H. (2023). The effects of digital economy on breakthrough innovations: evidence from Chinese listed companies. *Technol. Forecast. Soc. Chan.* 196:122866. doi: 10.1016/j.techfore.2023.122866

Liu, J., and Ren, Y. (2023). Can digital inclusive finance ensure food security while achieving low-carbon transformation in agricultural development? Evidence from China. *J. Clean. Prod.* 418:138016. doi: 10.1016/j.jclepro.2023.138016

Liu, Y., and Hao, Y. (2023). How does coordinated regional digital economy development improve air quality? New evidence from the spatial simultaneous equation analysis. *J. Environ. Manag.* 342:118235. doi: 10.1016/j.jenvman.2023.118235

Liu, Y., Zhao, X., Liu, Y., and Kong, F. (2023). The dynamic impact of digital economy on the green development of traditional manufacturing industry: evidence from China. *Econ. Anal. Policy* 80, 143–160. doi: 10.1016/j.eap.2023.08.005

Liu, Z., Tian, J., Wang, K., and Lan, J. (2023). The impact of farmland circulation on the carbon footprint of agricultural cultivation in China. *Econ. Analysis Policy* 78, 792–801. doi: 10.1016/j.eap.2023.04.010

Lu, S., Zhuang, J., Sun, Z., and Huang, M. (2024). How can rural digitalization improve agricultural green total factor productivity: empirical evidence from counties in China. *Heliyon* 10:e35296. doi: 10.1016/j.heliyon.2024.e35296

Lv, L., and Chen, Y. (2024). The Collision of digital and green: digital transformation and green economic efficiency. *J. Environ. Manag.* 351:119906. doi: 10.1016/j.jenvman.2023.119906

Lyu, Y., Wu, Y., Wu, G., Wang, W., and Zhang, J. (2023). Digitalization and energy: how could digital economy eliminate energy poverty in China? *Environ. Impact Assess. Rev.* 103:107243. doi: 10.1016/j.eiar.2023.107243

Ma, X., Feng, X., Fu, D., Tong, J., and Ji, M. (2024). How does the digital economy impact sustainable development? —an empirical study from China. *J. Clean. Prod.* 434:140079. doi: 10.1016/j.jclepro.2023.140079

Mikhaylov, A., Moiseev, N., Aleshin, K., and Burkhardt, T. (2020). Global climate change and greenhouse effect. *JESI* 7, 2897–2913. doi: 10.9770/jesi.2020.7.4(21)

Nambisan, S., and Baron, R. A. (2013). Entrepreneurship in innovation ecosystems: entrepreneurs' self–regulatory processes and their implications for new venture success. *Entrep. Theory Pract.* 37, 1071–1097. doi: 10.1111/j.1540-6520.2012.00519.x

O'Connell, S., Boles, J., McClellan, R., and Demers, D. (2023). Mapping food security in Arkansas. *Appl. Geogr.* 158:103020. doi: 10.1016/j.apgeog.2023.103020

Olumba, C. C., Olumba, C. N., and Okpara, U. (2023). Household headship, resource ownership and food security: new evidence from Southeast Nigerian cities. *Sci. Afr.* 22:e01974. doi: 10.1016/j.sciaf.2023.e01974

Papaioannou, T., Wield, D., and Chataway, J. (2009). Knowledge ecologies and ecosystems? An empirically grounded reflection on recent developments in innovation systems theory. *Environ. Plann. C Politics Space* 27, 319–339. doi: 10.1068/c0832

Raihan, A. (2023). Toward sustainable and green development in Chile: dynamic influences of carbon emission reduction variables. *Innov. Green Dev.* 2:100038. doi: 10.1016/j.igd.2023.100038

Rong, J., Hong, J., Guo, Q., Fang, Z., and Chen, S. (2023). Path mechanism and spatial spillover effect of green technology innovation on agricultural CO2 emission intensity: a case study in Jiangsu Province, China. *Ecol. Indic.* 157:111147. doi: 10.1016/j.ecolind.2023.111147

Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., et al. (2019). Automated pastures and the digital divide: how agricultural technologies are shaping labour and rural communities. *J. Rural Stud.* 68, 112–122. doi: 10.1016/j.jrurstud.2019.01.023

Shao, J., Zhang, L., and Cai, C. (2024). Dynamic evolution and spatial spillover effect of agricultural green development on eight economic regions in China. *Heliyon* 10:e33188. doi: 10.1016/j.heliyon.2024.e33188

Shen, X., and Wang, Z. (2024). Can digital industrialization promote energy conservation development in China? Empirical evidence based on national big data comprehensive pilot zone policy. *J. Environ. Manag.* 368:122125. doi: 10.1016/j.jenvman.2024.122125

Shi, R., Shen, Y., Du, R., Yao, L., and Zhao, M. (2024). The impact of agricultural productive service on agricultural carbon efficiency—from urbanization development heterogeneity. *Sci. Total Environ.* 906:167604. doi: 10.1016/j.scitotenv.2023.167604

