

Article

Building a Sustainable Yangtze River Delta: Spatiotemporal Evolution and Obstacle Factor Analysis of Coupling Coordination

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Abstract

Achieving the coordinated development of the digital economy (DE), the tourism industry (TI) and the ecological environment (EE) is of great significance for regional sustainable development. This paper constructs a comprehensive evaluation index system for the digital economy–tourism industry–ecological environment (DTE) complex system. Indicator weights are determined via the entropy method, and the comprehensive development levels of the three subsystems in the Yangtze River Delta (YRD) region from 2010 to 2023 are systematically assessed. Based on this, the coupling coordination degree model is applied to measure the coordination of the DTE system, and the obstacle degree model is employed to identify the key factors restricting its coupling coordinated development. The results show the following: (1) From 2010 to 2023, the overall level of comprehensive development of the DE and EE in the YRD showed an upward trend, while the TI declined significantly during 2020–2022 due to the COVID-19 pandemic. (2) In terms of temporal evolution, the coupling coordination degree rose from 0.434 to 0.676 between 2010 and 2019, steadily improving from near disorder to primary coordination; although there were fluctuations between 2020 and 2023, it remained stable at a primary coordination level. Spatially, the region exhibited a “higher in the east, lower in the west” pattern. (3) From 2010 to 2019, the primary bottleneck in coordinated development stemmed from the DE subsystem; after 2020, the degree of constraints in the TI rose rapidly, creating a dual-system constraint pattern where the DE and the TI coexist. This study provides theoretical insights and practical recommendations for fostering positive DTE interactions in the YRD and offers valuable experience for other regions. This study has limitations regarding its research scale and indicator system, and it does not account for external influencing factors. Future research could adopt municipal or county-level analyses, apply causal inference methods such as panel Granger causality and system GMM, refine the evaluation index system, integrate internal and external factors, and thoroughly analyze the underlying mechanisms governing interactions within the DTE system.



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Keywords: regional sustainable development; digital economy; tourism industry; ecological environment; coupling coordination degree; obstacle degree

1. Introduction

At a critical juncture in global development, the United Nations officially launched the 2030 Agenda for Sustainable Development (SDGs) in 2015, establishing a systematic framework for action to enable all of humanity to work together to address development challenges and advance toward sustainable development [1]. The SDGs include objectives such as ensuring access to affordable, reliable, and sustainable modern energy for all (SDG

7) and establishing sustainable consumption and production patterns (SDG 12), aiming to address global challenges through sustainable development across the social, economic, and environmental dimensions. Against this backdrop, the synergistic development of the digital economy (DE), the tourism industry (TI), and the ecological environment (EE) presents opportunities for achieving global sustainable development [2,3]. In China, in particular, the Chinese government issued the “Outline of the 14th Five-Year Plan for National Economic and Social Development of the People’s Republic of China and the Long-Range Objectives Through the Year 2035” in 2021. This document proposed development goals such as leveraging digital technologies to empower the upgrading of traditional service industries, developing green and low-carbon industries such as eco-tourism, and building smart cities and digital villages, reflecting the intrinsic logic and development vision of the integrated development of the DE, TI, and EE [4].

Currently, the academic community is engaged in extensive discussions regarding the interconnections and mutual influences among the DE, TI, and EE. The application of digital technologies has demonstrated significant advantages in enhancing data sharing and resource access, reducing energy demand, improving energy efficiency [5], minimizing ecological footprints [6], and unlocking the potential for technological innovation. The infrastructure of the DE has facilitated green and clean manufacturing processes, improved production efficiency, reduced costs, and enhanced the quality of the EE. However, the DE has not completely decoupled economic growth from energy consumption [7], and the production of digital products also consumes large amounts of raw materials and energy [8], thereby increasing carbon emissions [9]. While the TI generates economic revenue, the energy demands of tourism activities—such as transportation, accommodation, and dining—continue to expand [10], exacerbating air, water, and soil pollution and leading to ecological degradation [11]. At the same time, the EE does not always function as a supportive resource; it also constrains the expansion of the DE and the TI [12,13]. It can be observed that these discussions are often limited to the binary interaction levels of “DE-TI,” “DE-EE,” or “TI-EE,” failing to place all three within a unified, mutually reinforcing analytical framework. Some scholars have focused on the interrelationships among the DE, TI, and EE. Jiang et al. argue that the DE can mitigate the negative effects of increased carbon dioxide emissions resulting from tourism development [14]; Chen et al. contend that the positive development of the DE influences tourism ecological efficiency through technological effects and industrial restructuring [15]; and Li et al. point out that rural digitization moderates the relationship between tourism development and regional green productivity indicators [16]. Li et al. note that digitalization and greening significantly enhance the high-quality development of tourism enterprises, generating significant synergistic effects between the two [17]. Nevertheless, existing work largely applies fixed-effects or spatial Durbin models to empirically examine causal pathways and interaction effects among these variables. A deeper inquiry into how the three variables couple and coordinate, along with their actual coordination levels, remains underexplored [18].

This Yangtze River Delta region within the PRC offers an ideal site for examining coordinated DTE development. As a pivotal national node for optimizing the spatial configurations of economic transition and external opening, while also establishing a superior-quality growth demonstration zone and a forerunner area for upgrading, the region has enjoyed ongoing policy backing. In December 2019, the State Council issued the “Outline of the Yangtze River Delta Regional Integration Development Plan,” calling for enhanced capabilities in scientific and technological innovation and industrial integration, the creation of a model for harmonious, symbiotic, and green development, and the pioneering achievement of infrastructure interconnectivity, the deep integration of science, technology, and innovation with industry, and joint protection and governance of

the ecological environment. The plan also aims to promote the integrated development of the tourism market and services, and jointly build a Digital Yangtze River Delta [19]. The digital transformation capacity of the YRD has been increasing year by year [20], yet this capacity exhibits a pattern of spatial imbalance [21]. The overall ecological efficiency of the TI shows a fluctuating downward trend, with Jiangsu and Zhejiang exhibiting higher ecological efficiency, while Shanghai and Anhui are relatively lower [22]. At the same time, the construction of the Shanghai–Nanjing–Hangzhou industrial base has led to increasingly sharp controversies over environmental quality [23]. As a frontier for the integrated development of China's DTE system, the YRD faces a contradiction between the development dividends of the digital economy, the tourism industry and ecological and environmental constraints in the pursuit of coordinated DTE development. These contradictions have had a profound impact on the integrated development of the YRD region, clearly revealing the complexity and urgency of promoting the coordinated development of the region's overall DTE. Therefore, it is necessary to explore the coordinated development of DTE in the YRD and, based on this, propose relevant recommendations to promote regional sustainable development.

The coupling coordination degree model (CCDM) is a well-established method for assessing the effects of interactions among multiple systems and quantitatively measuring the state of coupling coordination. It has been widely applied in diverse contexts of global sustainable development research. Huang et al. (2024) applied the CCDM to Kazakhstan, systematically assessing the coupling and coordination between urbanization and the ecological environment [24]. Kurniawan et al. extended the CCDM to the tourism socio-ecosystems of Indonesian islands, providing a methodological framework for assessing sustainable development in island regions [25]. On a global scale, Zhao et al. (2021) used the CCDM to investigate the global–spatial patterns of coupling between urbanization and environmental systems based on cross-sectional data from 209 countries and regions worldwide collected by the World Bank in 2014, thereby validating the method's broad applicability across countries at different levels of development [26]. Chen et al. used this model, based on global urban data, to measure the coupling relationship between urban land expansion and carbon emissions during the low-carbon transition, revealing the dynamic coordination patterns between urban growth and environmental pressures [27]. The above studies indicate that the CCDM has expanded from single-region or country-level case studies to transnational comparisons and global-scale applications, becoming an effective tool for diagnosing the state of coordination in complex systems.

The obstacle degree model and the CCDM are highly complementary methodologies and serve as core tools for identifying key internal factors that constrain the development of coupling coordination. In terms of combined methodological application, Wei et al. (2023) first used the CCDM to assess the degree of coupling coordination between water resource carrying capacity and the regional economic subsystem in Henan Province, and then further introduced the obstacle degree model to diagnose the limiting factors affecting this coordination [28]. Gui et al. (2025) combined the CCDM with the obstacle degree model to analyze the temporal evolution and spatial distribution characteristics of the coupled and coordinated development of tourism, the economy, and ecosystems in ecologically fragile areas of Southwest China, as well as the associated obstructing factors [29]. The combined CCDM and obstacle degree model approach has been widely validated as an effective methodological framework for diagnosing the state of coupling and coordination within systems and identifying key constraining factors.

Based on this, this study constructs a comprehensive evaluation index system, employs the entropy method to systematically assess the development levels of the DE, TI, and EE in the YRD region, adopts the CCDM to measure the temporal evolution trends

and spatial distribution characteristics of the DTE system's coupling coordination in the region, and combines the obstacle degree model to analyze the core factors influencing the coupling coordination of the DTE system. This holds significant theoretical and practical implications for promoting sustainable development in this region and in similar cities worldwide. Compared with traditional research frameworks on coupling and coordination, the innovations of this study are primarily reflected in three aspects:

First, in terms of the study area, the geographical scope of existing studies has primarily covered the national level [30], the Yellow River Basin [31], and the coastal regions of South China [32], neglecting a dedicated examination of the YRD—a globally representative urban agglomeration. As a strategic frontier for the integrated development of the DE, the TI, and the EE, the YRD exhibits unique characteristics in terms of DTE coordination conflicts. This study takes the YRD as its subject, depicting the spatial pattern of “higher in the east and lower in the west” in terms of coupling coordination, as well as Anhui's “catch-up” development characteristics. It offers important reference value for similar cities and urban agglomerations worldwide in coordinating the synergistic development of the digital economy, tourism industry, and ecological protection.

