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Study on the coupling and coordination relationship between the digital economy and green development: evidence from Guangdong province in China

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The digital economy city and green development of China are important engines with important backgrounds. This paper takes 21 prefecture-level cities in Guangdong Province as the research object. By constructing the index system of the digital economy and green development, this paper discusses the external spatial pattern and internal temporal evolution characteristics of the coordinated development of the digital economy and green development from the two perspectives of intercity and inner city. The results show that: 1) From the perspective of intercity, there is a large gap between the development level of the digital economy and the green development level of all cities, only Guangzhou and Shenzhen have the digital economy development level ahead of the green development level. The coupling level of the two systems presents an unbalanced pattern of "centre-edge," and "Guangzhou-Foshan-Shenzhen-Dongguan" becomes the core pole of the coupling development of the two systems in the province. The coordinated horizontal cascade distribution of the two systems is obvious, showing a spatial pattern of decreasing step by step from the first circle to the third circle. 2) From the perspective of inner city, the digital economy level and green development level of all cities showed an upward trend from 2013 to 2019. The coupling level shows a two-stage development trend: the stable development stage from 2013 to 2016, and he accelerated development stage from 2016 to 2019, and the internal interaction of the two systems is deepening. The coordination level of all cities improved significantly in 7 years, and in 2019, 21 cities all reached the level of moderate coordination or high coordination. Based on above research conclusions, in order to promote the positive interaction between digital economy and green development, this paper proposes to optimize resource allocation based on regional differences, and adhere to innovation-driven policy proposals to activate the potential of green development.

KEYWORDS

digital economy, green development, coupling coordination, China, entropy method

1 Introduction

China's economy is at a crucial stage of replacing old growth drivers with new ones and achieving high-quality development. Problems such as the dual economic structure, increasing labour costs, increasing demand for resources, and extensive development mode still exist. At present, the economic cycle is not smooth, development is not coordinated, and the green transition is facing greater pressure. At the same time, the global economic landscape is being reshaped by the geopolitical landscape, the COVID-19 pandemic, the new round of technological revolution and industrial transformation, and the digital economy has become the main direction for countries to seize the commanding heights of the new global economic landscape. "The digital economy, as an emerging economic development mode, is gradually becoming an important pillar of China's national economic growth. Through the research and development of digital information technology, we can cultivate new drivers, promote the development of green industries, and achieve a fundamental improvement of ecological environment" the 14th Five-Year Plan for The digital economy Development points out. The report of the 20th National Congress of the Communist Party of China further pointed out "Accelerating the building of digital China." It can be seen that the booming digital economy not only brings opportunities for China to build new competitive advantages but also provides an important path for China's green development (Li et al., 2022).

As the vanguard of China's economy and the experimental area of reform and opening up, Guangdong has profound economic deposits, and the level of economic development has always ranked first in China. In 2021, the value-added scale of Guangdong's digital economy reached 5.9 trillion yuan, ranking first in China for five consecutive years. In the digital economy index, Guangdong province also consistently ranks among the top. However, the proportion of traditional industries in Guangdong is large, and problems such as inadequate green governance and ecological protection are still prominent. A large number of facts show that digital economy and green development have a logical correlation mechanism that promotes each other: On the one hand, the digital economy itself is a low-carbon circular economy, which can promote the upgrading of industrial structure and the improvement of resource allocation efficiency through technology empowerment, and provide digital momentum for green development; On the other hand, green development stimulates the demand of enterprises and individuals for the digital economy, expands the application scenarios of the digital economy, enricfies the business formats of the digital economy, and achieves the expansion of the scale of the digital economy. Therefore, how to realize the integration of digital economy and green development has become an important issue at present. The analysis of the coupling and coordination relationship between digital economy and green development has important theoretical and practical significance for understanding the internal logical correlation between digital economy and green development and realizing the positive interaction between digital economy and green development. In view of this, this paper takes Guangdong, which is at the forefront of the digital economy and green development in

TABLE 1 The digital economy and green development index system construction.

