

Article

Digital Economy, Spatial Imbalance, and Coordinated Growth: Evidence from Urban Agglomerations in the Middle and Lower Reaches of the Yellow River Basin

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Abstract

Amid the rapid evolution of the digital economy reshaping global competitiveness, China has advanced regional coordination through the Digital China initiative and the “Data Elements ×” Three-Year Action Plan (2024–2026). To further integrate digital transformation with high-quality growth in the urban agglomerations of the middle and lower Yellow River, this study aims to strengthen regional competitiveness, expand digital industries, foster new productivity, refine the development pathway, and safeguard balanced economic, social, and ecological progress. Taking the Yellow River urban clusters as the research object, a comprehensive assessment framework encompassing seven subsystems is established. By employing a mixed-weighting approach, entropy-based TOPSIS, hotspot analysis, coupling coordination models, spatial gravity shift techniques, and grey relational methods, this study investigates the spatiotemporal dynamics between the digital economy and high-quality development. The findings reveal that: (1) temporally, the coupling–coordination process evolves through three distinct phases—initial fluctuation and divergence (1990–2005), synergy consolidation (2005–2015), and high-level stabilization (2015–2022)—with the average coordination index rising from 0.21 to 0.41; (2) spatially, a persistent “core–periphery” structure emerges, while subsystem coupling consistently surpasses coordination levels, reflecting a pattern of “high coupling but insufficient coordination”; (3) hot–cold spot analysis identifies sharp east–west contrasts, with the gravity center shift and ellipse trajectory showing weaker directional stability but greater dispersion; and (4) grey correlation results indicate that key drivers have transitioned from economic scale and infrastructure inputs to green innovation performance and data resource allocation. Overall, this study interprets the empirical results in both temporal and spatial dimensions, offering insights for policymakers seeking to narrow the digital divide and advance sustainable, high-quality development in the Yellow River region.

Keywords: digital economy; high-quality development; combined weight method; spatial heterogeneity; grey correlation; coupling coordination



Academic Editor: Jianming Cai

Received: 3 September 2025

Revised: 25 October 2025

Accepted: 27 October 2025

Published: 31 October 2025

Citation: Li, Y.; Xu, B.; Wan, Y.; Li, Y.; Li, H. Digital Economy, Spatial Imbalance, and Coordinated Growth: Evidence from Urban Agglomerations in the Middle and Lower Reaches of the Yellow River Basin. *Sustainability* **2025**, *17*, 9743. <https://doi.org/10.3390/su17219743>

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1. Introduction

Since the implementation of the reform and opening-up policy, China’s pattern of economic development has evolved from an extensive growth approach toward one centered on efficiency and quality improvement. However, persistent spatial disparities—particularly the pronounced economic divide between eastern and western

regions—remain an enduring challenge [1]. As a new round of scientific and technological revolution unfolds, the digital economy has become a critical source of momentum for economic expansion and a central engine for promoting high-quality growth in China [2,3]. The 19th National Congress of the Communist Party of China affirmed that the country has entered a development stage that prioritizes quality-driven progress. According to the China Digital Economy Development Report (2023), the scale of China's digital economy reached 50.2 trillion yuan in 2022, representing a year-on-year increase of 10.3% and accounting for 41.5% of GDP. The convergence of computing power and communication technologies under the Internet era has fundamentally reshaped the circulation of information and driven profound structural transformation across industries [4]. The Decision of the Central Committee of the Communist Party of China on Further Deepening Reform and Advancing Modernization highlighted the need to accelerate institutional reform to support the growth of the digital economy, while improving the policy system for digital industrialization and the digital transformation of traditional sectors [5]. In 2023, the Overall Layout Plan for Building Digital China issued by the CPC Central Committee and the State Council underscored that digitalization is indispensable for enhancing China's international competitiveness [6]. One year later, the National Bureau of Statistics and other departments jointly introduced the Three-Year Action Plan for Data Elements × (2024–2026), which aims to integrate digital technologies deeply into the real economy, improve the utilization efficiency of data resources, and facilitate society-wide digital transformation [7]. Taken together, these policies demonstrate that the digital economy has become a pivotal force in driving China's modernization, industrial restructuring, and high-quality development. Yet, limited attention has been paid to how the digital economy interacts with the coordinated and high-quality growth of urban agglomerations. Therefore, investigating this linkage provides valuable insights for advancing the sustainable development of China's urban clusters.

Prior research has consistently confirmed that the digital economy contributes positively to national economic development and modernization [8,9]. Within the field of urban sustainability, existing studies have primarily examined how digitalization affects carbon emissions and green transformation, emphasizing themes such as digital innovation efficiency, green productivity, carbon abatement performance, total factor productivity enhancement, low-carbon transition pathways, and ecological efficiency improvement. Other research streams have sought to construct indices for evaluating digital economy development and to investigate its spatial mechanisms and diffusion effects [10–16]. Parallel investigations have linked the digital economy to various socio-environmental outcomes, including urban environmental pollution, residents' health conditions, the interplay between digitalization and green growth, the synergy between technological progress and eco-efficiency, industrial structure upgrading, and improvements in living standards. Spatial and temporal heterogeneity in the digital economy's development across city clusters has also been a central topic [17–21]. Collectively, this literature underscores the dual roles of the digital economy—as both a facilitator and a catalyst—in driving structural upgrading and sustainable transformation across multiple domains in China. Policy directions echo these academic findings. The 14th Five-Year Plan stresses the importance of “leveraging the leading role of central cities and urban agglomerations,” recognizing them as growth poles and strategic hubs for narrowing development disparities and promoting sustainable urban progress [22]. Empirical analyses likewise demonstrate that digital transformation substantially supports high-quality urban development [23]. European experience provides complementary insights: EU research shows that digital innovation substantially enhances public health services, environmental performance, and social welfare [24]. The establishment of digital innovation centers offers firms technological, managerial, and

ecosystem support for adopting digital tools, forming a multilayered innovation network through the coordination of regional, national, and EU-level initiatives [25]. Moreover, digital transformation has been identified as a key driver in strengthening the National Recovery and Resilience Plans (NRRPs) across member states and regions [26]. Regarding high-quality urban development, earlier studies have covered a wide range of subjects—from governance of urban land and spatial resources [27], challenges of urban renewal and transformation [28], spatial spillovers of new-type urbanization [29], and sustainable development pathways [30], to functional optimization, driving forces, and constraints in building high-quality urban systems [31,32]. Methodologically, these studies have adopted diverse analytical frameworks, including the construction of indicator systems, analysis of driving mechanisms, and validation of mediating effects. Frequently applied models include spatial spillover analysis [33], mediation effect models [34], coupling-coordination assessments [35], entropy-based and entropy-weighted TOPSIS methods [36,37], as well as spatial Durbin and panel threshold models [38,39]. Together, this body of work forms a robust theoretical and empirical foundation for the present study.

In conclusion, although previous research has established a valuable foundation, important gaps remain concerning the intrinsic synergistic mechanisms and spatiotemporal evolution between the digital economy and high-quality development within the urban agglomerations of the middle and lower Yellow River Basin—a region of strategic significance. Most existing analyses adopt single-direction or linear modeling frameworks, which do not adequately uncover the complex nonlinear interactions and spatial linkages that occur among interrelated subsystems. To address these limitations and enrich the theoretical exploration of how the digital economy and high-quality development interact in urban clusters, this study adopts an integrated analytical perspective. A multidimensional evaluation framework is constructed, consisting of seven subsystems: economic growth, shared prosperity, ecological progress, educational advancement, scientific and technological innovation, digital economy expansion, and digital industrialization. By embedding both the digital economy and high-quality development within a unified coupling–coordination analytical model, this research deepens the theoretical interpretation of their dynamic synergy. From a methodological standpoint, this study applies a combination of quantitative techniques—including the combined weighting approach, entropy-weighted TOPSIS, coupling coordination analysis, hot-spot detection, spatial gravity-center shift analysis, and grey correlation modeling—to develop a cross-validated comprehensive evaluation model. This framework allows a more precise identification of the intensity of intersystem linkages, spatial–temporal heterogeneity, and the driving mechanisms underlying coordinated growth. Empirically, the study selects six major urban agglomerations located in the middle and lower reaches of the Yellow River and 62 prefecture-level cities spanning 1990–2022. Based on this dataset, it establishes an indicator system for both digital-economy development and high-quality urban progress, and then empirically examines their interrelationships. Integrating these dimensions within a unified coupled-coordination framework enables analysis of their independent and joint influences on regional growth, as well as the spatial heterogeneity of such effects across different agglomerations. This approach provides a new pathway for resolving coordination challenges between digital-economic expansion and high-quality development, while extending existing research on their mutual evolution in China’s urban clusters.

2. Regional Overview and Research Methods

2.1. Regional Overview

The middle and lower reaches of the Yellow River are characterized mainly by plateaus and plains, with terrain gradually sloping from the elevated west to the lower-lying east.