Second, regarding the research framework, most existing studies are limited to binary correlation analyses such as “DE–TI,” “DE–EE,” or “TI–EE,” and analyses of barrier factors are mostly static in nature. This study constructs a unified ternary DTE analytical framework and combines the barrier degree model with time-phase segmentation to identify the dynamic evolution of constraining factors. Based on this methodology, this paper identifies two dynamic patterns: (i) a structural shift in constraint patterns, specifically an evolution from “DE single-system constraints” during 2010–2019 to “DE and TI dual-system constraints” during 2020–2023; and (ii) the existence of a “talent–enterprise–market” three-factor lock-in cycle within the digital economy subsystem, manifesting as a self-reinforcing mechanism of skill ecosystem failure. This dynamic analytical framework helps transcend the identification of static factors and provides an analytical approach for understanding the structural transformation of bottlenecks during the evolution of complex systems.

Third, existing research typically reports only the upward or downward trends in coupling coordination, but rarely explains why a system remains stagnant at a certain level for an extended period, unable to achieve autonomous transition. This study introduces the adaptive cycle model and the concept of functional lock-in, demonstrating that the Yangtze River Delta DTE system is unable to transition to intermediate coordination due to switching costs, institutional inertia, and barriers to factor mobility. These findings not only deepen our understanding of the mechanisms underlying development bottlenecks in DTE systems but also provide a theoretical basis for formulating breakthrough policies targeting the primary coordination stage.

The remainder of this paper is structured as follows: Section 2 provides an in-depth analysis of the mechanisms underlying coupling and coordination in DTE systems; Section 3 introduces the research data and methodology and establishes a comprehensive evaluation framework; Section 4 summarizes the research findings and discusses the results; and Section 5 presents the conclusions and research implications, while also analyzing the limitations of this study.

2. Coordination Mechanism

The essence of coupling coordination within the DTE system lies in digital technology empowering tourism and ecological conservation, while tourism demand drives digital innovation and ecological constraints compel a green digital transformation. Consequently, the DE, TI, and EE form a dynamic, composite, and complex system. As a branch of systems science, Hermann Haken's theory of synergetics posits that open systems can

spontaneously generate ordered structures in terms of time, space, and function through internal synergy [33]. Based on synergetics, this study explores the mechanisms of coupling coordination among the DE, TI, and EE to achieve a dynamic equilibrium among them.

2.1. The Impact of the DE on the TI and the EE

On the one hand, the DE leverages technologies such as 5G, big data, blockchain, and artificial intelligence to build social media platforms, conduct tourism marketing and promotion, provide an explosion of tourism information, and continuously stimulate users' motivation and demand for travel [34]. On the other hand, the DE guides the TI toward digital transformation through digital technologies, enabling intelligent and digital management of the sector. As a result, the industry's operational processes, business strategies, products and services, business models, and value creation methods are being transformed and enhanced [35], continuously expanding the industry's boundaries and value. The DE analyzes collected tourism data to capture trends in the tourism market, uncover latent knowledge and information, and predict consumer choices [36,37]. These data are used to develop tourism products and optimize service processes, thereby promoting supply-side reform in the TI. At the same time, the deep integration of digital technology with the traditional tourism sector has given rise to new business models in the industry, such as virtual tourism, cultural tourism, night tourism, smart tourism, and metaverse tourism [38].

By enhancing resource utilization efficiency and reshaping industrial ecosystems, the DE drives the minimization of environmental pollution and carbon emissions [39] and leads the process of green socioeconomic transformation. The development of the DE can, through a crowding-out effect, reduce the scope for high-energy-consumption and high-emission industries, improve urban industrial structures [40], and reduce local carbon emissions, thereby promoting green, high-quality urban development. In the industrial manufacturing sector, digital technologies are driving production and manufacturing toward intelligent and automated processes, thereby reducing environmental pollution emissions [41]. Through the collection, analysis, and in-depth mining of production process data, production procedures can be optimized and innovated, leading to reduced energy consumption [42]. Furthermore, digital technologies use intelligent sensing and recognition to collect and analyze environmental information in real time, enabling smart management of the EE [43] and promoting resource conservation and environmental protection.

2.2. The Impact of the TI on the DE and the EE

The development of the TI can effectively drive the high-quality development of the DE. On the one hand, the substantial economic benefits generated by the booming tourism industry provide a vital financial foundation for the evolution of the DE [44], creating opportunities for the improvement in digital infrastructure and the research and development of digital technologies. On the other hand, the development of the TI generates large-scale, multidimensional datasets on "users" and "user engagement," which contain rich information on the core characteristics of tourism service demand and supply, comprehensively covering the entire lifecycle of tourism activities. These data constitute key resources for in-depth information mining and analysis in the DE [45], providing solid data support for the development of the DE. In this process, digital enterprises extract, measure, govern, and value tourism user metrics through various channels, thereby transforming them into usable digital assets [46]. Furthermore, the massive volume of tourism data poses new demands on computing and analysis, prompting relevant digital enterprises to continuously increase investment in digital technology R&D, thereby stimulating the sustained development of the DE.

The unregulated expansion of the TI can place a strain on a region's EE [47]. The environmental standards required for the development of the TI are driving regions to upgrade their industrial structures [48] and develop high-quality forms of tourism, such as ecotourism and educational tourism; these emerging tourism formats can play a key role in both protecting and sustainably utilizing the natural environment.

2.3. *The Impact of the EE on the DE and the TI*

Environmental quality and the need for green transition exert a dual influence on the development of the digital economy. On the one hand, the operation of the digital economy relies heavily on digital infrastructure such as data centers and communication base stations, and these energy-intensive facilities require a stable power supply [49]. If the energy mix for power generation is dominated by fossil fuels, it will generate significant carbon emissions, thereby exacerbating environmental pressures; this constitutes a constraint on the development of the DE imposed by environmental factors. On the other hand, the application of renewable energy sources such as wind, solar, and hydroelectric power can significantly reduce the carbon footprint of digital infrastructure [50], providing the technical means for the digital economy to achieve low-carbon operations. At the same time, driven by institutional constraints such as environmental regulations and carbon emission targets, as well as market mechanisms like green consumption preferences [51], the demands for building a green ecological environment and achieving a low-carbon societal transition collectively compel digital technologies to continuously innovate, iterate, and upgrade in key areas such as energy efficiency improvement, clean energy integration, and intelligent operation and maintenance.

The EE provides the TI with abundant ecotourism resources and a favorable natural setting for its development. A high-quality ecological environment shapes a region's tourism image and serves as the core competitive advantage for regional tourism development [52]. The ecological label of the TI can empower high-end tourism formats [53], and ecotourism projects can provide high-value-added tourism experiences. At the same time, ecological threshold theory indicates that tourist destinations have absolute ecological limits regarding their capacity to support tourist influx and the expansion of tourism infrastructure [54]. If TI activities continue to expand, they will trigger a "limiting factor" effect [55], and the carrying capacity threshold of the EE will constrain the sustainable development of the TI. Global climate change is driving public engagement in ecological conservation practices [56] and encouraging the exploration of sustainable tourism models such as metaverse tourism and virtual tourism [57] to protect natural resources [58].

3. Materials and Methods

3.1. *Study Area and Data Source*

The YRD of China is located in the lower reaches of the Yangtze River basin and encompasses the entire territories of Jiangsu Province, Zhejiang Province, Anhui Province, and Shanghai Municipality (Figure 1). The YRD continues to lead China's four major economic circles in terms of digital economic development, ranking at the forefront across 20 indicators, including internet broadband penetration rates and the number of newly registered digital economy enterprises. The YRD is one of China's largest tourism markets with the strongest consumer spending power. In 2023, the three provinces and one municipality of the YRD collectively received 2.574 billion domestic tourist visits and generated 3.1 trillion yuan in domestic tourism revenue, surpassing 2019 levels and accounting for 52.6% and 63.1% of the nation's total domestic tourist visits and revenue, respectively. From 2010 to 2023, under the pressure of sustained growth in the region's total economic output, the EE of the YRD underwent a transformation from worsening pollution to coor-

minated governance, and from localized improvements to comprehensive positive trends. However, coal still dominates the energy mix, and total energy consumption and carbon emissions continue to expand [59], with the pressure to address air pollution yet to be fundamentally alleviated.

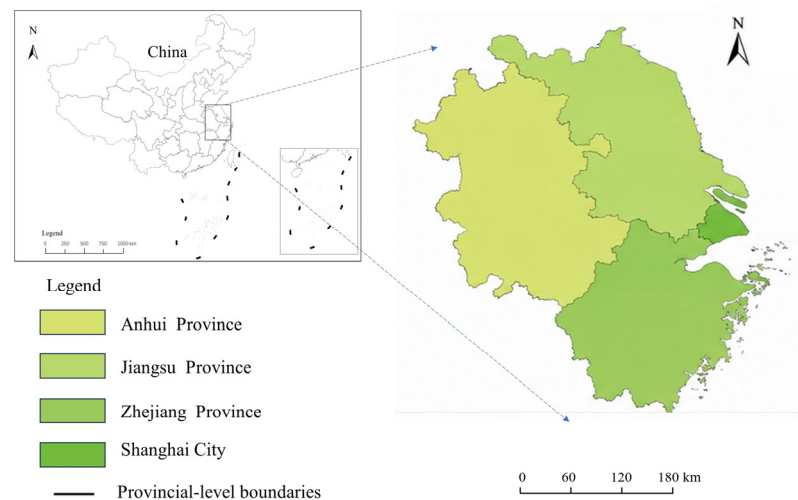


Figure 1. Study area location map.

All data in this study are primarily sourced from the *China Urban Statistical Yearbook*, the *China Environmental Statistical Yearbook*, the *China Tourism Statistical Yearbook*, the *Shanghai Statistical Yearbook*, the *Jiangsu Statistical Yearbook*, the *Zhejiang Statistical Yearbook*, the *Anhui Statistical Yearbook*, and the official website of the National Bureau of Statistics. The data used in this paper cover the period from 2010 to 2023. The Digital Inclusive Finance Index is derived from the “Peking University Digital Inclusive Finance Index” compiled by the Peking University Digital Finance Center (<https://idf.pku.edu.cn/> (accessed on 22 May 2026)).