Index system	First-order index	Secondary index	Units	Attribute
The digital economy	Digital business scale	Total volume of telecommunication service	Hundred million yuan	+
		Share of employees in information transmission, software and information technology services	%	+
	Digital infrastructure	Mobile phone subscriber	Ten thousand households	+
		Number of Internet broadband access users	Ten thousand households	+
	Digital technology innovation	Percentage of R&D expenditure in GDP	%	+
		Number of patent applications granted	Piece	+
		Output value of high-tech products	Hundred million yuan	+
		Number of high-tech enterprises	Unit	+
Green development	Environmental governance	Urban sewage treatment rate	%	+
		Rate of harmless disposal of municipal solid waste	%	+
	Urban ecology	Standard number of urban buses in operation	one	+
		Urban *per capita* park green space	Square meter	+
	Energy conservation and emission reduction	Electricity consumption	Hundred million kilowatt hours	-
		Discharge of industrial wastewater	Hundred million tons	-
		Total industrial dust emissions	Ten thousand tons	-
		Production of industrial solid wastes	Ten thousand tons	-

China, as an example, constructs an indicator system, and discusses the external spatial pattern and internal temporal evolution characteristics of the coupled and coordinated development of digital economy and green development from the perspectives of intercity and inner city, to provide experience and reference for the high-quality development of global economy.

2 Review of relevant literature

In recent years, the digital economy and green development have become hot topics that governments all over the world pay close attention to. The academic circle has also carried out multi-dimensional research on it. In the field of the digital economy, the research mainly focuses on connotation characteristics, influencing factors, development level measurement and so on. On the basis of sorting out the origin and evolution of the digital economy, Han and Chen (2022) proposed the connotation and characteristics of the digital economy from the four aspects of technology, industry, scene application and governance. Ge et al. (2022) discussed the driving factors of the digital economy from the perspectives of international cooperation, factor accumulation, regulatory system, macro policy, and new infrastructure construction. Li and Han (2022) construct the development level index of the digital economy from the aspects of digital infrastructure, digital industrialization, industrial digitalization, etc., and find that China's digital economy is growing rapidly, and predict that the growth level of the digital economy will continue to increase in the future. Niftiyev (2022a) discoveries economic growth, government effectiveness, and the public services index would positively impact E-government development. Wu and Wang (2022) point out that although China's digital economy industry develops rapidly, the regional imbalance is expanding. Sadik-Zada et al. (2022) reveals that e-government offers one of the greatest opportunities for socio-economic development and improves the efficiency and effectiveness of public administration. Niftiyev (2022b) noted the need to improve economic reforms and policies to keep pace with regions driven by FDI and successfully integrated into global value chains.

In the field of green development, the existing researches mainly focus on the internal logic of green development and the measurement of green development level. Wang and Gao (2016) made a comprehensive review and study on the status and policies of green development since China's reform and opening up. Wu and Zhang (2017) sorted out the internal logic of the green development concept and predicted the future trend of green development. Huang and Li (2017) take urban agglomerations in China as the research object and find that the level of green development fluctuates, rises and diverges. Chen and Xu (2019) focused on the 11 provinces of the Yangtze River Economic Belt, and built an index system from five dimensions, including environmental carrying capacity, environmental management ability, environmental friendliness, environmental stress resistance and environmental stability, and pointed out that the overall level of green development in these provinces is improving.

With the increasing importance of the digital economy and green development, in recent years, scholars have begun to pay attention to the relationship between the digital economy and green development. The research mainly focuses on the following two aspects:

(1) The impact of the digital economy on green development. Han et al. (2022) pointed out that digital economy can trigger a comprehensive green revolution from production factors to productivity and production relations, and realize the all-round empowerment of green development. Wei and Hou (2022) carried out research using efficiency analysis and the entropy value method and pointed out that there were obvious regional differences between the digital economy and green development level in prefecture-level cities, and the digital economy could improve the green development level of cities. Different scholars also try to explore from different perspectives. Liu et al. (2022) measured and analyzed the level of economic development from two dimensions industrial digitalization and digital industrialization. Liu and Kong (2021) take 110 prefecture-level cities in the Yangtze River Economic Belt as examples to explore the effect mechanism of the digital economy on urban green transformation, and the results show that the digital economy exerts a positive effect in promoting urban green transformation. From the perspective of space, some scholars adopted the spatial Dubin model to study 30 provinces in China during 2006–2019 and found that the digital economy development has direct and spillover effects on green total factor productivity, and the promotion effect of central and western China is stronger than that of eastern China (Wu et al., 2022). Zhang (2022) found a significant spatial correlation between urban digital economy development and green total factor productivity.
(2) Research on the coordinated development of the digital economy and green development. Hu et al. (2022) proved that China's digital economy and green development have been effectively coordinated, showing a good trend year by year. Zheng et al. (2021) explored and found that the coordination level of public coupling between the digital economy and green development presents a spatial feature of "high in the east and low in the central and western regions" from two aspects of public coupling and content coupling. Li et al. (2022) proved that the digital economy, technological innovation and their interaction can positively promote green development.