The Loess Plateau, recognized as the largest of its kind globally, lies in the river's middle reaches (Figure 1). The climate belongs to the warm temperate continental monsoon zone, featuring hot, rainy summers, cold and dry winters, and relatively short transitional seasons. Average July temperatures exceed 24 °C in most areas, while January temperatures often fall below 0 °C. Spring is marked by a rapid warming trend, strong winds, and high evaporation, whereas autumn typically presents clear skies, cool breezes, and abundant sunshine. Annual precipitation ranges between 400 and 800 mm, with July and August contributing nearly 70% of the yearly total. Rainfall distribution exhibits strong seasonal variation, gradually decreasing from the southeast and south toward the northwest. This region is also the most densely populated and economically advanced stretch of the Yellow River basin, with superior infrastructure compared to other sections. Five provinces in the middle and lower reaches consistently rank among the top six provincial economies along the river, together generating a GDP of 23.04 trillion yuan, which represents about 75% of the basin's total output (Figure 2). The empirical indicators adopted in this study are primarily obtained from the China City Statistical Yearbook (1990–2022) and the China County Statistical Yearbook (1990–2022), complemented by geographic information extracted from the Earth Resources Data Cloud Platform (available at www.gis5g.com 20 September 2025).

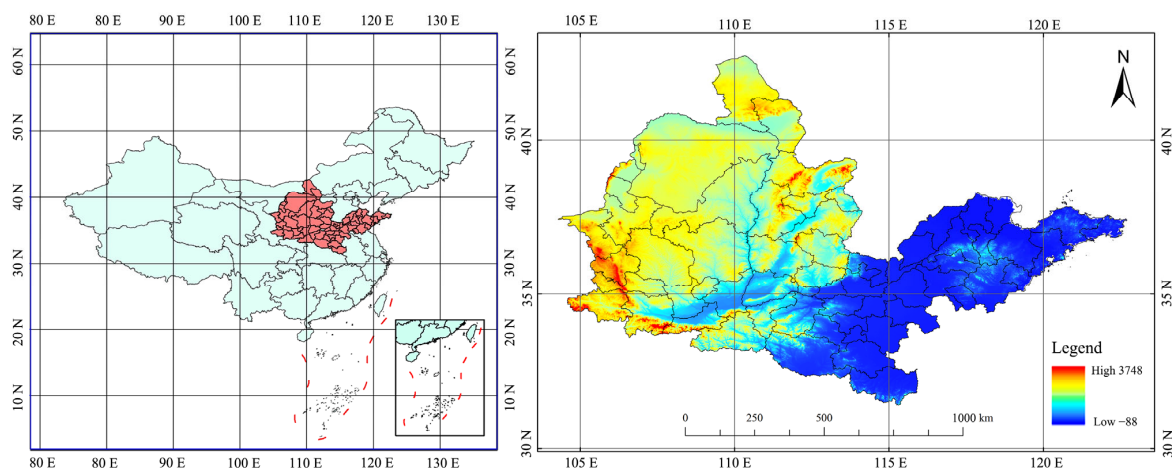


Figure 1. Elevation distribution of the study area.

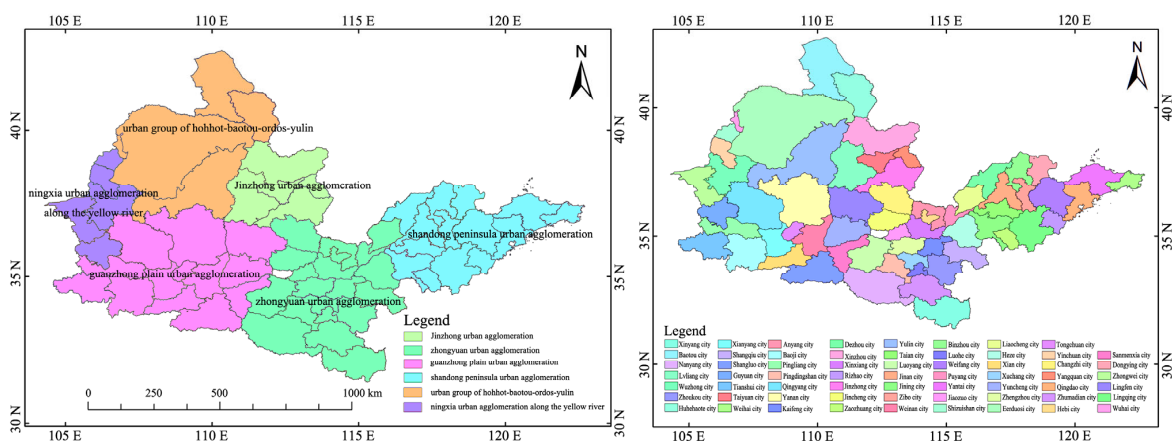


Figure 2. Spatial distribution of urban agglomerations.

Research Framework and Analysis Steps

This research proceeds through five major phases, as illustrated in Figure 3. First, we compiled and refined data indicators pertaining to urban agglomerations in the middle and lower reaches of the Yellow River Basin. These indicators were categorized into seven

dimensions of digital economy and high-quality development: economic performance, inclusive growth, green transition, educational advancement, scientific and technological innovation, digital economy expansion, and digital industrialization. Second, the relevant indicators of digital economy and high-quality development for the selected urban agglomerations were standardized and processed for subsequent quantitative analysis. Third, based on the research framework, we applied a suite of analytical techniques, including factor analysis, the entropy method, combined weighting, the entropy-weighted TOPSIS model, coupling coordination modeling, spatial hot–cold spot analysis, gravity-center shift analysis, and grey relational analysis. Fourth, using these methods, we identified the spatiotemporal variations in the coupling and coordination levels of the digital economy and high-quality development, analyzed the spatial distribution of hot and cold spots, examined gravity-center shifts, and extracted the driving factors shaping regional evolution patterns. Finally, the empirical findings were compared with existing domestic and international research to derive theoretical and policy implications. From this, we propose three key policy directions: establishing a “digital infrastructure + institutional innovation” collaborative regional development mechanism, optimizing a “core–periphery” gradient diffusion structure, and advancing “digital governance capacity modernization.” The study concludes with three principal findings, followed by a discussion of its limitations and suggestions for future research.

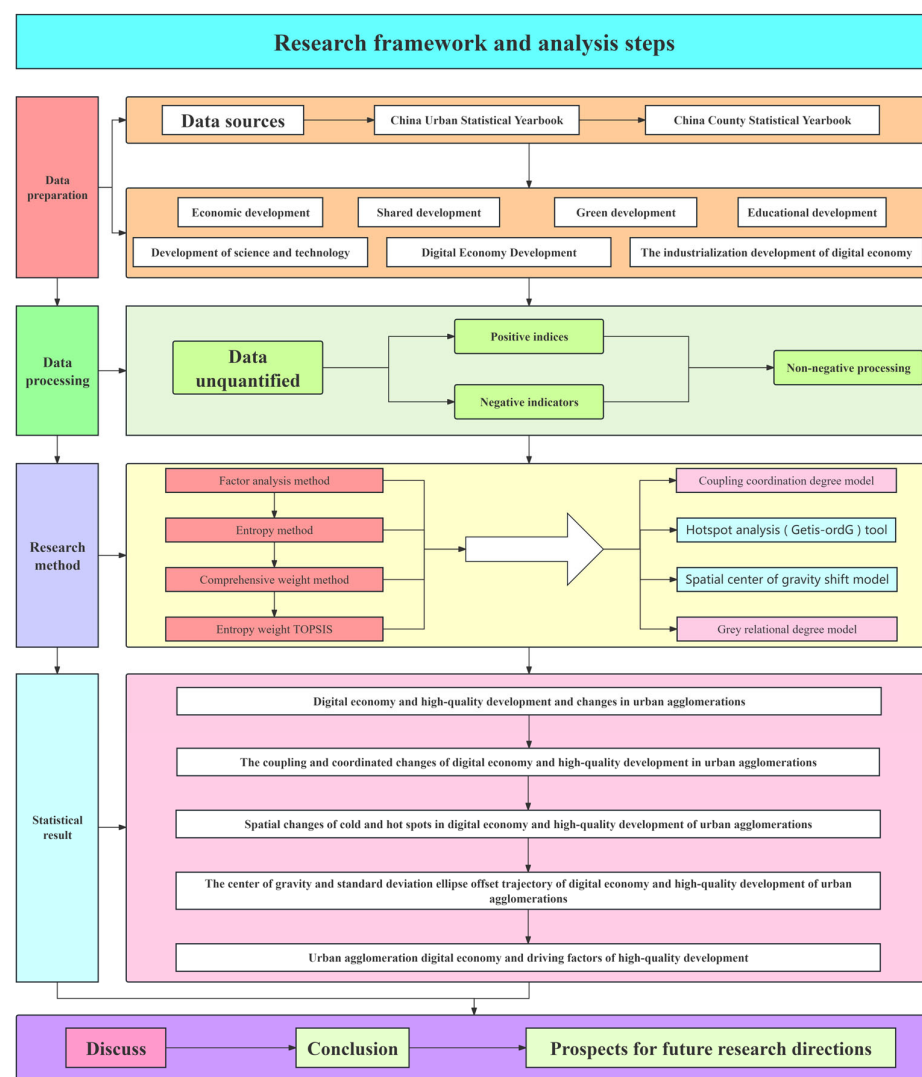


Figure 3. Research framework and analysis steps.