3.2. Index System Construction

Based on the existing literature and taking into account both data availability and practical feasibility, this paper establishes a comprehensive evaluation index system comprising three subsystems: the DE, the TI, and the EE (Table 1). First is the DE evaluation index system [60,61], which consists of eight indicators across four dimensions: digital infrastructure (B1), digital industrialization (B2), industrial digitization (B3), and digital innovation (B4). Digital infrastructure reflects the development of information-carrying platforms. Internet broadband penetration rates indicate a region’s network coverage and access capacity, serving as a foundational metric for digital infrastructure. The metric of domains per thousand people transcends the limitations of basic user scale to reflect the enabling quality, application depth, and economic conversion efficiency of digital infrastructure, making it a crucial basis for assessing the quality of digital economic development. Mobile phone penetration rate indicates the level of adoption of mobile communication devices. A high mobile phone penetration rate indicates widespread access to digital services and supports the digital transformation of real-world activities. Digital industrialization reflects the degree to which data elements are industrialized, commercialized, and marketized. The number of legal entities in the information transmission, software, and information technology services sector reflects the scale and vitality of digital industrialization, while the percentage of employees in the information transmission, computer services, and software industry reflects the investment in human capital within the digital industry. Industrial digitalization reflects the degree of integration between digital technologies and

traditional industries. The Digital Inclusive Finance Index reflects the degree of integration between digital technologies and financial services, demonstrating the accessibility and inclusiveness of financial services within industrial digitalization. E-commerce sales revenue reflects the effectiveness of traditional commerce enterprises in achieving transaction model innovation and market expansion through digital technologies. Digital innovation manifests as the level of intelligent technologies and digital innovation within the digital economy. The intensity of Research and Development (R&D) expenditure reflects a region's level of financial investment in basic research, applied development, and experimental development within digital economy-related fields. It serves as a key input-based indicator for measuring digital innovation resource endowments and sustained innovation capacity, providing the core driving force for breakthroughs in digital technology, the iteration of intelligent algorithms, and the commercialization of digital innovation outcomes.

Table 1. DE-TI-EE comprehensive evaluation index system.

Target Layer	Element Layer	Indicator Layer	Unit	Weight	Nature
Digital Economy	Digital Infrastructure (B1)	Internet broadband penetration rate (C1)	%	0.0726	+
		Number of domain names per 1000 people (C2)	u./10 ³ pers.	0.1489	+
		Mobile phone penetration rate (C3)	%	0.0548	+
	Digital Industrialization (B2)	Number of legal entities in information transmission, software, and information technology services sector (C4)	u.	0.1960	+
		Percentage of employees in information transmission, computer services, and software industry (C5)	%	0.2103	+
	Industrial Digitalization (B3)	Digital Inclusive Finance Index (C6)		0.0679	+
		E-commerce sales revenue (C7)	100 M RMB	0.1935	+
	Digital Innovation (B4)	Intensity of research and development (R&D) expenditure (C8)		0.0559	+
Tourism Industry	Tourism Industry Scale (B5)	Number of star-rated hotels (C9)	u.	0.1566	+
		Number of travel agencies (C10)	u.	0.1459	+
		Number of Grade A tourist attractions (C11)	u.	0.1378	+
		Number of people employed in tourism industry (C12)	pers.	0.0648	+
		Total number of domestic visitors (C13)	10 k pers.	0.1030	+
		Total number of inbound tourists received (C14)	10 k pers.	0.1531	+
	Tourism Industry Benefits (B6)	Domestic tourism revenue (C15)	100 M RMB	0.1057	+
		Foreign exchange earnings from tourism (C16)	100 M USD	0.1331	+
	Environmental Endowments (B7)	Forest cover (C17)	%	0.0936	+
		Per capita public green space (C18)	m ²	0.0863	+
		Percentage of days with good or excellent ambient air quality (C19)	%	0.0752	+
Ecological Environment	Environmental Pressures (B8)	Industrial wastewater discharge (C20)	100 M t	0.0646	–
		Industrial exhaust emissions (C21)	100 M Nm ³	0.0798	–
		Industrial solid waste generated (C22)	10 k t	0.1093	–
		Urban domestic wastewater discharge (C23)	100 M t	0.0742	–
	Environmental Governance (B9)	Annual Investment in environmental pollution governance (C24)	100 M RMB	0.1628	+
		Household waste collected (C25)	10 k t	0.1783	+
		Urban sewage treatment rate (C26)	%	0.0601	+
		Safe disposal of municipal solid waste rate (C27)	%	0.0159	+

Second is the comprehensive evaluation index system for the TI [31]. This system comprises eight indicators across two dimensions: tourism industry scale (B5) and tourism

industry benefits (B6). The scale of the tourism industry reflects the supply capacity of tourism products and services as well as market demand; the number of star-rated hotels indicates accommodation capacity and service standards; the number of travel agencies reflects the breadth of the tourism organization and distribution network; the number of Grade A tourist attractions demonstrates the richness of core tourist attractions; the number of people employed in the tourism industry represents the scale of human resource investment in the sector; and the total number of domestic and inbound tourists directly measures the scale of tourism market demand and the structure of tourist sources. The benefits of the tourism industry reflect its value creation capacity. Domestic tourism revenue reflects the direct contribution of tourism activities to the regional economy, while foreign exchange earnings from tourism reflect the economic returns of international tourism competitiveness.

Third is the comprehensive evaluation index system for the EE [62,63]. This system comprises eleven indicators across three dimensions: ecological endowment (B7), ecological pressure (B8), and ecological governance (B9). Ecological and environmental endowments reflect the stock of natural ecological and environmental elements inherent to a region; forest cover reflects the abundance of forest resources and the region's ecological regulation capacity; per capita public green space area reflects the level of urban greening and the ecological quality of residents' living environments; and the percentage of days with good or excellent ambient air quality indicates the cleanliness and livability of the atmospheric environment. Ecological and environmental pressures reflect the pollution load facing a region's ecological environment. The total volume of industrial wastewater discharge, the total volume of industrial exhaust emissions, and the volume of industrial solid waste generated measure the negative environmental impacts of industrial production from the dimensions of water, air, and solid waste, respectively, while the volume of urban domestic wastewater discharge reflects the scale and intensity of domestic pollution during the urbanization process. Ecological and environmental governance reflects a region's response to environmental pollution. Annual investment in environmental pollution governance reflects the scale of financial commitment and the government's level of priority placed on environmental governance. The volume of household waste collected reflects the operational scale of the solid waste collection and transfer system. The urban wastewater treatment rate indicates the level of purification for domestic and industrial wastewater, while the rate of safe disposal of municipal solid waste measures the environmental safety of final waste disposal.

3.3. Research Methodology

3.3.1. Data Preprocessing

The data are standardized or normalized using the range method to eliminate the influence of units. If the processed data yield a value of 0 or the data are 0, a data shift is performed by adding a positive number slightly greater than 0 (e.g., 0.001) to the processed results. Here, X_{ij} represents the raw data for indicator j in year i , and Y_{ij} is the standardized value of X_{ij} ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$). It should be noted that the indicators in this paper are divided into positive and negative indicators. For positive indicators, a higher value indicates a better level of development, while for negative indicators, a higher value indicates stronger development constraints. The following two sets of formulas perform the same-direction transformation for these two types of indicators. After normalization, all indicators become yield-based indicators; the larger the standardized value Y_{ij} , the better the corresponding development performance.

$$\text{Positive indicator : } Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \quad (1)$$

$$\text{Negative indicator : } Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \quad (2)$$

3.3.2. Entropy Method

To assign weights to metrics within the DTE framework, the entropy method was adopted. This objective technique uses each metric's entropy value to capture information differences, thereby scientifically determining their importance ranking [64].

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

$$E_j = -k \sum_{j=1}^n (P_{ij} \times \ln P_{ij}) \quad k = \frac{1}{\ln(m)} \quad (4)$$

$$G_j = 1 - E_j \quad (5)$$

$$W_j = \frac{G_j}{\sum_{j=1}^m G_j} \quad (6)$$

$$U_i = \sum_{i=1}^m W_j \times P_{ij} \quad (7)$$

Let m signify the assessment year. P_{ij} stands for a data point's share within the j -th metric's computation. E_j refers to the entropy of metric j . G_j (ratio of standard deviation to mean for metric j) and W_j (its relative importance) together yield U_i , the comprehensive evaluation score.

3.3.3. Coupling Coordination Degree Model

The coupling coordination degree (CCD) is a key indicator for evaluating synergies and interactions between systems, and it can be used to assess the interdependence and degree of coupling between systems [65].

(1) Calculate the coupling degree.

The coupling degree represents the extent of influence between subsystems; a higher value indicates greater mutual influence between systems.

The formula for the coupling degree C used in this paper is as follows when $n = 3$:

$$C = \sqrt[3]{\frac{U_1 U_2 U_3}{\left(\frac{U_1 + U_2 + U_3}{3}\right)^3}} = \frac{3\sqrt[3]{U_1 U_2 U_3}}{U_1 + U_2 + U_3} \quad (8)$$

(2) Calculate the comprehensive development degree.

While the coupling degree reflects the interactions among DTE composite systems, it does not adequately capture the overall synergistic effects between them. Therefore, a comprehensive coordination degree is further constructed, expressed as follows:

$$T = \alpha U_1 + \beta U_2 + \delta U_3 \quad (9)$$

T is the comprehensive development degree of the DTE system, reflecting the effects or contributions of the DE, TI, and EE subsystems to the coupling coordination of the DTE system. T represents the weights of the first-level indicators corresponding to the DE, TI,

and EE subsystems, where $\alpha + \beta + \delta = 1$. Since the three subsystems are considered to be of equal importance, $\alpha = \beta = \delta = 1/3$.

(3) Calculate the CCD.

The CCD reflects the overall effectiveness and coordination of interactions between systems.

$$D = \sqrt{C \times T} \quad (10)$$

As presented in Table 2, drawing on Ding et al. [66], ten intervals were defined to classify the degree of collaborative interaction in DTE systems, with each interval representing a different level.