After a comprehensive analysis of existing literature, it can be found that the academic circle has made a relatively comprehensive exploration in the research on the impact of the digital economy on green development and the measurement of the two, but the existing research on the interaction between the two systems still needs to be expanded and deepened. First, the relationship between the digital economy and green development is more than a single function. Clarifying the interaction between the two will provide a useful reference for China's high-quality development. Second, Guangdong is an important growth pole of China's digital economy and the vanguard of green development. The selection of Guangdong as a research object is typical and representative and can provide a reference for the construction of the Guangdong-Hong Kong-Macao Greater Bay Area and China's digital economy and green development. Based on the above analysis, this paper

takes Guangdong as an example to deeply explore the dynamic evolution process of the coupling and coordinated relationship between the digital economy and green development, in order to provide theoretical support and a decision-making basis for China's high-quality development.

3 Research design

3.1 Index selection

To ensure the accuracy of the evaluation system of the digital economy and green development, the index system of the digital economy and green development is constructed by referring to the existing research results and following the principles of systemization, hierarchy and accessibility. The digital economy system includes eight specific indicators from three dimensions: digital business scale, digital infrastructure and digital technology innovation. The green development system includes eight indicators from three dimensions: energy conservation and emission reduction, environmental governance and urban ecology as shown in Table 1.

3.2 Data source

This paper takes 21 cities in Guangdong Province as the research object to explore the relationship between the digital economy and green development. Based on data availability, the study spans from 2013 to 2019. The data on the digital economy and green development evaluation index are mainly collected from the China Statistical Yearbook of Science and Technology, the China Urban Statistical Yearbook, the Guangdong Statistical Yearbook, and the statistical yearbook and bulletin of each municipality. The year data of some cities are missing, and the interpolation method is used to complete them.

3.3 Research method

3.3.1 Entropy method

Since there are dimensional and order of magnitude differences among the index data, to facilitate the calculation and accuracy of each index, the design index is standardized:

$$\text{Positive index: } Y_{mij} = \frac{X_{mij} - X_{min}}{X_{max} - X_{min}} + 0.00001 \quad (1)$$

$$\text{Negative index: } Y_{mij} = \frac{X_{max} - X_{mij}}{X_{max} - X_{min}} + 0.00001 \quad (2)$$

where X_{min} and X_{max} represent the minimum and maximum values of the j-th index respectively. X_{mij} and Y_{mij} respectively represent the original value and the standardized value of the index, m represents the year, i represents the region, and j represents the index number.

3.3.2 Coupling coordination degree model and type division

In view of the validity reduction caused by the uneven distribution of C values calculated by the traditional coupling degree model, the following coupling degree model is constructed by referring to the research of Wang et al. (2021):

$$C = \sqrt{\left[1 - \sqrt{(U_2 - U_1)^2}\right] \times \frac{U_1}{U_2}} = \sqrt{\left[1 - (U_2 - U_1)\right] \times \frac{U_1}{U_2}} \quad (3)$$

Where, the C value is the coupling degree, U_1 and U_2 are the comprehensive level of the digital economy system and green development, respectively. The more the C value approaches 1, the higher the coupling degree of the two systems.

The coupling degree can only reflect the interaction between the two systems. To further explore the coordination of the interaction between the two systems, the coordination degree model is introduced as follows:

$$T = \alpha U_1 \times \beta U_2 \quad (4)$$

$$D = \sqrt{C \times T} \quad (5)$$

Meanwhile, referring to the research of Han et al. (2019), the classification standards of coupling degree and coordination degree are set as shown in Table 2 below:

4 Empirical analysis

Because the coupling degree C value and the coordination degree D value measured by the coupling model are only relative values within a certain year or a certain region, rather than absolute values, the comparability is limited (Wang et al., 2021). Therefore, this paper will take the two perspectives of intercity and inner city as the entry point, based on the construction of an index system and entropy method, and calculate the comprehensive development level of the digital economy and green development of 21 cities in Guangdong from 2013 to 2019. The coupling degree model and coupling coordination degree model were used to measure the coupling degree and coordination degree of the two systems, and ArcGIS software was used for spatiotemporal analysis.