2.2. Research Methods

From a theoretical perspective, this study develops an integrated analytical framework drawing on new growth theory, sustainable development theory, new structural economics, and innovation system theory. New growth theory highlights innovation as the key driver of endogenous economic expansion [40]; sustainable development theory emphasizes the ultimate objective of harmonizing economic, social, and environmental systems [41]; new structural economics outlines the pathway of industrial upgrading under the joint role of effective markets and proactive government [42]; and innovation system theory stresses that innovation emerges through coordinated interaction among diverse actors [43]. Together, these perspectives provide the theoretical foundation of this study. Regarding data and indicator selection, the construction of the index system adheres to principles of availability, clarity, completeness, relevance, consistency, and scientific validity. The design also draws on prior research concerning regional integration of urban agglomerations [44], the digital economy's effects on land use [45], the role of digital governance in supporting high-quality urban development [46], and urban development measurement and factor analysis [47]. In addition, the framework is informed by existing studies on the efficiency of green development in Yellow River urban agglomerations, the coordination level of energy–economy–environment–technology systems, and ecological resilience [48–50].

2.2.1. Data Is Not Quantified

Dimensionless data: Since the selected indicators have different measurement units, the data are incomparable. Therefore, de-dimensionalization of each indicator can not only eliminate the dimensional relationship between variables, but also retain the relative meaning of the data.

- (1) Select n regions and m indicators, then the value of the j -th indicator in the i -th region is ($i = 1, 2, \dots, n; j = 1, 2, \dots, m$).
- (2) Standardize the indicators: First, standardize the data to eliminate the dimension effect. The initial matrix $X = x_{ij}, i = 1, 2, \dots, n; j = 1, 2, \dots, m$; i is the number of variables; j is the number of indicators. The indicators are divided into positive indicators and negative indicators for unscrupulous tempering treatment. The specific method is as follows:

$$\text{Positive indicators : } x_{ij} = \frac{x_{ij} - \min\{x_{1j}, \dots, x_{nj}\}}{\max\{x_{1j}, \dots, x_{nj}\} - \min\{x_{1j}, \dots, x_{nj}\}} \quad (1)$$

$$\text{Negative indicators : } x_{ij} = \frac{x_{ij} - \max\{x_{1j}, \dots, x_{nj}\}}{\max\{x_{1j}, \dots, x_{nj}\} - \min\{x_{1j}, \dots, x_{nj}\}} \quad (2)$$

Non-Negativity Treatment of Normalized Data

We assume that the normalized matrix is $R = (r_{ij})_{m \times n}$, where r_{ij} represents the normalized data. Since the normalized data has a value of 0, and the application of the logarithmic function in the entropy method requires that the value of 0 cannot appear, in order to eliminate this effect, we translate all elements of the normalized matrix R , that is, $r'_{ij} = r_{ij} + \varepsilon$, and at the same time ensure that the selected ε does not destroy the law of the original data, so the value of ε should be as small as possible. In this paper, ε is selected as 0.0001. The new matrix $R' = (r'_{ij})_{m \times n}$ is obtained.

2.2.2. Factor Analysis

The purpose of factor analysis is to simplify data, find out the basic data structure, and avoid the weight shift caused by the correlation between evaluation indicators. Therefore,

the prerequisite for using factor analysis is that the observed variables should have a strong correlation. If the correlation between variables is very small, the variables cannot share common factors, and the comprehensive ability of common factors for variables is weak. Therefore, before extracting common factors, the correlation between variables should be tested. SPSS26 provides two test methods: KMO test and Bartlett sphericity test.

In order to test whether the 46 indicator (variable) data are suitable for factor analysis, first perform a correlation test on them, and perform KMO test and Bartlett sphericity test on X1–X46 as shown in Table 1:

Table 1. KMO and Bartlett’s test.

KMO		0.915
Bartlett’s test of sphericity	Approximate Chi-Square	301,501.329
	Degrees of freedom (df)	1035
	Significance (p)	0.000

From Table 1, we can see that the chi-square value is 301,501.329, the degree of freedom is 1035, and the significance value is equal to 0.000, which meets the standard of less than 0.01, which shows that this group of data is suitable for factor analysis. The KMO test analyzes the correlation coefficient between variables. The closer the KMO sampling suitability value is to 1, the more suitable it is for factor analysis. The above table shows that the test value is 0.915, which means it is suitable for factor analysis. Combining the above two test results, it can be considered that this group of data is suitable for factor analysis.

2.2.3. Entropy Method

Calculate the proportion of the i th sample value under the j th index.

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^n X_{ij}} \quad (3)$$

Calculate the information entropy of each indicator

$$e_j = -K * \sum_{i=1}^n (P_{ij} * \ln(P_{ij})) \quad (4)$$

where $K = 1/\ln(n)$;

Information utility value d

$$d_j = 1 - e_j \quad (5)$$

Weight coefficient value w

$$w_j = \frac{d_j}{\sum_{j=1}^m d_j} \quad (6)$$

2.2.4. Combination Weight

Referring to previous research on factor analysis and entropy methods [51,52], based on the matrix concept, we use α and β to represent the relative importance of factor analysis weights and entropy method weights, respectively. The coefficients of factor analysis weights and entropy method weights are α_i and β_i , respectively, where $i = 1, 2, \dots, n$, and the formula is as follows:

$$\begin{cases} \alpha_i = v_i / (v_i + w_i) \\ \beta_i = w_i / (v_i + w_i) \end{cases} \quad (7)$$

where v_i is the weight obtained by factor analysis, and w_i is the weight obtained by entropy method.

Obtain the important coefficients A and D of subjective weight and objective weight; then, we can obtain the comprehensive weights G and H of each indicator, the formula is as follows:

$$Q_i = \frac{v_i \alpha_i + w_i \beta_i}{\sum_{i=1}^n (v_i \alpha_i + w_i \beta_i)} \quad (8)$$

Substituting the factor analysis weights and the entropy method weights obtained in SPSS26 into the above two formulas, we can finally obtain the comprehensive weights of the Yellow River high-quality development evaluation indicators, as shown in Table 2.

Table 2. Weights of digital economy and high-quality urban development indicators.

System Layer	Criteria Layer	Indicator Layer	Entropy Method	Factor Analysis	Comprehensive Weight
Coupling and coordination effects of digital economy and high-quality urban development	Economic Development	Regional GDP growth rate	0.001	0.015	0.013
		Gross Regional Product	0.027	0.028	0.024
		Number of industrial enterprises above designated size	0.019	0.024	0.019
		Number of foreign-invested enterprises	0.055	0.018	0.041
		Total fixed asset investment	0.036	0.025	0.028
		General fiscal revenue	0.035	0.027	0.028
		GDP per capita	0.019	0.023	0.019
	Shared Development	Number of employees at the end of the year	0.023	0.019	0.019
		Average salary of employees	0.016	0.026	0.020
		Number of hospitals and health centers	0.010	0.018	0.013
		Number of doctors	0.012	0.029	0.022
		Number of urban employees covered by basic pension insurance	0.016	0.026	0.020
		Number of participants in unemployment insurance	0.016	0.027	0.021
		Number of beds in social work institutions providing accommodation	0.013	0.019	0.015
	Green Development	Industrial sulfur dioxide emissions	0.001	0.017	0.014
		Industrial smoke emissions	0.000	0.014	0.013
		Industrial smoke and dust emissions	0.000	0.009	0.008
		Harmless treatment rate of domestic waste	0.005	0.017	0.013
		Comprehensive utilization rate of general industrial solid waste	0.004	0.016	0.012
		Centralized treatment rate of sewage treatment plants	0.002	0.016	0.013
		Annual average concentration of inhalable fine particulate matter	0.013	0.012	0.011
	Education Development	Education expenditure	0.026	0.026	0.023
		Number of employees in the culture, sports and entertainment industries	0.046	0.018	0.034
		Number of secondary vocational education/general colleges and universities	0.013	0.024	0.018
		Secondary vocational education/full-time teachers in general colleges and universities	0.046	0.024	0.034
		Number of college students per 10,000 people	0.017	0.020	0.017
		Public Library	0.007	0.025	0.019
		Public library books per 100 people	0.023	0.010	0.017
	Technological Development	Science spending	0.053	0.023	0.039
		Employment in the Information Transmission, Computer Services, and Software Sectors	0.036	0.029	0.029
		Employment in Scientific Research, Technical Services, and Geological Exploration Sectors	0.033	0.026	0.026
		Number of Employees Engaged in R&D Activities	0.031	0.023	0.024
		Internal R&D expenditure	0.055	0.011	0.043
		Number of patent applications	0.040	0.023	0.030

Table 2. Cont.