Table 2. Segmentation of the CCD.

Number	Coupling Coordination Degree D-Value Interval	Evaluation Criteria	Number	Coupling Coordination Degree D-Value Interval	Evaluation Criteria
1	[0, 0.10)	Extreme disorder	6	[0.50, 0.60)	Barely coordination
2	[0.10, 0.20)	Severe disorder	7	[0.60, 0.70)	Primary coordination
3	[0.20, 0.30)	Moderate disorder	8	[0.70, 0.80)	Intermediate level coordination
4	[0.30, 0.40)	Mild disorder	9	[0.80, 0.90)	Good coordination
5	[0.40, 0.50)	Near disorder	10	[0.90, 1]	Quality coordination

3.3.4. Obstacle Degree Model

The obstacle degree model is effective in identifying the primary factors that hinder the coordination of system coupling [67]. It facilitates the identification of the extent to which key coordination factors influence the coupling coordination of DTE systems, enabling the targeted development of measures to enhance the regional DE, TI, and EE, thereby improving the coordinated development of these three aspects.

The formula for calculating the obstacle degree is as follows:

$$Q_{ij} = (I_{ij} \times W_j) / \sum_{j=1}^m I_{ij} \times W_j \quad (11)$$

where $I_{ij} = 1 - X_{ij}$ represents the deviation of the indicator, which reflects the gap between the actual value of the indicator and its optimal value; W_j is its corresponding weight.

4. Results and Discussion

4.1. Comprehensive Evaluation of the DTE System in the YRD

4.1.1. Digital Economy

As illustrated in Figure 2, the comprehensive evaluation score of the YRD's DE system exhibited a rapid upward trajectory from 2010 to 2023, climbing from 0.0616 to 0.5538 with an average annual increase of 18.4%. This steady upward momentum, resilient even during the pandemic, reflects robust regional DE growth. Nevertheless, notable development gaps exist: Shanghai consistently ranks highest and maintains a leading position. The digital economy development scores of Jiangsu and Zhejiang have converged, placing them in the second tier among the three provinces and one municipality of the YRD, while Anhui's level of digital economy development has lagged significantly, forming a tiered development pattern. The findings of this study are consistent with the conclusions reached by Liu and Jiang based on panel data from 41 cities in the YRD covering the period 2011–2021, both of which indicate that the level of digital economic development exhibits a spatial pattern of “Shanghai > Zhejiang > Jiangsu > Anhui”. Shanghai boasts a stronger socioeconomic foundation and geographical advantages, providing favorable conditions for the development of the DE [68].

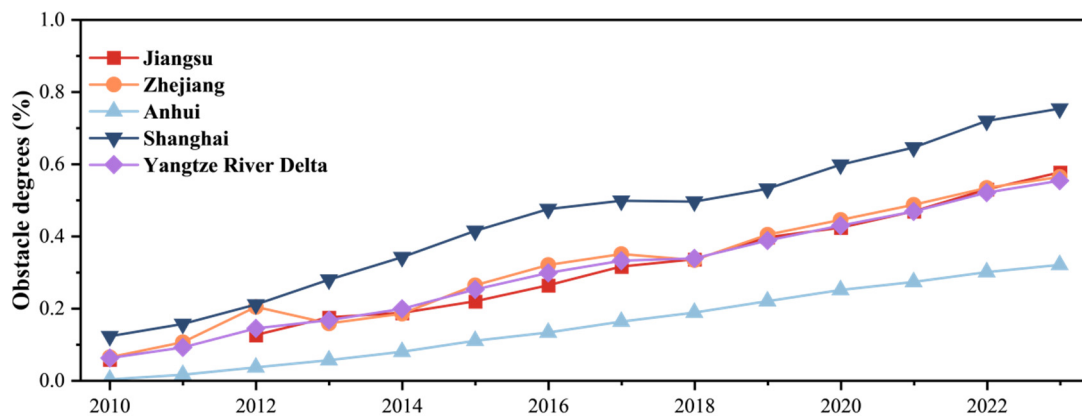


Figure 2. Comprehensive evaluation score for DE.

From 2010 to 2023, Shanghai's digital economy development score rose from 0.1221 to 0.7538, with an average annual growth rate of approximately 15%. Shanghai's focus in developing the DE lies in the industrialization of digital technologies, where it holds an absolute advantage in upstream and high-value-added sectors such as artificial intelligence, integrated circuits, industrial software, fintech, and e-commerce [69]. This is the fundamental reason why Shanghai's digital economy development score is far ahead of the others.

From 2010 to 2023, Zhejiang's score rose from 0.0638 to 0.5643, with an average annual growth rate of approximately 18.2%. Zhejiang excels at leveraging internet-based consumption and business models to unlock the value of data, and its platform economy model leads the nation. Jiangsu's digital economy development score increased from 0.058 to 0.5769, with an average annual growth rate of approximately 15.55%.

Jiangsu's industries are primarily concentrated in manufacturing. To promote the intelligent upgrading and digital transformation of the manufacturing sector, the province has continuously strengthened the integration of digital technology and innovation [70], thereby driving the development of the DE. This pattern resonates with existing empirical evidence. Chen et al. utilized data from China's manufacturing sub-sectors to confirm the significant role of the DE in promoting high-quality development in the manufacturing sector [71]. Zhang et al., using panel data from 30 provinces, further demonstrated that the DE drives high-quality development in both manufacturing and the DE itself by facilitating the integration of productive services with manufacturing; this enabling effect is particularly pronounced in major eastern manufacturing provinces such as Jiangsu [72]. Thus, Jiangsu's digital transformation trajectory is well aligned with the enabling role of the digital economy in a manufacturing-dominated regional context.

In contrast, Anhui's score grew from 0.0023 in 2010 to 0.3203 in 2023, with an average annual growth rate of 46.2%, exhibiting the typical characteristics of "catch-up growth." Gerschenkron's theory of the latecomer's advantage provides a classic explanation for this phenomenon: the technological gap itself constitutes exploitable development potential, and latecomer regions can achieve faster growth through imitation, learning, and technology transfer [73]. As a province with a long history of agriculture, Anhui lacked an early-mover advantage in the consumer internet sector of the digital economy and in the digitization of traditional industries. However, by actively attracting the relocation of high-end manufacturing from the YRD and focusing its development efforts on the manufacturing of economic hardware, the province has achieved rapid growth in the DE. Nevertheless, while growth can be achieved through the imitation and adoption of existing technologies when a region is far from the technological frontier, it must shift to an innovation-driven model as it approaches that frontier [74]. However, due to deficiencies

in human capital accumulation and innovation capabilities within the digital economy, a substantial gap remains between Anhui's level of digital economic development and that of more developed regions.

4.1.2. Tourism Industry

Figure 3 shows the trend in the comprehensive evaluation score of the tourism industry system in the YRD from 2010 to 2023. From an overall perspective of the YRD, the TI system maintained a general upward trend from 2010 to 2019. Due to the external shocks caused by the global COVID-19 pandemic, the development level of the TI system experienced a sharp decline from 2020 to 2022, reflecting the system's high sensitivity to changes in the external environment and its significant vulnerability [75]. In 2023, it rebounded rapidly, rising to 0.3794.

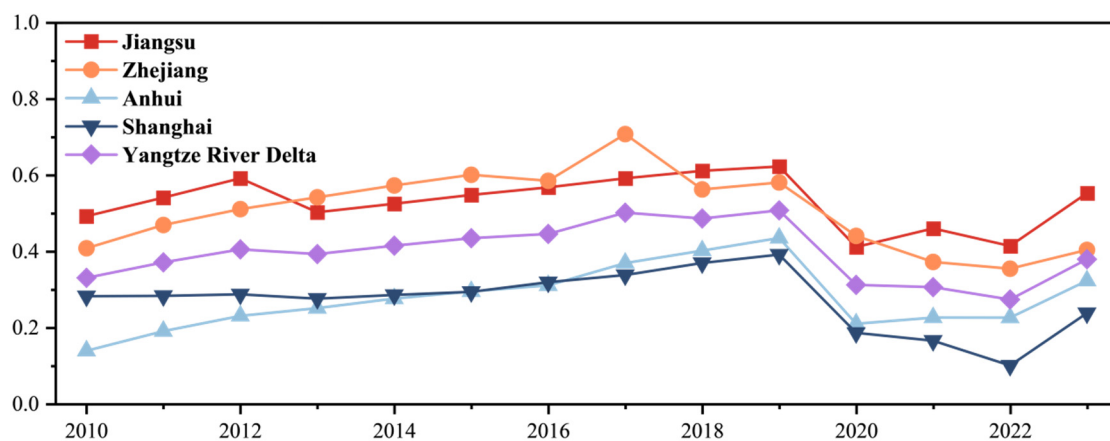


Figure 3. Comprehensive evaluation score for TI.

From 2010 to 2023, significant divergence emerged in the overall development trends of the TI in the YRD. Jiangsu and Zhejiang have long been in the first tier, with Jiangsu averaging 0.597 and Zhejiang averaging 0.514; Anhui and Shanghai, meanwhile, are in the second tier, with Shanghai averaging 0.284 and Anhui averaging 0.277.

Jiangsu and Zhejiang, with their developed economies, have driven the construction of tourism infrastructure and the renewal and improvement of the tourism industry chain, creating a strong attraction for visitors from surrounding cities and providing a competitive advantage for the tourism industries of both provinces. Jiangsu boasts a relatively comprehensive structure of cultural and tourism resources, with abundant aquatic, biological, and tangible cultural heritage resources, supporting the development of all-for-one tourism. Zhejiang places equal emphasis on natural landscapes and cultural resources, with active innovation in tourism models such as digital tourism and rural tourism, offering visitors rich opportunities for exploration. Although Anhui possesses top-tier tourism resources such as Mount Huang and Huizhou culture, its development levels in areas like all-for-one tourism, smart tourism, and the integration of culture and tourism remain relatively low [76]. At the same time, Shanghai's economic structure and urban functions have made it a gateway destination for the YRD, resulting in a significant flow of tourism spending to neighboring provinces. Based on the hub-and-spoke model proposed by Lue et al. [77] and the "pass-through but no consumption" mechanism identified by Brown and Jenkins [78], tourists radiate outward from Shanghai as a distribution hub without generating corresponding stays or expenditures locally. This disconnect between traffic and consumption has resulted in the relative lag in the development of Shanghai's TI.