4.1 Evolution of the comprehensive development level of the digital economy and green development

4.1.1 A view from an intercity perspective

To more intuitively analyze the evolution path of the digital economy and green development, the comprehensive development level data of the two systems in 2013, 2016 and 2019 are selected in this paper to draw Figure 1. As can be seen from Figure 1, there is a large gap between the comprehensive level of the digital economy and the comprehensive level of green development among cities. The development level of the digital economy in Guangzhou and Shenzhen is ahead of the level of green development while lagging behind the level of green development in other cities.

From the perspective of geographical space, the digital economy level of Guangzhou and Shenzhen is significantly higher than that of other regions, mainly because Guangzhou and Shenzhen, as the two core cities of Guangdong Province, have superior digital economy development environments. The specific manifestations are as follows: first, Guangzhou and Shenzhen have many high-tech

TABLE 2 Coupling level and coordination level classification criteria.

C	0 < C ≤ 0.2	0.2 < D ≤ 0.4	0.4 < D ≤ 0.6	0.6 < D ≤ 0.8	0.8 < D ≤ 1
Coupling level	Uncoupling	Low coupling	Antagonistic coupling	Run-in coupling	Highly coupled
D	0 < D ≤ 0.2	0.2 < D ≤ 0.4	0.4 < D ≤ 0.6	0.6 < D ≤ 0.8	0.8 < D ≤ 1
Coordination level	Serious dissonance	Moderate dissonance	Basic coordination	Moderate coordination	Highly coordinated

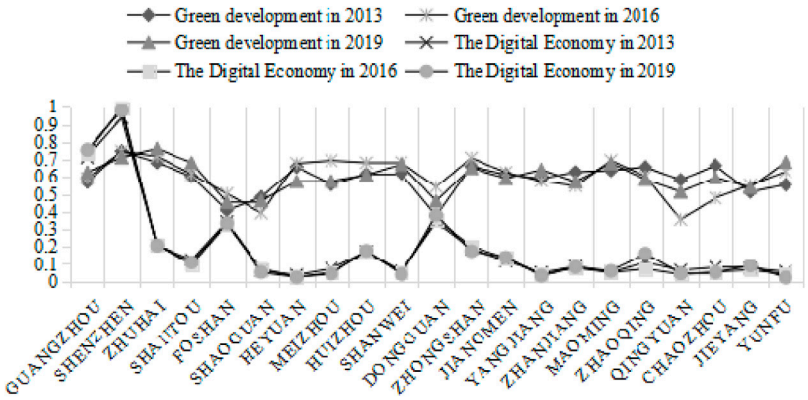

FIGURE 1
The trend of the digital economy system and green development system in 21 cities of Guangdong Province from the perspective of intercity from 2013 to 2019. Note: The author collated and calculated according to the relevant data of the Guangdong Statistical Yearbook, China City Statistical Year, China Science and Technology Statistical Yearbook, and various city statistical yearbooks and bulletins.

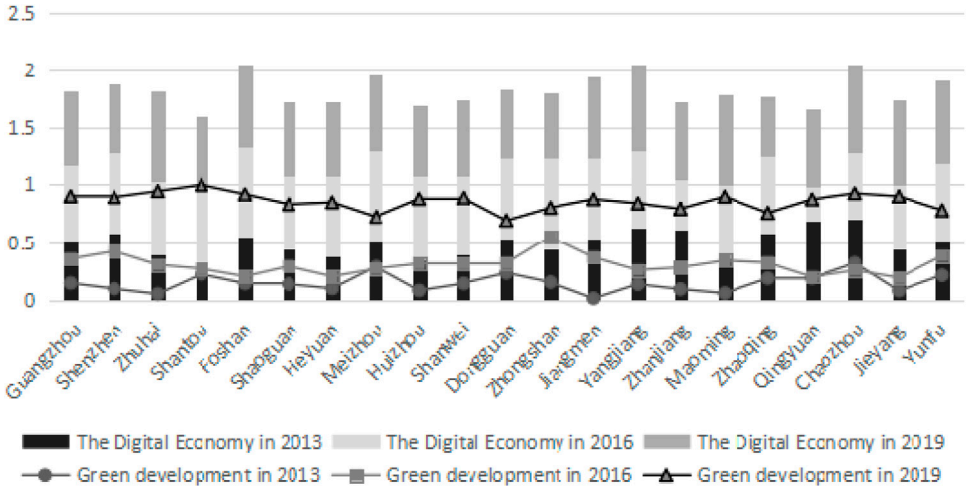

FIGURE 2
The changing trend of the digital economy system and green development system in 21 cities of Guangdong Province from the perspective of inner-city from 2013 to 2019. Note: The author collated and calculated according to the relevant data of the Guangdong Statistical Yearbook, China City Statistical Year, China Science and Technology Statistical Yearbook, and various city statistical yearbooks and bulletins.