Su, C.-W., Qin, M., Tao, R., and Umar, M. (2020). Financial implications of fourth industrial revolution: can bitcoin improve prospects of energy investment? *Technol. Forecast. Soc. Change* 158:120178. doi: 10.1016/j.techfore.2020.120178

Sun, C., Xu, S., and Xu, M. (2023). What causes green efficiency losses in Chinese agriculture? A perspective based on input redundancy. *Technol. Forecast. Soc. Change* 197:122907. doi: 10.1016/j.techfore.2023.122907

Tao, J., Wang, Z., Xu, Y., Zhao, B., and Liu, J. (2024). Can the digital economy boost rural residents' income? Evidence from China based on the spatial Durbin model. *Econ. Anal. Policy* 81, 856–872. doi: 10.1016/j.eap.2024.01.004

Tobler, W. R. (1970). A computer movie simulating urban growth in the Detroit region. *Econ. Geogr.* 46(Supp. 1), 234–240.

Uddin, M. R. (2023). The role of the digital economy in bangladesh's economic development. *Sustain. Technol. Entrep.* 3:100054. doi: 10.1016/j.stae.2023.100054

Wan, Q., Chao, R., Li, J., and Nawab, K. (2024). Toward a sustainable agricultural system in China: exploring the nexus between agricultural science and technology innovation, agricultural resilience and fiscal policies supporting agriculture. *Fronti. Sustain. Food Syst.* 8:1390014. doi: 10.3389/fsufs.2024.1390014

Wang, B., Wang, J., Dong, K., and Dong, X. (2023). Is the digital economy conducive to the development of renewable energy in Asia? *Energy Policy* 173:113381. doi: 10.1016/j.enpol.2022.113381

Wang, H., and Li, Z. (2024). Can the digitalization level of agriculture improve its ecological efficiency under carbon constraints: evidence from China. *Heliyon* 10:e26750. doi: 10.1016/j.heliyon.2024.e26750

Wang, Q., Sun, J., Pata, U. K., Li, R., and Kartal, M. T. (2023). Digital economy and carbon dioxide emissions: examining the role of threshold variables. *Geosci. Front.* 15:101644. doi: 10.1016/j.gsf.2023.101644

Wang, R., Cheng, J., Zhu, Y., and Lu, P. (2017). Evaluation on the coupling coordination of resources and environment carrying capacity in Chinese mining economic zones. *Resour. Policy* 53, 20–25. doi: 10.1016/j.resourpol.2017.05.012

Wang, Y., Wang, Y., and Shahbaz, M. (2023). How does digital economy affect energy poverty? Analysis from the global perspective. *Energy* 282:128692. doi: 10.1016/j.energy.2023.128692

Wu, L., Zhu, C., and Wang, G. (2024). The impact of green innovation resilience on energy efficiency: a perspective based on the development of the digital economy. *J. Environ. Manag.* 355:120424. doi: 10.1016/j.jenvman.2024.120424

Wu, Q., Qalati, S. A., Hussain, R. Y., Irshad, H., Tajeddini, K., Siddique, F., et al. (2023). The effects of enterprises' attention to digital economy on innovation and cost control: evidence from A-stock market of China. *J. Innov. Knowledge* 8:100415. doi: 10.1016/j.jik.2023.100415

Xin, Y., Song, H., Shen, Z., and Wang, J. (2023). Measurement of the integration level between the digital economy and industry and its impact on energy consumption. *Energy Econ.* 126:106988. doi: 10.1016/j.eneco.2023.106988

Yang, C., Ji, X., Cheng, C., Liao, shiou, Bright, O., and Zhang, Y. (2024). Digital economy empowers sustainable agriculture: implications for farmers' adoption of ecological agricultural technologies. *Ecol. Indic.* 159:111723. doi: 10.1016/j.ecolind.2024.111723

Yovo, K., and Gnedeka, K. T. (2023). Assess the level and the determinants of household food security in Togo: the food expenditures approach. *Sci. Afr.* 20:e01685. doi: 10.1016/j.sciaf.2023.e01685

Zhang, J., Lyu, Y., Li, Y., and Geng, Y. (2022). Digital economy: an innovation driving factor for low-carbon development. *Environ. Impact Assess. Rev.* 96:106821. doi: 10.1016/j.eiar.2022.106821

Zhang, Q., Wu, P., Li, R., and Chen, A. (2024). Digital transformation and economic growth efficiency improvement in the digital media era: digitalization of industry or digital industrialization? *Int. Rev. Econ. Finance* 92, 667–677. doi: 10.1016/j.iref.2024.02.010

Zhang, T., and Li, N. (2023). Measuring digital economy: from the perspective of digital industrialization and industry digitalization. *Procedia Comput. Sci.* 221, 1006–1012. doi: 10.1016/j.procs.2023.08.081

Zhang, Y., and Qu, Y. (2023). Has the digital economy improved the consumption of poor and subsistence households? *China Econ. Rev.* 83:102083. doi: 10.1016/j.chieco.2023.102083

Zhao, L., Rao, X., and Lin, Q. (2023). Study of the impact of digitization on the carbon emission intensity of agricultural production in China. *Sci. Total Environ.* 903:166544. doi: 10.1016/j.scitotenv.2023.166544