In 2020, the global pandemic severely impacted the YRD region, causing a synchronized decline in tourism development scores across its three provinces and one municipality. Over the next two years, Shanghai and Zhejiang experienced further decreases, a pattern associated with their epidemic response measures and reliance on specific tourist source markets. In August 2021, China's Ministry of Culture and Tourism introduced a "circuit breaker" rule for cross-provincial travel, requiring provinces (including autonomous regions and municipalities) containing medium- or high-risk zones to immediately halt local travel agencies and online platforms from offering interprovincial group tours or "flight + hotel" packages to or from those areas. Shanghai and Zhejiang triggered provincial "circuit breakers" multiple times between 2021 and 2022, which was the direct policy cause of the continued decline in their tourism industry development scores. Additionally, the tourism sectors in Shanghai and Zhejiang are highly dependent on interprovincial and international visitors, and their local markets struggle to offset the loss of external visitors. As an international metropolis, Shanghai's TI relies heavily on visitors from neighboring provinces and international tourists. Zhejiang's TI is renowned for its high-quality natural landscapes and rural tourism brands, yet it is similarly highly dependent on visitors from Shanghai and other provinces. The pandemic's direct disruption of interprovincial tourist flows dealt a double blow to the tourism markets of both provinces. This supports the findings of Liu et al., who found that differences in the origin structure of source markets serve as important moderating variables in the recovery from tourism destination crises, with scenic spots that rely heavily on local markets performing better in the long-term recovery process [79]. Shanghai and Zhejiang's high dependence on inbound tourists corresponds to a "low local dependency" resilience profile, posing challenges for their short-term recovery. Against this backdrop, government stimulus packages and intervention measures promoting technological innovation, fostering a sense of local belonging among residents, and boosting consumer and employee confidence will be key pathways to enhancing the resilience of the tourism industry and revitalizing regional tourism [80].

4.1.3. Ecological Environment

As shown in Figure 4, the comprehensive evaluation score for the YRD's ecological environment system over 2010–2023 reveals a generally rising development level, increasing from 0.4520 to 0.5451. This finding agrees with Ji et al. [81]. The score mainly ranged between 0.45 and 0.55, suggesting above-average eco-environmental quality in the region, though further enhancement of the EE system remains possible.

When examining individual provinces, the ecological and environmental development scores of the three provinces and one municipality all exhibited varying degrees of fluctuation over time. This reflects the complexity of the EE systems in each province (and municipality), which are influenced by a combination of natural and socioeconomic factors, as well as the instability in the effectiveness of ecological and environmental governance. Fluctuations in economic growth rates and development models directly impact energy consumption, emission intensity, and the use of ecological resources, leading to corresponding fluctuations in the ecological and environmental development score [82,83]. In 2020, the ecological and environmental development scores of the three provinces and one municipality showed a synchronous upward trend. In early 2020, the global COVID-19 pandemic caused a sharp short-term decline in industrial production, transportation, tourism, and leisure activities across the region, which objectively reduced pollutant emissions and directly contributed to improvements in ecological and environmental quality [84].

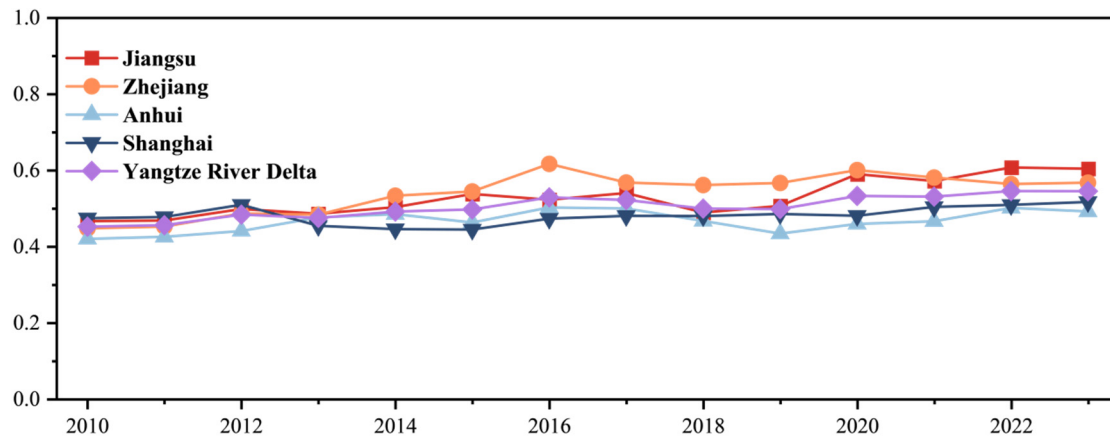


Figure 4. Comprehensive evaluation score for EE.

From 2010 to 2023, Zhejiang's score increased from 0.4475 to 0.5676, averaging an annual rise of 1.85%. A notable jump occurred in 2016; afterward, a mild drop took place, yet the score stayed comparatively high across the study interval. Among all areas in the YRD, Zhejiang had the top-performing ecological and environmental system, reflecting sustained advancement in this domain. On 15 August 2005, the concept that "lucid waters and lush mountains are invaluable assets" was first proposed [85]. It subsequently became a central consideration in Zhejiang's economic and social development, generating positive effects on the sustainable development of the province's EE. In this process, leveraging its digital economy foundation, Zhejiang took the lead in establishing a digitalized and refined environmental governance system, achieving real-time monitoring and intelligent early warning for environmental quality, pollution sources, and law enforcement across the province, which contributed to the province's outstanding ecological performance.

Shanghai's score has shown a relatively stable trend, fluctuating slightly around 0.48, with an overall steady trajectory. It dropped to 0.4444 in 2015 but has steadily rebounded since 2016. During the study period, Shanghai comprehensively promoted high-quality ecological and environmental conditions to support regional economic development and actively adjusted its industrial structure. The proportion of high-tech service industries continued to rise, and the dividends from industrial restructuring played a significant role in improving environmental quality [86]. December 15, 2017 witnessed State Council approval of the Shanghai Master Plan (2017–2035). The plan mandates reinforced eco-environmental protection and coordinated progress across environmental, economic, and rural–urban sectors, thus offering legal and planning assurances for Shanghai's green ecological advancement. Based on this, Shanghai has maintained strict standards for pollution control and ecological construction [87,88], continued to invest in environmental governance and infrastructure development, and made effective progress in implementing a green and low-carbon energy transition and accelerating the optimization and upgrading of its industrial structure, resulting in a significant improvement in environmental quality.

Between 2010 and 2023, Jiangsu's ecological development level exhibited a generally upward yet undulating trajectory, climbing from 0.4664 to 0.6042, a roughly 29.5% increase that ranked first among the four regions. Between 2010 and 2017, the ecological and environmental evaluation score fluctuated slightly around 0.50, but dropped significantly to a low point in 2018, falling to 0.4891. In 2020, Jiangsu's ecological and environmental development score rebounded to 0.59. In 2022 and 2023, the province's ecological and environmental conditions generally exhibited a trend of "steady progress and sustained improvement," with multiple indicators reaching their best-ever levels.

From 2010 to 2023, Anhui's score rose from 0.4198 to 0.4919. Located within the three major river basins of the Yangtze, Huai, and Xin'an Rivers, Anhui Province has long served as an upstream ecological barrier, resulting in significant pressure on its ecological carrying capacity. In 2014, Hefei City in Anhui Province was first included in YRD urban agglomeration. In 2016, eight cities in Anhui joined the YRD. While pursuing economic development, the province also became a major destination for the relocation of industrial pollution projects from coastal areas [89], leading to a rapid increase in total pollutant emissions in some local areas, a deterioration in environmental quality, and a downward trend in the ecological environment evaluation score. In 2019, the "Outline of the Yangtze River Delta Regional Integration Development Plan" incorporated the entire province of Anhui into the YRD planning framework. In addition to focusing industrial development on strategic emerging industries such as new energy vehicles, photovoltaics, and next-generation information technology, Anhui has made concerted efforts to advance ecological conservation and restoration, strengthen ecological and environmental governance, enhance supervision of river basin ecosystems, and promote the continuous improvement in water ecological and environmental quality. In 2023, Anhui's score rose to 0.4919, indicating significant improvements in the province's ecological environment and that the ecological benefits of environmental governance measures are beginning to materialize.

4.2. The Spatiotemporal Characteristics of the CCD of the DTE System in the YRD

4.2.1. Temporal Evolution Characteristics

Based on the CCDM, the CCD of the DTE system in the YRD from 2010 to 2023 was calculated (Figure 5). In terms of temporal characteristics, from 2010 to 2019, the CCD of the DTE system in the YRD showed an overall progressive upward trend, rising from 0.434 in 2010 to 0.676 in 2019. It steadily improved from a state of near disorder to primary coordination, with the level of synergy among the DE, TI, and EE subsystems continuously increasing. Between 2019 and 2022, the degree of coupling and coordination declined due to the impact of the global COVID-19 pandemic. Although the YRD region had opportunities to achieve technological breakthroughs in the DE during the pandemic and faced reduced pressure regarding ecological and environmental governance, the resilience of the tourism subsystem gradually weakened as the pandemic persisted. Under the combined influence of the aforementioned subsystems, the coupling coordination index in 2020, 2021, and 2022 remained below pre-pandemic levels. It is worth noting that this decline did not hit bottom immediately at the onset of the pandemic but exhibited a certain time lag [90]. The negative impact of the pandemic was gradually transmitted through mechanisms such as the decline in tourism resilience and the accumulation of negative feedback between subsystems, causing the sustained slump in coupling coordination to persist into 2022 rather than immediately reaching its lowest point in 2020. By 2023, the coupling coordination index had rebounded to 0.6901, reaching a historic high.