industries and open markets, which have brought a good foundation for the transformation of achievements in the digital economy. Second, the two cities have a large number of universities and talent, which can provide a steady stream of high-quality talent for the development of the digital economy. In terms of green development, the gap between cities is relatively small. Foshan,

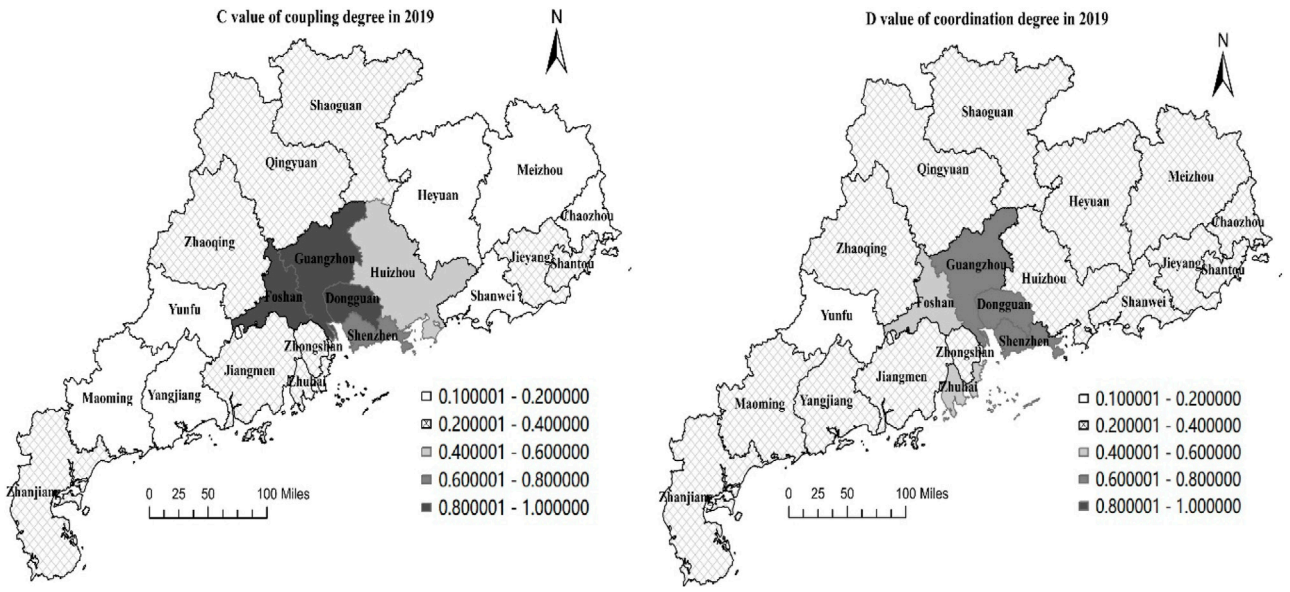

FIGURE 3
Coupling degree and coordination degree of the digital economy and green development in 21 cities of Guangdong Province in 2019 Note: The author collated and calculated according to the relevant data of the Guangdong Statistical Yearbook, China City Statistical Year, China Science and Technology Statistical Yearbook, and various city statistical yearbooks and bulletins.

Dongguan, Shaoguan and Qingyuan have a relatively low overall trend, with the comprehensive level of green development being 0.454, 0.461, 0.462 and 0.513 respectively in 2019, which is closely related to the development patterns and leading industries of the above cities. Among them, the industrial pattern of Foshan and Dongguan dominated by manufacturing and processing trade inhibits the green development space to a certain extent. Shaoguan and Qingyuan have received much of the heavy industry and high energy consumption capacity transferred from the Pearl River Delta region, which has a certain inhibiting effect on green development.

4.1.2 A view from an inner-city perspective

From 2013 to 2019, the level of the digital economy and green development in 21 cities in Guangdong showed an increasing trend. The development level of the digital economy in cities has been rising rapidly, especially in the 3 years from 2016 to 2019. Compared with the level of the digital economy, the level of green development is improved slowly and fluctuates significantly from year to year, showing a trend of fluctuating development as shown in Figure 2.