System Layer	Criteria Layer	Indicator Layer	Entropy Method	Factor Analysis	Comprehensive Weight
Coupling and coordination effects of digital economy and high-quality urban development	Digital Economic Development	Total Local Telephone Subscribers by Year-End	0.017	0.027	0.020
		Number of mobile phone users at the end of the year	0.026	0.028	0.024
		International Internet users	0.033	0.026	0.026
		Number of employees in transportation, warehousing, post and telecommunications industries	0.023	0.025	0.021
		Number of Internet broadband access users	0.036	0.029	0.029
	Industrial development of digital economy	The added value of the primary industry accounts for the proportion of GDP	0.008	0.025	0.019
		The added value of the secondary industry accounts for the proportion of GDP	0.003	0.016	0.012
		The added value of the tertiary industry accounts for the proportion of GDP	0.002	0.025	0.020
		Aggregate Profits of Industrial Enterprises above the Designated Size Threshold	0.009	0.022	0.016
		Aggregate Retail Sales of Consumer Goods	0.032	0.027	0.026
		Postal business volume	0.043	0.023	0.032
		Total telecommunications business	0.024	0.021	0.020

2.2.5. Summary of TOPSIS

Based on the indicator weighted matrix $R = (r_{ij})_{p \times q}$ constructed in Section 2.2.4 above, in Formula $r_{ij} = W_j \times P_{ij}$, we can determine the optimal solution Q_j^+ and the worst solution Q_j^- :

$$Q_j^+ = (\max r_{i1}, \max r_{i2}, \dots, \max r_{iq}) \quad (9)$$

$$Q_j^- = (\min r_{i1}, \min r_{i2}, \dots, \min r_{iq}) \quad (10)$$

Calculate the Euclidean distance d_i^+ and d_i^- between each measurement scheme and the optimal scheme Q_j^+ and the worst scheme Q_j^- :

$$d_i^+ = \sqrt{\sum_{j=1}^q (Q_j^+ - r_{ij})^2} \quad (11)$$

$$d_i^- = \sqrt{\sum_{j=1}^q (Q_j^- - r_{ij})^2} \quad (12)$$

Calculate the relative closeness of each measure scheme to the ideal scheme C_i :

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (13)$$

In the formula, the value of C_i is between 0 and 1, and the larger the value of C_i , the better the scheme. On the contrary, the worse the scheme.

2.2.6. Coupling Coordination Degree

To examine the interrelations and mutual constraints among the seven subsystems of digital-economy development and high-quality growth within the urban agglomerations of the middle and lower Yellow River Basin, this study employs the coupling-coordination model to evaluate the degree of coordinated development across the seven systems. The calculation is expressed as follows:

$$C = \frac{(\prod_{i=1}^n U_i)^{1/n}}{\frac{1}{n} \sum_{i=1}^n U_i} \quad (14)$$

The two-system case can be simplified to

$$C = \frac{2\sqrt{U_1 U_2}}{U_1 + U_2} \in [0, 1]$$

$$T = \sum_{i=1}^n W_i U_i \quad (15)$$

$$D = \sqrt{CT} \quad (16)$$

where C is the coupling degree; T is the comprehensive evaluation level; D is the coupling coordination degree; $U_i \in [0, 1]$ is the comprehensive index of the i -th subsystem; $W_i \geq 0$, $\sum_{i=1}^n W_i = 1$ is the weight of the i -th subsystem; n is the number of subsystems; D is the coupling coordination degree, and the value range is $[0, 1]$. The coupling coordination degree classification is shown in Table 3.

Table 3. Coupling coordination attitude grade division.

D	0~0.1	0.1~0.2	0.2~0.3	0.3~0.4	0.4~0.5
Coupling coordination	Extremely disordered	Serious disorder	Moderate Disorder	Mild disorder	On the verge of disorder
D	0.5~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
Coupling coordination	Barely out of tune	Primary Coordination	Intermediate Coordination	Good coordination	High-quality coordination

2.2.7. Spatial Distribution of Hot and Cold Spots

The Getis-Ord G_i^* statistic is employed to identify the spatial clustering of features with notably high or low values. Regions exhibiting significantly high values surrounded by similar high-value features are classified as hot spots, whereas those characterized by low values adjacent to other low-value features are defined as cold spots. The computation is expressed as follows:

$$G_i^* = \frac{\sum_{j=1}^n w_{ij} x_j - X^{-'} \sum_{j=1}^n w_{ij}}{S \sqrt{\frac{n \sum_{j=1}^n w_{ij}^2 - \left(\sum_{j=1}^n w_{ij} \right)^2}{n-1}}} \quad (17)$$

where w_j is the attribute value of feature j ; w_{ij} is the spatial weight between features i and j ; n is the total number of features; $X^{-'}$ is the mean of the indicator score; S is the standard deviation of the indicator score; G_i^* is the output statistic Z score.

2.2.8. Spatial Center of Gravity Shift Model

The concept of “center of gravity” in applied physics refers to the point where the gravity of each part of an object produces a resultant force. In the fields of geography and ecology, the concept of “center of gravity” is widely used. In this paper, the spatial shift change characteristics of the center of gravity and standard deviation ellipse of the center of gravity of the digital economy and high-quality development of each city in the urban agglomeration in the middle and lower reaches of the Yellow River can reflect the degree of change and trend of geographical phenomena [53]. The calculation formula is as follows:

$$G_\beta (x_\beta, y_\beta) = \frac{\sum [k_i \times M(x_i, y_i)]}{\sum k_i} \quad (18)$$

In the formula, G_β is the focus of the city’s digital economy and high-quality development; k_i is the digital economy and high-quality development of the i city; $M(x_i, y_i)$ is the coordinate of the geographic center.

2.2.9. Grey Correlation

Correlation coefficient

$$Q_{ij} = \frac{\min_j \times \min_k \times \Delta_{ij}(k) + \beta \times \max_j \times \max_k \times \Delta_{ij}(k)}{\Delta_{ij}(k) + \beta \times \max_j \times \max_k \times \Delta_{ij}(k)} \quad (19)$$

Q_{ij} is the grey correlation coefficient; $\Delta_{ij}(k) = x_i(k) - x_j(k)$ is the absolute difference between sequence $i\{x_i(k)\}$ and sequence $j\{x_j(k)\}$ at point k ; $\min_j \times \min_k \times \Delta_{ij}(k)$ is the minimum difference between the two poles; $\max_j \times \max_k \times \Delta_{ij}(k)$ is the maximum difference between the two poles; β is the resolution coefficient, its value is 0~1, take $\beta = 0.5$.

Grey relational degree

$$P_{ij} = \frac{1}{n} \sum_{k=1}^n Q_{ij}(k) \quad k = 1, 2, 3, \dots, n \quad (20)$$

3. Results

3.1. Ranking of Digital Economy and High-Quality Development of Urban Agglomerations

Supplementary Materials Table S1 presents the ranking outcomes for cities located in the middle and lower reaches of the Yellow River Basin, assessed according to their levels of digital-economy development and high-quality growth. Overall, regional disparities widened throughout the observation period, and spatial inequality became increasingly evident. Between 1990 and 2000, the highest-ranked cities were largely concentrated in the core areas of major urban agglomerations—most notably Jinan, Qingdao, Tai'an, Zhengzhou, Xi'an, Yinchuan, and Hohhot. Cities with upper- or middle-tier performance were mainly distributed across the Shandong Peninsula, the Central Plains, and the Guanzhong Plain regions. From 2000 to 2010, the range of leading urban clusters expanded further. Besides the Shandong Peninsula, Central Plains, and Guanzhong Plain, pivotal node cities within the Ningxia Yellow River and the Hohhot–Baotou–Ordos–Yulin urban agglomerations—such as Yinchuan and Hohhot—began to emerge among the top performers. During this decade, Qingdao, Jinan, Yantai, and Taiyuan consistently climbed in the rankings, reflecting the rapid progress of key provincial capitals and regional hubs. In the subsequent period, 2010–2022, high-ranking cities became increasingly concentrated within three principal urban agglomerations: the Shandong Peninsula, the Central Plains, and the Guanzhong Plain. Their provincial capitals occupied dominant positions, underscoring intensified spatial differentiation and stronger agglomeration effects. Meanwhile, the Ningxia Yellow River and Hohhot–Baotou–Ordos–Yulin urban clusters maintained moderate yet stable development, but the performance gap relative to the three eastern agglomerations continued to widen. This trend highlights the deepening spatial imbalance of digital-economy and high-quality development across the middle and lower reaches of the Yellow River Basin.