However, since 2015, the coupling coordination level has remained at the primary coordination stage for an extended period, never reaching intermediate or high coordination levels. This suggests that the coordinated development of the DTE system in the YRD may have hit a bottleneck during the phase of high-quality development. This corroborates the conclusion of Wu Zhicai et al. on the coupling coordination of the digital economy, tourism development, and low-carbon economy efficiency (CCDTL) system, which found that CCDTL exhibits strong path dependence and transition inertia, making it difficult for provinces to alter their development states [91]. Thus, after achieving initial coordination, the DTE system in the YRD faces significant path dependence and lock-in effects that hinder further transition. This phenomenon stems not only from internal resource bottlenecks but also from technological lock-in and efficiency constraints [92].

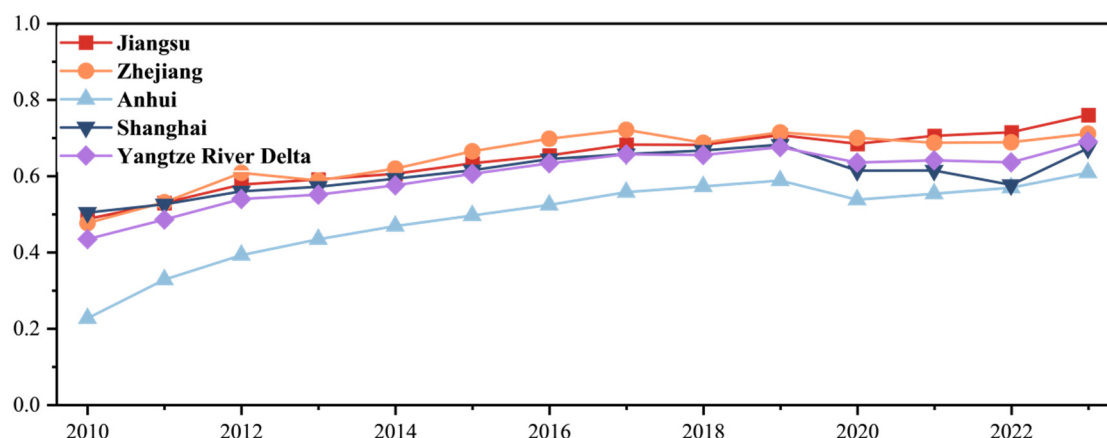


Figure 5. Time-varying trends of the CCD.

Gunderson and Holling's Adaptive Cycle Model divides socio-ecological systems into four phases: rapid growth, conservation, release, and reorganization. The conservation (or maintenance) phase is when the system's structure is most stable and internal couplings are strongest, but it is also when the system is most rigid. During this phase, path dependence becomes entrenched, institutional rigidity intensifies, and factor mobility is impeded [93]. The DTE system in the YRD clearly entered the conservation phase after 2015, with the development paths of the DE and TI becoming fixed. For example, Jiangsu, Zhejiang, and Anhui have adopted platform-based economies and the digital transformation of manufacturing as their primary pathways, while a joint ecological environment prevention and control mechanism among the three provinces and one municipality has taken initial shape. Consequently, the system has reached equilibrium under a specific combination of institutions, technologies, and industries. Due to switching costs and inertia, it has become path-locked, ultimately stagnating at the "primary coordination" stage. This has also significantly weakened the system's adaptive capacity when facing external shocks and internal structural contradictions. Isaksen and Trippel also note in their research on regional innovation systems that mature regions may experience functional lock-in, whereby the system continuously reinforces itself along a given technology-institution trajectory while rejecting superior alternative pathways [94]. Together, these studies demonstrate that long-term coordinated development requires a holistic strategy. To achieve high-level synergistic development among the DE, TI, and EE, it is necessary to break this state lock-in.

During the study period, the Jiangsu DTE system maintained a leading position in terms of coupling coordination, growing steadily from 0.487 in 2010 to 0.760 in 2023, with its coordination level improving from "near disorder" to "intermediate level coordination". Over the 14-year period, the CCD of the Jiangsu DTE system declined slightly only in 2020 but quickly recovered, reaching a record high of 0.760 in 2023. Zhejiang's CCD grew rapidly in the early stages, reaching 0.721 in 2017 and entering the intermediate level coordination stage. In 2023, both Jiangsu and Zhejiang were in the intermediate coordination stage. In 2010, the CCD of Shanghai's DTE system was 0.504, the highest among the three provinces and one municipality, placing it in the barely coordination stage. Between 2020 and 2022, the degree declined continuously, falling from 0.614 to 0.577, dropping from the primary coordination stage back into the barely coordination stage. In 2023, it rebounded sharply to 0.673, reflecting that the Shanghai DTE system has not yet established a stable pattern of coordinated development and remains vulnerable to external shocks.

In 2010, Anhui's CCD stood at only 0.226; by 2023, it had risen to 0.609. During the study period, there was no significant decline, indicating a trend of steady improvement. The coordination level rose steadily from "moderate disorder" to "primary coordination",

demonstrating a clear catch-up effect in Anhui's synergy across the DE, TI, and EE. While Anhui's CCD has generally maintained an upward trend, it remains below the overall level of the YRD. This is the result of multiple factors, including geographical location, the stage of regional economic development, industrial foundations, ecological functional positioning, and the allocation of policy resources. In its early stages, Anhui relied primarily on traditional manufacturing and agriculture, and it started relatively late in developing the DE and TI. The scale and quality of its core digital economy industries and tourism services lag behind those of Jiangsu, Zhejiang, and Shanghai, which has impacted the efficiency of synergy among systems. Furthermore, as an important ecological barrier within the YRD [95], Anhui imposes moderate constraints on the intensity of industrialization and tourism development. This development strategy, which prioritizes ecology, has to some extent limited the short-term expansion of industry and tourism, resulting in the failure to fully realize the synergistic benefits of the regional ecosystem. This phenomenon aligns with the trade-off dilemma of regional synergistic growth under ecological constraints proposed by the international academic community in recent years. Research by Shu et al. on the YRD indicates that strict ecological controls have subjected Anhui's industrial transformation zones to regulatory pressures exceeding local adaptive capacity, thereby hindering coordinated development [96].

It is worth noting that Anhui's growth rate has accelerated significantly in recent years, and the gap between the province and the overall development level of the YRD has continued to narrow. This indicates that the province is gradually catching up in the integration process, reflecting the positive enabling role of the YRD integration strategy. Empirical research by Campos et al. on EU regional integration found that joining the EU can increase member states' per capita income by an average of approximately 12% over a ten-year period [97], while peripheral regions can gain an additional 0.6 percentage points in annual productivity growth from deep institutional integration [98]. This mechanism closely mirrors Anhui's development trajectory within YRD integration—through institutional alignment, market connectivity, and industrial synergy, peripheral regions are able to accelerate their catch-up.

In 2023, the coupling coordination levels across the three provinces and one municipality of the YRD generally rebounded to historical highs, reflecting the region's positive achievements in promoting synergy among the DE, TI, and EE systems.

4.2.2. Spatial Evolution Characteristics

To visualize the spatial distribution and evolutionary trends of the CCD of DTE systems in the YRD, this study selected four representative years—2010, 2015, 2020, and 2023—and generated spatial distribution maps using ArcGIS 10.8 (Figure 6).

In terms of spatial distribution, from 2010 to 2023, the level of coupling and coordination within the DTE system in the YRD generally exhibited a spatial pattern characterized by “higher values in the east and lower values in the west”. The high-value areas were primarily located in the two provinces and one municipality in the eastern part of the region, while the low-value areas were mainly concentrated in Anhui Province in the west, indicating significant regional disparities. This spatial pattern primarily reflects the comparative advantages inherent in the region's socioeconomic development. This supports the view put forward by Yang et al., who argue that the spatial distribution of coupling and coordination is closely linked to the “Matthew effect”—that is, through spatial agglomeration effects, a region's initial advantages are self-reinforcing [99], thereby leading to further widening of the gap between high-performing and low-performing regions.

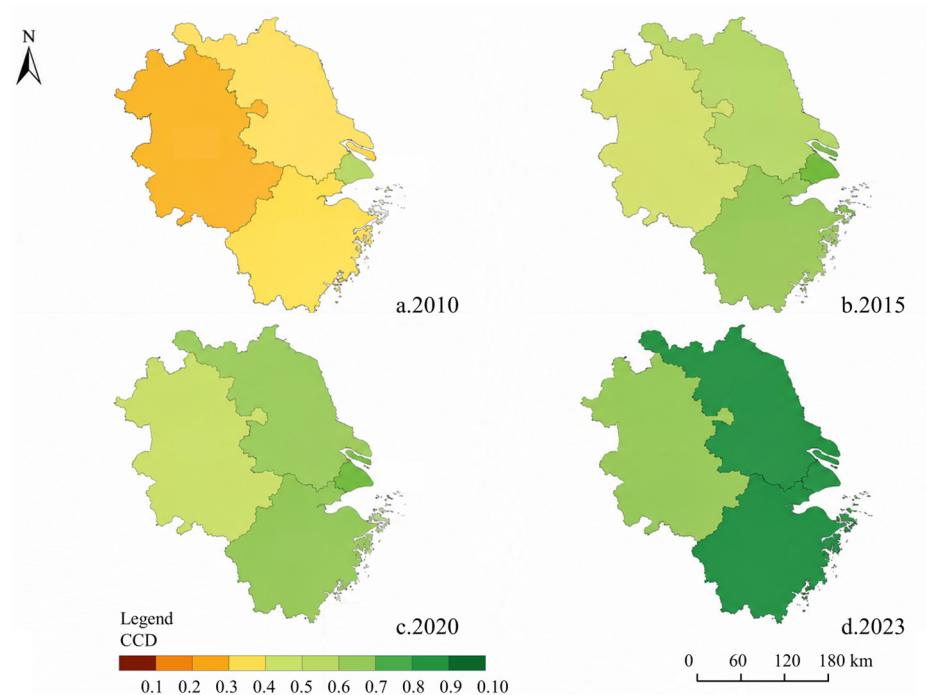


Figure 6. Spatial distribution of CCD.