4.2 Analysis of the degree of coupling and coordination between the digital economy and green development

4.2.1 A view from an intercity perspective

By calculating the coupling degree and coordination degree of the digital economy and green development in 21 cities of Guangdong from 2013 to 2019, we find that: The interannual variation of the coupling degree and coordination degree of the two systems in each city is not obvious. Therefore, the calculation results of 2019 are selected, and ArcGIS software is used for spatial visualization processing to form the spatial distribution map of the coupling degree and coordination degree of the digital economy and green development in 2019 (as shown in Figure 3).

In terms of the coupling degree of the two systems, the coupling degree of the digital economy and green development in 21 cities in Guangdong presents an unbalanced pattern of "centre-edge." "Guangzhou-Foshan-Shenzhen-Dongguan" has become the core pole of the coupling development of the two systems in the province, and the C values are 0.85, 0.804, 0.729 and 0.872, respectively. Except Shenzhen is in the run-in coupling stage, the other three cities are in the highly coupled stage. The coupling degree of Huizhou was 0.404, which was in the antagonistic stage. Other cities in the Pearl River Delta have reached the low coupling stage, which is mainly due to the spillover effect of core cities. In the west, east and north of Guangdong, Qingyuan, Shaoguan, Zhanjiang, Jieyang and Shantou are at the low coupling stage, while other cities are at the uncoupling stage. The east and west of Guangdong are regions with rapid economic growth but mainly rely on resource-consuming industries and have prominent green weaknesses, so the industrial ecology still needs to be improved. Due to its geographical location, northern Guangdong has low accessibility and is less attractive to technical talents and foreign enterprises. The digital economy develops slowly, with a single industrial structure and a large number of high-emission and high-pollution industries. However, as a green ecological barrier in northern Guangdong, a good interaction between the digital economy and green development can be realized by improving resource utilization efficiency.

In terms of the coordination degree of the two systems, the spatial evolution and coupling degree are close to the same level, and the regional differences are significant. The coordination level of

TABLE 3 Coupling degree and coordination degree index of the digital economy and green development in Guangdong Province.

	Coupling degree C			Coordination degree D		
	2013	2016	2019	2013	2016	2019
Guangzhou	0.428	0.610	0.752	0.372	0.556	0.767
Shenzhen	0.293	0.646	0.698	0.313	0.605	0.723
Zhuhai	0.292	0.561	0.845	0.254	0.514	0.857
Shantou	0.790	0.528	0.661	0.462	0.486	0.740
Foshan	0.392	0.317	0.786	0.366	0.398	0.800
Shaoguan	0.462	0.553	0.812	0.364	0.505	0.777
Heyuan	0.433	0.378	0.789	0.320	0.413	0.769
Meizhou	0.673	0.395	0.926	0.514	0.460	0.800
Huizhou	0.418	0.496	0.726	0.297	0.511	0.737
Shanwei	0.512	0.537	0.762	0.371	0.518	0.768
Dongguan	0.547	0.534	0.897	0.458	0.521	0.763
Zhongshan	0.496	0.717	0.731	0.383	0.695	0.706
Jiangmen	0.105	0.594	0.823	0.170	0.562	0.808
Yangjiang	0.331	0.467	0.907	0.355	0.468	0.849
Zhanjiang	0.272	0.726	0.867	0.308	0.513	0.797
Maoming	0.327	0.620	0.900	0.263	0.548	0.874
Zhaoqing	0.441	0.565	0.752	0.410	0.527	0.699
Qingyuan	0.364	0.784	0.799	0.400	0.436	0.789
Chaozhou	0.523	0.535	0.814	0.518	0.476	0.825
Jieyang	0.335	0.468	0.839	0.295	0.417	0.831
Yunfu	0.534	0.630	0.944	0.441	0.577	0.844

Note: The author collated and calculated according to the relevant data of the Guangdong Statistical Yearbook, China City Statistical Year, China Science and Technology Statistical Yearbook, and various city statistical yearbooks and communique.