3.2. Coupling and Coordination Between Digital Economy and High-Quality Development

Figure 4 illustrates the spatiotemporal evolution of the coupling and coordination relationship between the digital economy and high-quality development within the urban agglomerations of the middle and lower Yellow River Basin. During the period 1990–2005, the system demonstrated a pattern of “high coupling but low coordination.” The coupling-coordination degree remained around 0.2, suggesting a state of moderate disequilibrium. This indicates that, although the two systems were closely linked, their positive interactions had not yet materialized. After 2005, both the coordination level and the coupling-coordination degree showed a marked upward trend, approaching con-

vergence by 2022. Since 2015, the system has entered an initial stage of coordinated development, advancing to an intermediate-coordination phase after 2020. These dynamics reveal a substantial improvement in synergy between the digital economy and high-quality development since 2015, reflecting a clear tendency toward synchronous and mutually reinforcing optimization.

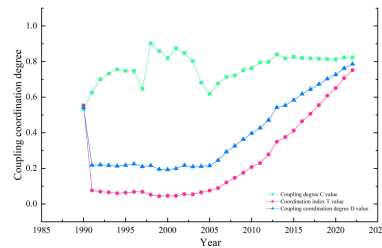


Figure 4. Coupling and coordination of spatiotemporal changes.

Figure 5 depicts the dynamic coupling–coordination relationship between economic development and the high-quality advancement of the digital economy across the urban agglomerations situated in the middle and lower reaches of the Yellow River Basin. From 1990 to 2022, both the coordination level and the coupling–coordination degree between economic development and each subsystem exhibited a consistent upward trajectory, whereas the coupling degree itself remained relatively stable. Prior to 2005, the interaction between the systems followed a typical “high coupling but low coordination” pattern. During this stage, the coupling–coordination degree was mostly within the moderately unbalanced interval of 0.1–0.3, suggesting that although the systems were tightly linked, effective coordination had not yet been achieved. After 2005, the coordination level rose markedly, with both the coordination and coupling–coordination degrees increasing rapidly and nearing the coupling level by 2022. This indicates a substantial improvement in inter-system compatibility and the gradual establishment of a mutually reinforcing relationship. By 2022, economic development had reached a state of high-level coordination with digital industrialization, digital-economy expansion, green transformation, and shared development, while maintaining an intermediate coordination relationship with scientific and technological progress and educational development.

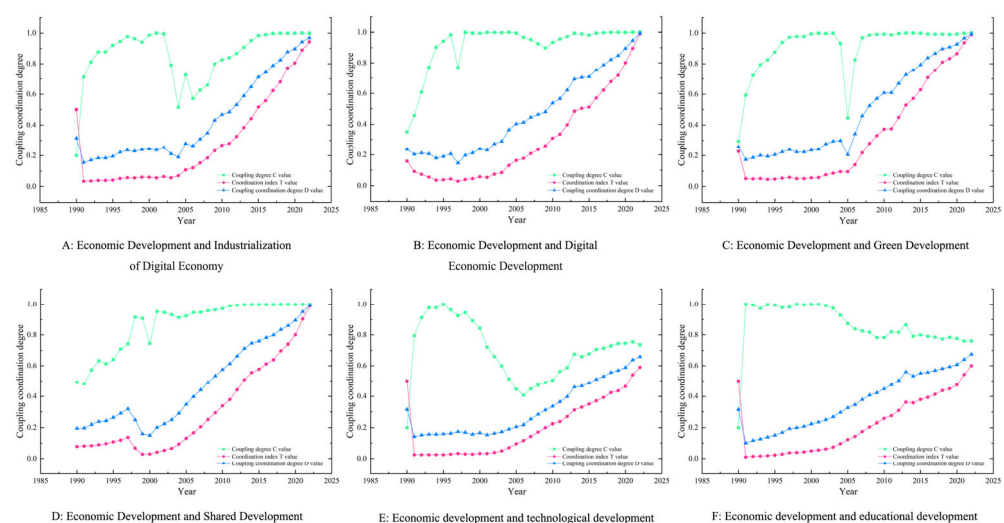


Figure 5. Coupling diagram of economic development and other sub-items.

Figure 6 illustrates the coupling–coordination dynamics between shared development and the high-quality development of digital-economy subsystems within the urban agglomerations located in the middle and lower reaches of the Yellow River Basin. Over

the period 1990–2022, both the coordination level and the coupling–coordination degree between shared development and other subsystems displayed a steady upward trajectory, whereas the coupling degree itself experienced only minor fluctuations. Prior to 2005, the systems exhibited a characteristic “high coupling yet low coordination” state, with coupling–coordination values generally ranging from 0.1 to 0.3—corresponding to a condition of moderate to severe disequilibrium. This pattern suggests that, despite strong interconnections among subsystems, synergistic effects remained weak. Following 2005, both the coordination and coupling–coordination degrees rose sharply, converging toward the coupling level by 2022. Inter-system adaptability improved markedly during this stage, and a progressively positive interactive mechanism began to take shape. By 2022, shared development had reached high-level coordination with digital industrialization, digital-economy expansion, and green development, while maintaining primary coordination relationships with technological and educational development.

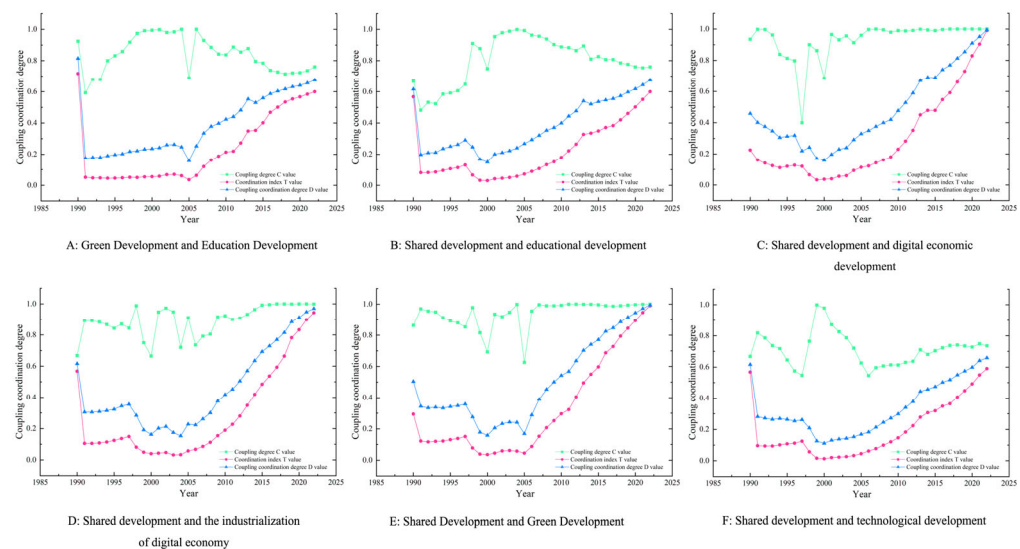


Figure 6. Coordination diagram of shared development and other sub-items.

Figure 7A–F presents the coupling–coordination relationships among the green development, educational development, and high-quality digital-economy subsystems within the urban agglomerations of the middle and lower reaches of the Yellow River Basin. From 1990 to 2022, both the coordination level and the coupling–coordination degree of these subsystems exhibited an overall upward trajectory, although variations in the coupling degree were more irregular. Before 2005, the interaction pattern could be characterized as “high coupling yet low coordination,” with coupling–coordination values mostly between 0.1 and 0.3, signifying conditions ranging from moderate to severe imbalance. This suggested close linkages between the systems but limited synergistic effects. After 2005, both indicators improved substantially, and a progressively positive interactive mechanism began to emerge, indicating that coordination and coupling strength evolved in tandem. By 2022, green development demonstrated marked advancement—achieving good coordination with digital-industry development, high-quality coordination with overall digital-economy progress, and initial coordination with scientific and technological development. In contrast, educational development attained only primary coordination with digital-economy growth and continued to display a pronounced misalignment with digital-industry development, revealing a structural disconnect between the education system and the demands of digital-industry transformation.

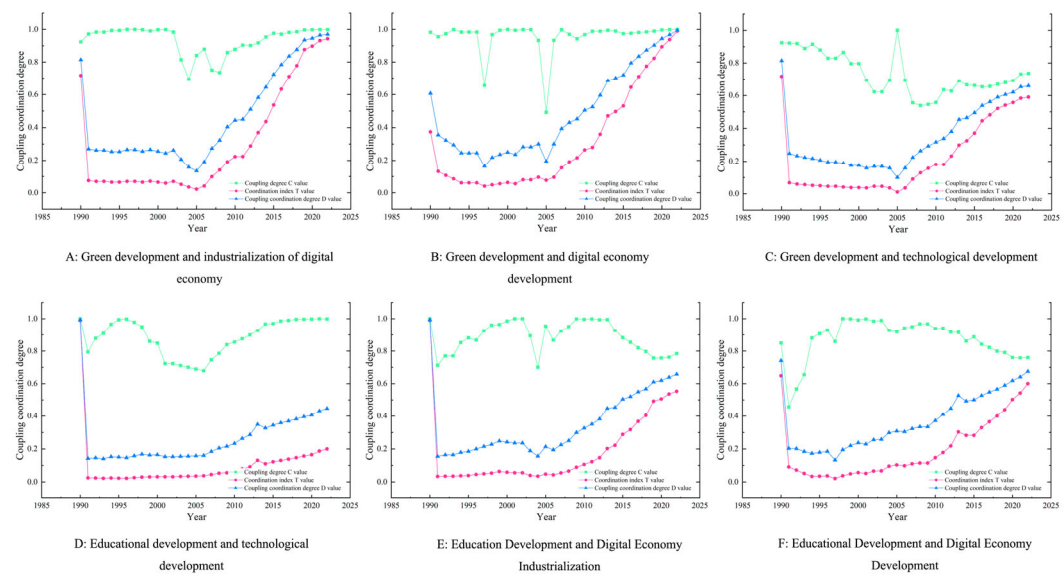


Figure 7. Coupling diagram of green development and other sub-items.