Zhejiang, Jiangsu, and Shanghai continue to lead in terms of coordination and synergy, primarily due to their multiple advantages in terms of location, economic foundations, and human capital [100]. First, their advantageous locations, with Shanghai as the regional hub and Jiangsu and Zhejiang as adjacent core areas, combined with an efficient transportation network, facilitate the sharing of tourist sources and market synergy, making it easier to access domestic and international tourism markets. Meanwhile, through technical cooperation, R&D investment, and policy guidance, these regions gain access to advanced international digital technologies, accelerating digital innovation that supports tourism transformation and ecological protection. Second, Jiangsu, Zhejiang, and Shanghai possess a solid economic foundation, well-developed digital infrastructure, high industrial concentration, and a significant proportion of high-tech industries. These advantages have further driven the advancement of digital technology, thereby promoting the innovation and upgrading of the TI, accelerating the region's green and low-carbon transition, and fostering a virtuous cycle among the DE, TI, and EE subsystem. Third, Shanghai, Jiangsu, and Zhejiang possess richer educational resources, with the number and overall quality of their universities ranking among the top in the country. They have cultivated a large number of highly skilled and high-caliber professionals, and their inherent resource advantages have also attracted high-tech talent from across the nation. This has built up a sufficient reserve of high-level human capital for the development of the regional DTE system, thereby promoting its coordinated development. In contrast, as a peripheral region, Anhui lags behind in terms of resource aggregation, policy support, and factor mobility, resulting in a relatively lower level of coordinated development.

Currently, the CCD among the DTE systems of the three provinces and one municipality in the YRD has improved significantly; however, disparities in regional development persist, and the path toward achieving long-term, sustainable coordinated development in the region remains arduous.

4.3. Obstacle Degree Analysis

To further analyze the key factors constraining the coupling coordination of the DTE system in the YRD, this paper uses the obstacle degree model to calculate the obstacle degree at the DTE target layer for the region from 2010 to 2023 (Figure 7), as well as the primary obstacle factors at the indicator layer for the DTE system in the YRD in 2010, 2015, 2020, and 2023 (Table 3).

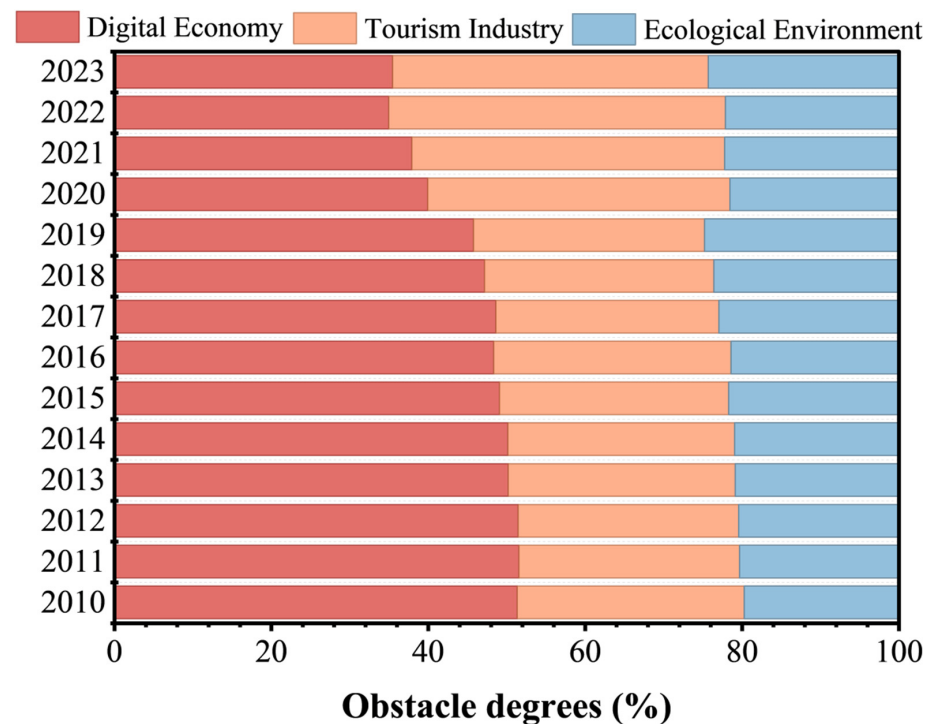


Figure 7. Obstacle degrees at target layer.

Table 3. The top 3 obstacle factors at the indicator layer.

Region	Year	First Obstacle Factor (Obstacle Degree)	Second Obstacle Factor (Obstacle Degree)	Third Obstacle Factor (Obstacle Degree)
Yangtze River Delta	2010	C5 (11.10%)	C7 (10.52%)	C4 (10.32%)
	2015	C5 (11.58%)	C7 (11.14%)	C4 (11.12%)
	2020	C7 (9.78%)	C5 (9.75%)	C14 (8.18%)
	2023	C2 (9.65%)	C5 (9.58%)	C9 (8.74%)
Jiangsu	2010	C5 (12.20%)	C7 (11.27%)	C4 (10.93%)
	2015	C5 (12.94%)	C7 (12.08%)	C4 (10.51%)
	2020	C5 (12.83%)	C7 (10.75%)	C4 (8.84%)
	2023	C5 (15.09%)	C2 (12.53%)	C14 (10.40%)
Zhejiang	2010	C5 (11.57%)	C7 (10.86%)	C4 (10.38%)
	2015	C5 (14.35%)	C7 (12.78%)	C4 (11.66%)
	2020	C5 (12.61%)	C7 (11.54%)	C14 (9.41%)
	2023	C5 (12.09%)	C2 (10.47%)	C14 (8.64%)
Anhui	2010	C5 (10.07%)	C4 (9.49%)	C7 (9.37%)
	2015	C5 (10.88%)	C7 (10.30%)	C4 (10.26%)
	2020	C5 (10.96%)	C7 (9.80%)	C4 (8.48%)
	2023	C5 (11.13%)	C7 (9.90%)	C2 (8.61%)
Shanghai	2010	C7 (10.59%)	C5 (10.53%)	C4 (10.48%)
	2015	C4 (12.07%)	C7 (9.42%)	C5 (8.14%)
	2020	C4 (12.06%)	C9 (8.56%)	C14 (7.89%)
	2023	C4 (13.79%)	C9 (10.68%)	C24 (8.87%)

From a systemic perspective, between 2010 and 2023, the DE system consistently served as the key factor hindering the coupling coordination of the YRD's DTE system, with the obstacle degree remaining above 33.33% throughout this period. This indicates that the DE system serves as the foundation for the coordinated development of the YRD's DTE system, with both the smart transformation of the TI and the digital monitoring of the EE highly dependent on the integration of digital economy technologies. If the DE itself is deficient, it becomes difficult to drive the coordinated development of the DTE system. Beginning in 2020, the obstacle degree of the tourism industry system rose to 38.56%, joining the digital economy system in hindering the coordinated development of the Yangtze River Delta's DTE system. From 2021 to 2023, the obstacle degree of the tourism industry system continued to rise, reaching 40.26% in 2023. This indicates that the regional tourism industry did not recover quickly following the impact of the global COVID-19 pandemic. Without timely and effective intervention measures, the tourism industry system will also pose a significant challenge to achieving the coupled and coordinated development of the DTE system. These findings are consistent with the conclusions of Pan et al., who, based on a study of 278 cities nationwide, identified the digital economy and tourism development subsystems as the primary sources of barriers to the coupling and coordination of the DTE system [90]. However, this study further reveals the temporal evolution of these barriers, indicating that the factors constraining the coupling and coordination of the DTE system exhibit distinct phased characteristics.

From an indicator perspective, between 2010 and 2015, key indicators constraining the coordinated development of the YRD's DTE system remained prominent. These specifically include the proportion of employees in the information transmission, computer services, and software industry (C5); e-commerce sales revenue (C7); and the number of legal entities in the information transmission, software, and information technology services sector (C4). All three indicators fall under the DE subsystem. As a national hub for the DE, the Yangtze River Delta, despite its massive digital economy scale, still faces significant shortcomings in three key areas: digital talent, digital enterprises, and digital markets. Moreover, these three shortcomings are intertwined, further hindering the rapid development of the DE system.

Further analysis indicates that the obstacles facing the DE system are not temporary phenomena but rather structural and path-dependent. Specifically, a self-reinforcing vicious cycle has formed within the DE subsystem: a shortage of digital talent constrains the growth of digital enterprises; an insufficient number and low quality of digital enterprises limit the expansion of the e-commerce market; and the constrained market scale, in turn, hinders the cultivation and aggregation of digital talent. This finding corroborates the research conclusions of Zhang et al., who found that per capita GDP, industrial structure upgrading, whether a city is a municipality directly under the central government or a provincial capital, high-speed rail accessibility, the number of employees in the information transmission and computer services sectors, the number of patent applications, the level of internet infrastructure, and research and fiscal expenditures all have a significant impact on the location decisions of digital enterprises [101]. Once such a closed loop is formed, it generates a strong self-reinforcing effect that is difficult to break through with a single policy measure alone. In their study of Europe's digital and green transitions, Carstensen et al. noted that skills shortages are not isolated talent gaps but rather systemic manifestations of a failing skills ecosystem [102]. A healthy skills ecosystem requires a dynamic balance among talent supply, corporate demand, and the market environment. However, the DE system in the YRD has fallen into an "imbalance trap"; the feedback loop among these three elements has not formed a virtuous cycle but instead constrains one another. This clearly indicates that the "skills ecosystem" within the region's DE system has already

failed. Therefore, while pursuing the expansion of the DE's scale, greater attention must be paid to its density, the vitality of its participants, and market depth.