cities is as follows: there are 3 cities with moderate coordination level, 2 cities with basic coordination level, 15 cities with moderate dissonance level, 1 city with serious dissonance level, and no city reaches high coordination level. It can be seen that the synergistic interaction between the two internal indexes of each city still needs to be further improved. The coordination degree of Guangzhou, Shenzhen and Dongguan has always been at a high level, and the D value of the coordination degree reached 0.767, 0.786 and 0.606 respectively, which is in the moderate coordination stage and classified as the first level. This is closely related to its superior geographical location, rich resources, diversified industrial structure, convenient transportation and policy support. Driven by the radiation of core cities, the economic interaction of surrounding cities increased, and the spillover effect is obvious. The D values of Foshan and Zhuhai reached 0.563 and 0.411 respectively, which were at the basic coordination stage. Fifteen cities, including Zhongshan, Huizhou, Jiangmen, Shaoguan, Qingyuan, Zhaoqing, Jieyang, Shanwei and Zhanjiang, were in the moderate dissonance stage. These cities are classified as the second level. Yunfu City is the only city in the serious dissonance stage, with a D value of 0.191, which is classified into the third level. On the whole, the coordination level of 21 cities in Guangdong showed a descending spatial pattern from the first level to the third level.

4.2.2 A view from inner-city

To analyze the inter-annual variation trend of the coupling and coordination degree of the digital economy and green development in Guangdong cities, this paper further measures from the time series dimension and the results are shown in Table 3. The results show that the C value of the coupling degree between the two systems from 2013 to 2019 is between 0.105 and 0.999, with a large span. It indicates that the coupling degree between the digital economy and green development varies greatly from year to year. The coupling degree of each city shows an overall fluctuation rising trend. Some cities such as Shantou, Heyuan and Meizhou showed a "U-shaped" development trend, and the development was relatively slow from 2013 to 2016. After 2016, the coupling degree accelerated and the coupling trend became better year by year. In 2019, all cities reached the running-in coupling and highly coupling stages, indicating that with the timing development, the digital economy system and the green development system within each city began to

promote each other and check each other, showing the characteristics of the ordered development of resonance coupling. The main reason is that China is committed to accelerating the development of high-tech industries and strategic emerging industries, and many major scientific and technological achievements have reached the world's advanced level. In green development, new progress has been made in promoting an ecological civilization. Functional zones have been gradually improved, the discharge of major pollutants has been steadily reduced, and energy conservation and environmental protection have been significantly improved. Cities have responded to national policies and made positive contributions to the digital economy and green development.

Further analysis of the coordination degree between the digital economy and green development in Guangdong shows that the fluctuation of the D value of the coordination degree of all cities increased from 2013 to 2019, showing a good development trend. In 2013, D values of coordination degree ranged from 0.170 to 0.518, spanning three levels of serious dissonance, moderate dissonance and basic coordination. Six cities, including Shantou and Meizhou, reached the basic coordination level, accounting for about 29% of the overall proportion. Fourteen cities, including Guangzhou, Shenzhen and Zhuhai, were in the moderate dissonance level, accounting for 66% of the total. Only Jiangmen City is in the serious dissonance stage, accounting for about 5%. In 2016, the overall coordination degree of each city showed a slight increase, and the D value ranged from 0.398 to 0.695. Except for Foshan, whose coordination degree was 0.396, which was in the stage of moderate dissonance, the other cities reached the level of basic coordination and moderate coordination. In 2019, the coordination degree of all cities increased significantly, with the D value exceeding 0.7. There were 14 cities at moderate coordination level, accounting for 67% of the whole. There were 7 highly coordinated cities, accounting for about 33%. This shows that the digital economy level of the 21 cities in Guangdong province has been effectively improved, and the green development level has also achieved good results.

5 Conclusion and policy recommendations

This paper constructs an evaluation index system of the digital economy and green development to measure and analyze the comprehensive development level of the digital economy system and green development system in 21 cities of Guangdong province during 2013–2019 from the perspectives of intercity and inner city. This paper also reveals the spatiotemporal evolution characteristics of the coupling and coordination degrees of the two systems. The research in this paper shows that:

The characteristics of urban spatial pattern from the perspective of intercity. 1) Characteristics of comprehensive development level: From the perspective of intercity, there is a large gap between the digital economy development level and the green development level of each city. The digital economy development level of Guangzhou and Shenzhen is ahead of the green development level, while other cities lag behind the green development level, showing obvious regional differences. 2) Coupling characteristics: the coupling degree of the digital economy and green development in each city presents an unbalanced pattern of "centre-edge," and "Guangzhou-Foshan-Shenzhen-Dongguan" has become the core pole of the coupled development of the two systems in the province. 3) Coordination characteristics: the coordination degree of the two systems presents echelon distribution. Guangzhou, Shenzhen and Dongguan are the first levels; Fifteen cities, including Foshan, Zhuhai, Zhongshan, Huizhou, Jiangmen, Shaoguan, Qingyuan, Zhaoqing, Jieyang, Shanwei and Zhanjiang, are in the second level. Yunfu City is the third level.