Figure 8A–C illustrate the coupling–coordination dynamics among scientific and technological development, digital-economy growth, and digital-industry expansion within the urban agglomerations of the middle and lower Yellow River Basin. From 1990 to 2022, both the coordination level and the coupling–coordination degree across these subsystems demonstrated a consistent upward trajectory, although the coupling degree itself fluctuated to some extent. Prior to 2005, the systems displayed the typical pattern of “high coupling but low coordination,” with coupling–coordination values mainly concentrated between 0.1 and 0.3, suggesting moderate to severe disequilibrium. This stage reflected close inter-system connections but a lack of substantial synergistic reinforcement. Following 2005, the coordination and coupling–coordination degrees rose together, indicating enhanced adaptive interactions and the gradual establishment of a mutually beneficial relationship among the subsystems. By 2022, scientific and technological development had entered a stage of primary coordination with both digital-industry development and overall digital-economy progress, as well as with green development. Meanwhile, the digital-economy development and digital-industry subsystems advanced further to achieve a high-quality coordination level, underscoring stronger integration within the regional innovation ecosystem.

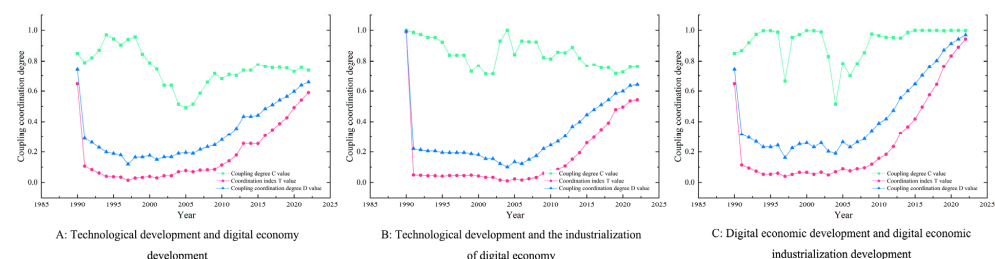


Figure 8. Coupling diagram of scientific and technological development and other sub-items.

3.3. Spatial and Temporal Variation Trends of Hot and Cold Spots

Figure 9 depicts the spatial distribution of hot and cold spots in the digital-economy and high-quality development levels of urban agglomerations located in the middle and lower reaches of the Yellow River Basin. Over the study period, the regional spatial pattern displayed distinct polarization and continuous evolution: hot spots increasingly concentrated toward the eastern region, whereas cold spots persisted in the central and western parts, resulting in a stronger degree of spatial differentiation. In 1990 (Figure 9A),

hot and sub-hot spot areas were mainly concentrated within the Shandong Peninsula urban agglomeration, as well as portions of the Central Plains, the Guanzhong Plain, and the Hohhot–Baotou–Ordos–Yulin urban cluster. Conversely, cold and sub-cold spots were found primarily in central Shanxi, the Ningxia segment of the Yellow River Basin, the Hohhot–Baotou–Ordos–Yulin region, and northern Central Plains, forming an initial southeast–northwest spatial contrast. By 1995 (Figure 9B), the cold-spot areas expanded further, covering most of central Shanxi, Ningxia, northwestern Central Plains, and the northern Guanzhong Plain, reinforcing the southeast–northwest differentiation pattern. Between 2000 and 2010 (Figure 9C–E), hot spots contracted sharply and became concentrated across the Shandong Peninsula, with smaller clusters appearing in parts of the Central Plains and Guanzhong Plain. Cold-spot zones continued to expand, extending across large portions of central and western China and gradually forming an east–west differentiation structure with the Central Plains urban agglomeration serving as the transitional boundary. From 2015 to 2022 (Figure 9F–H), the distribution of hot spots remained relatively stable, centering around the Shandong Peninsula and the major cities of the Central Plains and Guanzhong Plain. Cold spots were consistently observed in central Shanxi, along the Yellow River in Ningxia, throughout the Hohhot–Baotou–Ordos–Yulin corridor, and in the northern Guanzhong Plain, extending into much of the Central Plains. Transitional zones appeared sporadically between these clusters. Overall, the spatial evolution reveals that hot spots shifted markedly eastward throughout the observation period, while cold spots consolidated in the central and western regions. This persistent east–west polarization underscores deepening regional disparities in the digital-economy and high-quality development of the Yellow River Basin’s middle and lower reaches.

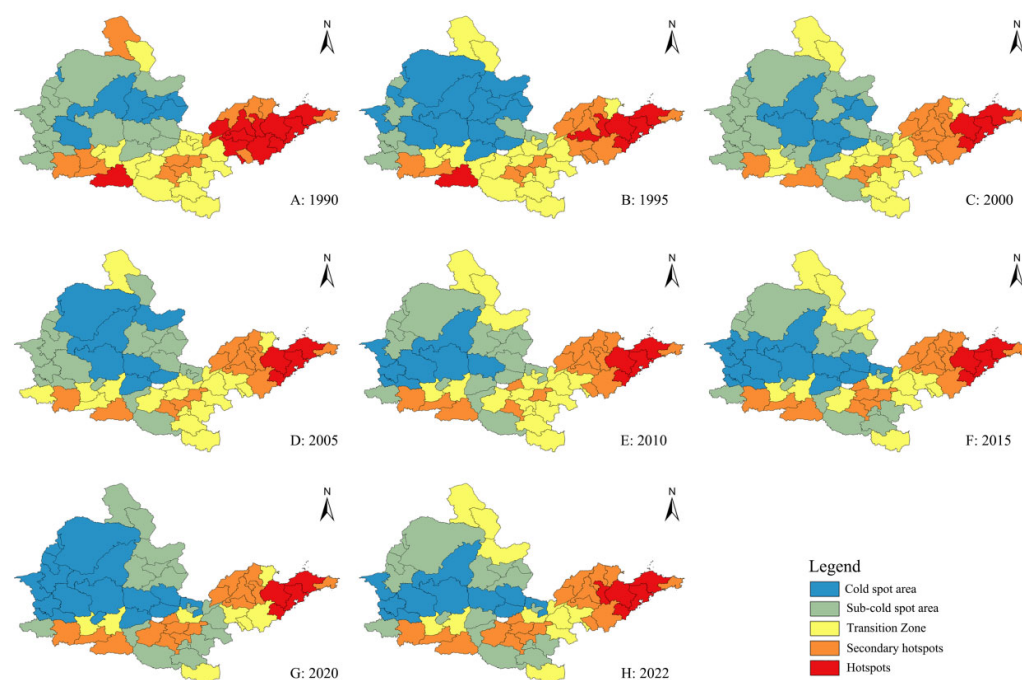


Figure 9. Spatial and temporal changes of hot and cold spots.

3.4. Center of Gravity and Standard Deviation Ellipse Offset Trajectory

Marked spatial imbalances are evident in the digital economy and high-quality development of urban agglomerations in the middle and lower reaches of the Yellow River. The gravity center is mainly located in Shangdang District of Changzhi City, Shanxi Province, and its migration path can be divided into four distinct stages (Figure 10). From 1990 to 2000, it shifted northwestward; between 2000 and 2010, it moved to the northeast; during

2010–2020, the trajectory turned southward; and from 2020 to 2022, it again shifted north-eastward. The morphology of the standard deviational ellipses shows a similar four-stage evolution: first northwestward, then northeastward, later southward, and finally north-eastward, which aligns with the migration of the gravity center. These patterns reveal that the spatial distribution of the digital economy and high-quality development in the region has become less directional while exhibiting greater dispersion. In other words, the misalignment between the gravity center and the standard deviation ellipse is gradually moving eastward within the urban agglomerations of the middle and lower Yellow River.