After 2020, the number of domain names per thousand people (C2), the number of star-rated hotels (C9), and the total number of inbound tourists (C14) became key factors influencing the coupling coordination of the DTE system in the YRD. With the outbreak of the COVID-19 pandemic in 2020, international travel came to a virtual standstill. As an export-oriented economic zone, the YRD saw a sharp decline in C14, and the slump in the TI severely hampered the coupling coordination of the DTE system. C2 became the largest obstacle factor (9.65%) in 2023, indicating that while the YRD region has accelerated its digital transformation, digital infrastructure resources such as domain name registration and website development have not grown in tandem. This has resulted in a situation where the intensity of digital infrastructure usage is overloaded while the breadth of application remains insufficient. When network bandwidth and computing resources are heavily occupied by high-frequency applications, the barriers and costs for small and medium-sized entities and start-ups to deploy new domains and applications rise. This will lead to a slowdown in the growth of the number of domains per thousand people, a relative increase in the degree of obstruction, and constraints on the digital economic development of the DTE system. In 2023, the C9 entered the top three for the first time, indicating a slow recovery of the high-end service sector post pandemic, with insufficient high-end tourism and business hospitality facilities emerging as a new constraining factor.

From 2015 to 2023, the proportion of employees in the information transmission, computer services, and software industry (C5) was the primary obstacle affecting the coordinated development of the DTE system in Jiangsu, Zhejiang, and Anhui. In Shanghai, however, the situation was entirely different: the number of legal entities in the information transmission, software, and information technology services sector (C4) was the primary obstacle. The differences in primary constraints between Jiangsu, Zhejiang, Anhui, and Shanghai essentially reflect two distinct patterns of constraints—digital talent shortages and insufficient business ecosystems—resulting from varying stages of development. Jiangsu, Zhejiang, and Anhui are all in a phase of rapid expansion of the digital economy, with rapid growth in industrial scale; however, the supply of digital professionals cannot keep pace, making C5 the primary obstacle. As the leading city in the YRD, Shanghai has entered the maturity phase of the digital economy and possesses distinct advantages in terms of salary levels, career development, and innovation resources. Some high-end digital talent cultivated in Jiangsu, Zhejiang, and Anhui tends to migrate to Shanghai; however, excessively high office rents, labor costs, and compliance costs are stifling the viability of information service enterprises.

Between 2020 and 2023, the obstacle degree for the total number of inbound tourists (C14) regarding the coupling coordination of Zhejiang's DTE system decreased from 9.41% to 8.64%. Although the obstruction has eased somewhat, it still ranks among the top three, indicating that the recovery of inbound tourism remains Zhejiang's most urgent and challenging task, requiring the timely implementation of targeted measures such as digital marketing and product innovation. In 2023, the obstacle degree of the number of domain names per thousand people (C2) with the DTE systems of Jiangsu and Anhui increased, indicating that enterprises in both provinces lack sufficient attention and investment in domain names—a fundamental digital asset—during their digital transformation processes.

It is worth noting that in 2023, the obstacle degree of annual investment in environmental pollution governance (C24) for Shanghai's DTE system increased. This may be attributed to Shanghai's comprehensive economic recovery in 2023, which saw a surge in activities such as the digital economy and high-end tourism, leading to a sharp rise in energy consumption, carbon emissions, and waste disposal pressures. However, invest-

ment in environmental pollution control requires long-term planning and substantial fiscal expenditure. Actual investment in 2023 failed to keep pace with the speed of economic recovery, causing the C24 obstacle degree to reach 8.87% and become the third-largest obstacle for the first time. Shanghai's local challenges reflect the structural difficulties faced by developing countries worldwide. International estimates indicate that developing countries face an annual funding gap of approximately \$4 trillion in achieving the SDGs and climate goals, with the specific gap in the area of green and low-carbon transition accounting for more than 60 percent of this total, constituting a systemic fiscal constraint that hampers their development process [103]. This suggests that if investment in environmental governance fails to keep pace during the economic recovery phase, the costs of lagging environmental governance will continue to accumulate over time and may ultimately exert negative pressure on regional sustainable development.

5. Conclusions and Implications

This paper constructs a comprehensive evaluation index system for the DE, TI, and EE. By applying a coupling coordination degree model and an obstacle degree model, it examines the coupling coordination of the DTE system in China's YRD region from 2010 to 2023 and investigates the key obstacle factors affecting the sustainable development of the DTE system.

5.1. Conclusions

- (1) From 2010 to 2023, the development levels of the DE and EE in the YRD generally trended upward. The tourism sector grew from 2010 to 2019 but then experienced a sharp decline from 2020 to 2022 due to the global pandemic. Significant regional disparities existed in DE, forming a tiered structure: Shanghai ranked the highest, Jiangsu and Zhejiang were in the second tier, and Anhui lagged significantly behind. For the TI, development trends diverged clearly: Jiangsu and Zhejiang have long been in the first tier, while Anhui and Shanghai have been in the second tier. Regarding the EE, Jiangsu and Zhejiang showed marked improvement, Shanghai remained stable at a relatively high level, and although Anhui continued to improve, it still lagged behind overall.
- (2) From a temporal perspective, between 2010 and 2019, the coupling and coordination level of the Yangtze River Delta DTE system rose steadily from 0.434 to 0.676, gradually improving from near-dysfunction to a state of primary coordination, confirming the effectiveness of the YRD integration strategy. From 2020 to 2023, although the level of coupling and coordination fluctuated, it remained stable at the primary coordination stage, indicating that the system still has room for further improvement. In terms of spatial distribution, the level of coupling and coordination of the DTE system across the three provinces and one municipality in the YRD generally exhibits a pattern of "higher in the east and lower in the west".
- (3) The results of the barrier analysis indicate that from 2010 to 2019, the bottleneck in the coordinated development of the Yangtze River Delta DTE system primarily stemmed from the digital economy subsystem; after 2020, the barrier level of the tourism subsystem rose rapidly, creating a pattern where both the digital economy and tourism subsystems act as mutual constraints. The proportion of employees in the information transmission, computer services and software industry (C5) remained a persistent constraint throughout the study period. In 2010 and 2015, e-commerce sales revenue (C7) and the number of legal entities in the information transmission, software, and information technology services industry (C4) were major obstacle factors, but after 2020, new constraints such as the total number of inbound tourist

volume (C14), the number of domain names per 1000 people (C2), and the number of star-rated hotels (C9) became increasingly prominent.

5.2. Implications

5.2.1. Theoretical Implications

This study makes three theoretical contributions to the literature on regional sustainable development and coupled systems. First, by transcending binary interactions (DE-TI, DE-EE, TI-EE) to construct a unified ternary DTE framework, we demonstrate that the coordination of the three systems is not a linear process but is subject to structural lock-in during the “conservative phase” of the adaptation cycle. This challenges the traditional assumption that “the higher the level of economic development, the greater the system coordination”. On the contrary, our findings indicate that even developed regions such as the YRD may fall into a “low-level coordination trap”, where the stability of local optima hinders further upgrading. Second, the dynamic identification of constraints reveals that bottlenecks exhibit phased characteristics. The transition from single-system (DE) to dual-system (DE + TI) constraints highlights the importance of incorporating temporal phases into coupling analysis. This temporal perspective adds a new dimension to the existing literature, which has largely treated constraints as static. Third, the “talent–enterprise–market” lock-in cycle within the digital economy system provides a micro-level mechanism that explains how skill ecosystem failures become self-reinforcing and hinder system-wide coordination. This extends the application of skill ecosystem theory from industrial and labor economics to the field of regional sustainable development governance.

5.2.2. Practical Implications

- (1) The YRD must strengthen policy harmonization and coordination in implementation, and establish mechanisms for the cross-regional mutual recognition of professional titles and the mobility of digital talent to alleviate the conflict between talent shortages in Jiangsu, Zhejiang, and Anhui and the “brain drain” in Shanghai. Localities should jointly build a YRD smart tourism platform and develop new business models such as virtual tourism to reduce reliance on inbound tourists. At the same time, they need to establish a dynamic monitoring mechanism for emerging obstacles to promptly address issues such as lagging growth in the number of domain names per thousand people, the slow recovery of star-rated hotels, and environmental governance investments failing to keep pace with economic recovery, thereby promoting the orderly and coordinated development of the digital economy, the tourism industry, and the ecological environment.
- (2) Localities must implement differentiated policies. Jiangsu should intensify efforts to cultivate local digital talent, reduce operational costs for small and medium-sized IT enterprises, support companies in building independent websites and registering their own domain names, and expand the scale of e-commerce. Zhejiang should develop alternative products such as virtual tourism and wellness tourism to reduce over-reliance on inbound tourists, while consolidating its advantages in the digital economy to prevent talent outflow. Shanghai should lower the cost of doing business for IT enterprises, increase investment in pollution control, ensure that environmental investments keep pace with economic recovery through channels such as green bonds, and convert existing properties into boutique hotels through urban renewal to meet high-end tourism demand. Anhui should address shortcomings in digital infrastructure, provide subsidies for domain name registration and website development, collaborate with universities in Jiangsu, Zhejiang, and Shanghai to cultivate digital talent, attract the return of talent, and facilitate the transfer of digital industries. At

the same time, it should seize the opportunities presented by regional integration to address shortcomings in environmental infrastructure and develop a green economy.

5.3. Limitations and Future Prospects

This study has four main limitations. First, the indicator system is incomplete, missing variables such as digital innovation outputs and micro-level ecological behaviors. Second, it focuses only on internal factors, excluding external drivers like human capital and environmental regulations. Third, the provincial-level analysis may hide intra-provincial disparities, as cities within the same province differ greatly in digital infrastructure, tourism resources, and environmental governance. Fourth, it lacks statistical testing, including trend significance tests, spatial clustering tests, and causal inference methods. This is due to the exploratory nature of the research and the small provincial sample of only four units. Accordingly, future research will adopt a finer spatial scale based on prefecture-level city data, apply causal inference methods such as panel Granger causality and system GMM, refine the indicator system, incorporate external drivers, and reveal interregional synergy patterns to inform policy.

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