Characteristics of temporal development from the perspective of the inner city. 1) Characteristics of comprehensive development level: The digital economy level and green development level of 21 cities in Guangdong showed an increasing trend from 2013 to 2019; while the digital economy is accelerating rapidly, the level of green development shows a fluctuating trend. 2) Coupling characteristics: The coupling degree of the digital economy and green development within each city can be roughly divided into two stages: steady development before 2016 and accelerated development after 2016. The coupling trend is getting better year by year, which indicates that the functions of the two systems within the city are deepening. 3) Coordination characteristics: From 2013 to 2019, the D value of the coordination degree between the digital economy and green development in each city increased, showing a good development trend. In 2013, the coordination degree was in three levels: serious dissonance, moderate dissonance and basic coordination. In 2019, the coordination degree of each city increased significantly, with the D value exceeding 0.7, which was between moderate coordination and high coordination.

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

5.1 Optimize resource allocation based on regional differences

Since the coupling level and coordination level of the digital economy and green development between different cities are significantly different, each city should implement a regional differentiation development strategy, based on its own reality, comprehensively consider the existing advantages and weaknesses, and make overall layout and scientific planning. On the one hand, efforts should be made to strengthen the leading role of Guangzhou, Shenzhen and the Pearl River Delta urban agglomeration, give full play to its advantages in the field of the digital economy, strengthen cooperation and exchanges with other cities in the field of the digital economy and green development, exert spillover effect, stimulate the development of surrounding cities, and eliminate the digital divide between regions. On the other hand, for the cities with weak digital economy foundation and dominated by traditional industries in the east, west and north of Guangdong, the government should give some support to the digital economy development in these areas, actively guide enterprises to use digital technologies to transform and upgrade traditional businesses in a multi-directional and whole-chain way, and promote enterprises to realize digital and intelligent transformation. At the same time, the government should encourage enterprises to adopt the concept of green production and green consumption, accelerate the promulgation of relevant policies and regulations, deepen the supervision system of ecological and environmental protection, implement the responsibility system of environmental governance, make green development

standardized and strict, and force enterprises to carry out green transformation.

5.2 Pursue innovation-driven development and unleash the potential for green development

Science and technology innovation is the foundation of the digital economy and an important driving force of green development. Therefore, scientific and technological innovation has become a breakthrough for the problem of disconnection between the digital economy and green development. Due to the long R&D cycle and slow benefits of technological innovation in the green field, problems such as insufficient endogenous impetus and insufficient innovation are prominent in the R&D of digital technologies in the green field. Therefore, colleges and universities should constantly improve training mechanisms, not only to cultivate senior R&D talents with the spirit of exploration, but also to focus on the training of senior technicians in related fields, integrate the green scientific spirit and green innovative thinking into education, and guarantee the talents for the green development. Enterprises, especially leading enterprises, should increase investment in green technology research, strengthen innovation in resource utilization technology, pollution control technology and clean energy development, promote digital and green development of enterprises, and build a green and circular production system. Finally, enterprises can cooperate with universities, scientific research institutions, industrial parks, etc., to jointly conduct technology research and development, jointly overcome the difficulties in green technology, and jointly promote the coordinated development of digitalization and greenization.

Due to the limitation of the length of this paper, this paper only discusses the dynamic evolution characteristics of the coupling and coordination relationship between digital economy and green development before the outbreak of COVID-19. However, it is well known that the digital economy has become an important driver of economic development in the post-epidemic era, and the interactive relationship between the digital economy and green development will also show new characteristics in the post-epidemic era. Therefore, to explore the differences and reasons of the coupling and coordination relationship between digital economy and green development before and after the epidemic, and to comprehensively examine the impact of COVID-19 on the interaction between digital economy and green development, is an important direction for further research in the future.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

XZ: Writing–original draft, Writing–review and editing. ZC: Writing–original draft, Writing–review and editing. BP: Writing–original draft, Writing–review and editing. TC: Writing–original draft, Writing–review and editing.

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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.

Publisher's note

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