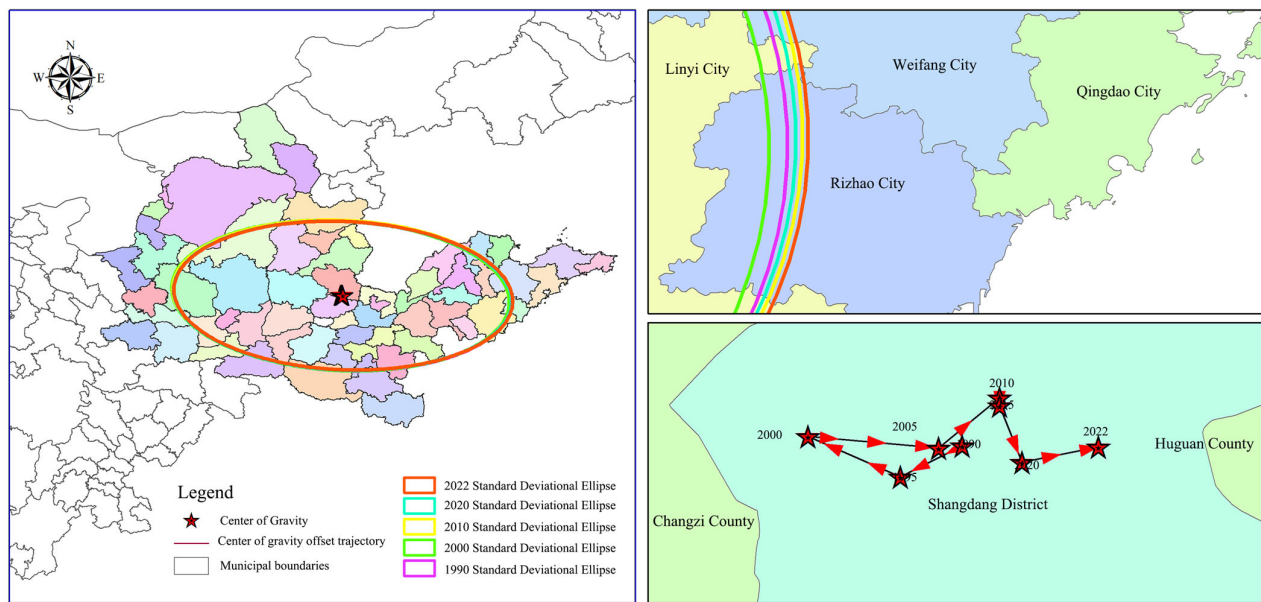


Figure 10. Center of gravity and standard deviation ellipse deviation trajectory.

3.5. Digital Economy and Driving Factors of High-Quality Development in Urban Agglomerations

Table 4 presents the correlations between the driving factors of the digital economy and high-quality development in urban agglomerations of the middle and lower Yellow River. Over the study period, the dominant drivers experienced notable shifts, reflecting phased adjustments in regional development priorities. In 1990, the leading factors included per capita GDP, the number of hospitals and health centers, employment in information transmission, computer services and software industries, the harmless disposal rate of domestic waste, and the number of large industrial enterprises. These findings suggest that economic growth and technological progress exerted the strongest influence, while healthcare and environmental governance played supporting roles. By 1995, the key factors shifted to hospitals and health centers, education expenditure, per capita GDP, employment in the information and software sectors, and the number of public libraries, underscoring the rising importance of healthcare, education, and culture, alongside continued contributions from science, technology, and economic development.

During 2000–2005, public libraries, hospitals and health centers, education spending, per capita GDP, and waste disposal efficiency emerged as the primary factors. The roles of education, healthcare, and green development became increasingly prominent, while the weight of per capita GDP declined. From 2010 to 2022, the harmless treatment rate of domestic waste, public library numbers, education expenditure, annual average concentration of fine particulate matter, and regional per capita GDP constituted the main drivers. With the advancement of development levels, the emphasis gradually shifted from economic expansion, technological progress, and healthcare toward green transformation, cultural-educational development, and shared well-being. This trajectory reflects a strate-

gic transition of the region from growth-centered priorities to a model oriented toward ecological sustainability, innovation, cultural progress, and inclusive development.

Table 4. Grey correlation analysis.

1990	Ranking	1995	Ranking	2000	Ranking	2005	Ranking
GDP per capita	1	Number of hospitals and health centers	1	Number of public libraries	1	Number of public libraries	1
Number of hospitals and health centers	2	Education expenditure	2	Number of hospitals and health centers	2	Education expenditure	2
Number of employees in information transmission, computer services and software industries	3	GDP per capita	3	Education expenditure	3	Harmless treatment rate of domestic waste	3
Harmless treatment rate of domestic waste	4	Number of employees in information transmission, computer services and software industries	4	GDP per capita	4	Number of hospitals and health centers	4
Number of industrial enterprises above designated size	5	Number of public libraries	5	Harmless treatment rate of domestic waste	5	GDP per capita	5
Number of public libraries	6	Harmless treatment rate of domestic waste	6	Number of employees in information transmission, computer services and software industries	6	Postal business volume	6
Number of employees in transportation, warehousing, post and telecommunications industries	7	Number of industrial enterprises above designated size	7	Number of industrial enterprises above designated size	7	Number of employees in information transmission, computer services and software industries	7
Total telecommunications business	8	Number of employees in transportation, warehousing, post and telecommunications industries	8	Science spending	8	Annual average concentration of inhalable fine particulate matter	8
Education expenditure	9	Total telecommunications business	9	Annual average concentration of inhalable fine particulate matter	9	Science spending	9
Postal business volume	10	Postal business volume	10	Total telecommunications business	10	Total telecommunications business	10
Annual average concentration of inhalable fine particulate matter	11	Science spending	11	Number of employees in transportation, warehousing, post and telecommunications industries	11	Number of employees in transportation, warehousing, post and telecommunications industries	11
Science spending	12	Annual average concentration of inhalable fine particulate matter	12	Postal business volume	12	International Internet users	12
International Internet users	13	International Internet users	13	International Internet users	13	Number of industrial enterprises above designated size	13

Table 4. Cont.

2010	Ranking	2015	Ranking	2020	Ranking	2022	Ranking
Harmless treatment rate of domestic waste	1	Harmless treatment rate of domestic waste	1	Harmless treatment rate of domestic waste	1	Harmless treatment rate of domestic waste	1
Number of public libraries	2	Number of public libraries	2	Annual average concentration of inhalable fine particulate matter	2	Annual average concentration of inhalable fine particulate matter	2
Education expenditure	3	Annual average concentration of inhalable fine particulate matter	3	Number of public libraries	3	Number of public libraries	3
Annual average concentration of inhalable fine particulate matter	4	Education expenditure	4	GDP per capita	4	GDP per capita	4
Number of hospitals and health centers	5	GDP per capita	5	Education expenditure	5	Education expenditure	5
Postal business volume	6	Number of hospitals and health centers	6	International Internet users	6	Number of hospitals and health centers	6
GDP per capita	7	International Internet users	7	Number of hospitals and health centers	7	International Internet users	7
International Internet users	8	Total telecommunications business	8	Number of industrial enterprises above designated size	8	Total telecommunications business	8
Number of employees in information transmission, computer services and software industries	9	Number of employees in transportation, warehousing, post and telecommunications industries	9	Total telecommunications business	9	Number of industrial enterprises above designated size	9
Science spending	10	Postal business volume	10	Number of employees in transportation, warehousing, post and telecommunications industries	10	Number of employees in transportation, warehousing, post and telecommunications industries	10
Number of employees in transportation, warehousing, post and telecommunications industries	11	Number of industrial enterprises above designated size	11	Postal business volume	11	Postal business volume	11
Total telecommunications business	12	Number of employees in information transmission, computer services and software industries	12	Science spending	12	Science spending	12
Number of industrial enterprises above designated size	13	Science spending	13	Number of employees in information transmission, computer services and software industries	13	Number of employees in information transmission, computer services and software industries	13

4. Discussion

This study establishes an integrated evaluation framework to assess the digital economy and high-quality development in the middle and lower reaches of the Yellow River Basin, revealing nonlinear synergistic mechanisms and threshold characteristics between the two systems. In this way, it extends beyond the explanatory limits of conventional linear-driving theories. Earlier research primarily emphasized the unidirectional promoting effect of the digital economy on regional economic growth, confirming its significant positive spatial spillover on development outcomes [2,54–57]. In contrast, our empirical analysis demonstrates that when digital-technology penetration surpasses the critical value

of 0.4, the coupling–coordination index increases sharply in an exponential manner. This finding validates the “technology–institutional synergy threshold hypothesis” [58] and resonates with Krugman’s core–periphery framework, highlighting how digital diffusion and institutional adaptation jointly reshape regional coordination dynamics.

The spatial disparities observed in the Yellow River Basin arise not only from geographic gradients but also from mismatches between digital economy expansion and high-quality development [59]. Ding et al. [57] argued that China’s overall level of digital economy and high-quality development remains modest, characterized by coexistence of high and low agglomeration, and strong alignment between spatial dependence and spatial lock-in. Based on an eight-year panel of 108 Yangtze River Economic Belt cities, Luo et al. [10] demonstrated that the digital economy significantly enhances green development efficiency (GDE), indirectly advancing GDE through technological innovation, human capital accumulation, and industrial upgrading. Similarly, Zhu et al. [60] showed that in Hangzhou, the pace of urban expansion closely parallels the spatial layout of the digital economy, underscoring its greater role in shaping urban spatial structure compared with conventional urbanization. These findings resonate strongly with the spatial dynamics observed in the Yellow River’s middle and lower reaches, reinforcing the pivotal role of the digital economy in regional development trajectories.

The main drivers of development in the urban agglomerations of the middle and lower Yellow River have shifted over time: from an initial reliance on per capita GDP as the dominant force, toward a broader emphasis on factors such as waste treatment efficiency, annual average PM_{2.5} concentration, employment in information and software services, international Internet penetration, education expenditure, public libraries, and hospitals. This evolution highlights the growing importance of green, technological, educational, and shared development dimensions. It also indicates that advancing the “technology–industry–institution” nexus is essential for overcoming regional development bottlenecks. Yang et al. [61], through a coupling–coordination analysis of the digital economy and green agricultural growth in major grain-producing areas, observed a transformation from “incoordination” to “coordination,” confirming the digital economy’s significant role in agricultural green development. Tang et al. [62] further demonstrated that the allocation of data factors constitutes a critical channel for enhancing urban quality through digitalization. Zhu et al. [60] emphasized that policy-driven models remain indispensable to urban progress, while evidence also shows that the digital economy directly promotes green total factor productivity (GTFP) [63]. Other studies corroborate this role in sustainable transitions. Wang et al. [64] found that innovations and applications within the digital economy, alongside economic expansion and job creation, exert mixed effects—positively supporting high-quality urban development but simultaneously adding to CO₂ emissions. Nonetheless, the expansion of the service sector and the advancement of green technologies significantly mitigate these pressures. Similarly, Zhang et al. [65] confirmed that China’s digital economy has become a crucial driver of low-carbon development, with environmental governance, innovation, and industrial upgrading as the main pathways. More broadly, the digital economy’s contribution to low-carbon and sustainable urban transitions is widely recognized [64]. At the same time, in the context of the continued development of the digital economy and high-quality development, potential endogeneity problems [66–68] and spatial autocorrelation problems [69–71] are increasingly receiving attention in research and are one of the important contents to ensure the authenticity and scientificity of regional research. In sum, the interplay of technology, industry, and institutions emerges as a fundamental prerequisite for breaking through regional growth constraints. Building on this recognition, this study proposes the following policy recommendations.

First, a regional collaborative development mechanism integrating digital infrastructure construction with institutional innovation should be established. Priority should be given to fostering emerging digital-economy industries in urban agglomerations with relatively low coordination levels—such as the Jinzhong Urban Agglomeration and the Ningxia Yellow River Urban Agglomeration. It is essential to advance the creation of cross-provincial, inter-city, and inter-agglomeration platforms that enable joint development, co-governance, and shared utilization of data resources. Furthermore, the implementation of a “digital-economy enclave” cooperative development model can be explored as a pilot initiative. Through the optimization of tax frameworks and the provision of preferential land use policies, eastern China’s high-growth digital enterprises can be encouraged to expand westward, establishing operations in these regions. Such measures will facilitate the diffusion of digital innovation, thereby accelerating the digital transformation and high-quality development of the urban agglomerations across the middle and lower reaches of the Yellow River Basin.

Second, optimize the “core-periphery” gradient diffusion system. Prioritize the establishment of national-level digital industry innovation centers in provincial core cities such as Jinan, Zhengzhou, Xi’an, Taiyuan, Yinchuan, and Qingdao to strengthen their radiating influence on surrounding cities. Establish a “digital industry counterpart support” mechanism, requiring high-coordination cities to transfer at least 1% of digital technology patents annually to low-coordination cities. Implement a regional development model based on individual cities, industrial clusters, and urban agglomerations, strengthening the complementary advantages and mutual benefits among urban agglomerations and creating new forms of digital cooperation and win-win outcomes.

Third, efforts should focus on modernizing digital governance. It is necessary to construct a “monitoring–early warning–response” mechanism for the digital economy, covering 62 prefecture-level cities and six major urban agglomerations, to track in real time the degree of coordination between digital economy development and high-quality growth in the middle and lower reaches of the Yellow River. In addition, a high-tech incubation platform for the digital economy should be established to nurture and support innovative SMEs not yet fully captured by conventional indicators. Parallel to this, talent training programs that integrate digital technology with green economy skills should be promoted, thereby strengthening the foundation for advancing both the digital economy and high-quality development in the region.

Despite its contributions, this research still has certain limitations. First, concerning data, the analysis primarily relies on official publications such as the China City Statistical Yearbook and the China County Statistical Yearbook. Changes in statistical definitions and the omission of specific indicators may introduce potential measurement bias. Second, regarding indicator design, some latent dimensions—such as institutional context, governance efficiency, and regional digital divides—are not fully captured, which may constrain result precision. Third, in terms of temporal coverage, the study employs panel data spanning 1990–2022, allowing for an examination of long-term spatiotemporal evolution in coupling coordination. Nevertheless, with ongoing transformations in policy orientation, technological progress, and regional structures, the temporal generalizability of these results should be interpreted with caution. Finally, from a methodological standpoint, although the coupling–coordination model, combined weighting, entropy-weighted TOPSIS, and grey relational analysis shed light on system interactions, they are limited in explaining nonlinear dynamics and spatial spillover effects. Future research could address these gaps by incorporating spatial econometric approaches and dynamic threshold modeling to deepen and broaden the analytical framework.

5. Conclusions

This research constructs an integrated evaluation framework to measure the coupling and coordination relationship between the digital economy and high-quality development within the urban agglomerations of the middle and lower Yellow River Basin. The framework encompasses seven interrelated subsystems: economic growth, inclusive development, green transformation, educational advancement, scientific and technological innovation, digital-economy expansion, and digital industrialization. Employing a combination of quantitative approaches—including the composite weighting method, entropy-weighted TOPSIS, spatial gravity-center model, hot–cold spot analysis, and the coupling–coordination model—the study identifies and interprets the spatiotemporal interaction patterns linking digital-economic progress with high-quality regional development. The core empirical findings can be summarized as follows:

First, the coupling–coordination degree exhibits a three-stage evolutionary pattern of “fluctuating differentiation—synergistic strengthening—advanced equilibrium.” In all stages, the coupling level of each subsystem remains higher than both the coordination degree and the overall coupling–coordination degree, consistently reflecting a “high coupling but low coordination” trend. Over time, the average coordination index rose from 0.21 in 1990 to 0.41 in 2022, with an annual growth rate of 2.1%.

Second, the spatial distribution of hot and cold spots highlights a growing east–west imbalance. The gravity center and standard deviation ellipse trajectory show that hotspot areas have expanded around core cities in the eastern agglomerations, while coldspots have contracted into the Jinzhong, Ningxia Yellow River, and Hohhot–Baotou–Ordos–Yulin clusters in the central and western regions. The shifting mismatch between the gravity center and the ellipse trajectory indicates weaker directional stability and greater dispersion, with the spatial focus gradually moving eastward.

Third, grey correlation analysis reveals an evolution of driving forces. Initially dominated by per capita GDP and economic growth, the key drivers have shifted toward environmental management (waste disposal rates, PM_{2.5} levels), digital and information industries, Internet penetration, education investment, public libraries, and healthcare institutions. This transformation underscores that the coordinated advancement of “technology–industry–institution” is essential for bridging the regional digital divide.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17219743/s1>, Table S1: Ranking of city clusters. The content of the supplementary material is based on the ‘China Urban Statistical Yearbook’ from 1990 to 2022 and the ‘China County Statistical Yearbook’ from 1990 to 2022. The selected indicators of digital economy and high-quality development of urban agglomerations in the middle and lower reaches of the Yellow River are calculated. The ranking table of digital economy and high-quality development level of cities in urban agglomerations in the middle and lower reaches of the Yellow River is used to analyze the continuous differentiation trend and spatial imbalance of the development level of each city in the region during the study period.

Author Contributions: Conceptualization, H.L. and Y.W.; methodology, Y.L. (Yuan Li); software, Y.L. (Yuan Li) and H.L.; validation, Y.W., B.X. and Y.L. (Yan Li); formal analysis, B.X.; investigation, H.L. and Y.L. (Yuan Li); resources, B.X.; data curation, Y.L. (Yan Li); writing—original draft preparation, Y.L. (Yuan Li); writing—review and editing, H.L. and Y.L. (Yuan Li); visualization, Y.L. (Yuan Li); supervision, H.L. and B.X.; project administration, Y.W.; funding acquisition, H.L. and B.X. All authors have read and agreed to the published version of the manuscript.

Funding: Central-level public welfare basic scientific research operating expenses special funding (CAFYBB2021ZB003); Special Funding for Basic Research Operating Expenses of Central Public Welfare Research Institutions (CAFYBB2020MC005).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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