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MEASUREMENT OF DIGITAL RURAL DEVELOPMENT LEVEL AND ITS INFLUENCING FACTORS IN THE YANGTZE RIVER DELTA REGION

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Abstract: This paper proposes a data-driven method for measuring the level of regional digital rural development. Based on data collection and application across dimensions such as digital infrastructure, digitalization of rural economy, digital governance, and digital rural life, an evaluation index system for digital rural development is constructed. The entropy weight TOPSIS model is applied to measure and evaluate the overall level of digital rural development and its four subsystems, providing targeted policy recommendations. The obstacle degree model is employed to identify key factors constraining the improvement of digital rural development. Taking the Yangtze River Delta region from 2014 to 2023 as a case study, the paper demonstrates the implementation process of the data-driven approach. The research results validate the feasibility of the proposed methodology, offering theoretical and methodological support for digital rural development studies and management, and providing decision-making foundations for enhancing regional digital rural development, promoting high-quality rural development, and achieving common prosperity.
Keywords: Data-driven; Digital rural construction; Entropy-weighted TOPSIS method; Obstacle degree model

1 INTRODUCTION

In the era of rapid development of the digital economy, its inherent disruptive and inclusive effects are opening up an unprecedented historical window for rural transformation. This is not only the core engine driving the modernization of agriculture and rural areas, but also the key breakthrough point for resolving the bottlenecks in digital rural development and achieving systematic reconfiguration [1]. Since China implemented the digital rural strategy, digital technologies have deeply integrated into the organizational structure and economic operation of rural society: driving the iterative upgrading of rural industries, improving the quality of rural residents' lives, and reconstructing the modern rural governance system, becoming an indispensable strategic fulcrum in rural revitalization [2]. According to the "China Digital Rural Development Report (2024)", in 2023, China's rural online retail sales reached 2.49 trillion yuan, the agricultural production informatization rate increased to 26.5%, and the rural internet penetration rate reached 66.5%, marking the achievement of phased-scale expansion of the rural digital ecosystem. However, the deep-seated structural problem of uneven digital development among regions remains prominent. This imbalance not only restricts the release of overall strategic effectiveness, but is also likely to exacerbate the development gap between regions [3]. Therefore, accurately assessing the level of digital rural development in different regions, scientifically identifying its key constraints, optimizing resource allocation, promoting coordinated development, and constructing an inclusive modern digital rural governance system are all necessary to provide decision-making basis for promoting digital rural development from scale coverage to a high-quality stage of quality improvement and efficiency enhancement.

The research on digital rural construction is highly in line with the global trend of driving sustainable development and inclusive growth through digital transformation. Currently, the related discussions in the academic community have formed a relatively clear framework, and the research results mainly focus on the following two aspects: First, the research on the connotation of digital rural construction. Clarifying the connotation of digital rural is the prerequisite for implementing the digital rural strategy and also the basis for measuring the level of digital rural construction. From the perspective of the development process, digital rural is a gradual evolutionary process of digital technology in the agricultural and rural fields, from introduction, penetration, integration to endogenous development. It is not only a linear expansion of technology application, but also a systematic reshaping of the rural economic and social structure, governance model, and production and lifestyle [4-5]; from the technological perspective, digital rural is the comprehensive penetration, deep integration and innovative application of new-generation information technologies in the agricultural and rural fields, and the construction of a digital, networked and intelligent technology system for agricultural production methods, governance models and lifestyles [6-8]; from the governance perspective, digital rural is the process of rural governance modernization transformation where digital technology is embedded in the rural governance system, promoting the diversification of governance subjects, transparency of governance processes, intelligence of governance methods and precise governance effectiveness [9-10]; from the systems perspective, digital rural is a complex adaptive system centered on data elements, with the interaction of various subsystems such as technology, economy, governance, society and ecology, achieving the optimization, upgrading and innovation of the overall functions, structure and model of the rural area [11-13]. Second, the measurement of the level of digital rural construction. Some scholars have constructed indicators from four dimensions: digital economic environment, digital infrastructure, agricultural digital transformation, and life digitalization, and measured the level of rural digital economic development using entropy method, Dagum Gini coefficient, Kernel density estimation method and Moran's I index [14]; some scholars have constructed a digital rural evaluation index system from four dimensions: digital capital investment, digital industry development, digital information foundation and digital service level, and measured the level of digital rural construction using entropy method, Theil index, Moran index and other methods [15-16]; some scholars have constructed an index system of digital rural infrastructure, digital rural development environment, rural digital application and rural digital governance from four dimensions, and measured the level of digital rural development using AHP-entropy weight method [17]; some scholars have constructed an evaluation index system from six dimensions: digital foundation, digital industry, digital culture, digital governance, digital service and green development, and measured the level using entropy method [18].

In conclusion, although scholars have achieved considerable research results on the construction of digital villages and have laid a theoretical foundation for this study, there are still certain limitations. Firstly, the definition of the concept of digital village construction remains inconsistent; secondly, the construction level index system of digital villages focuses on infrastructure and development environment dimensions, failing to fully reflect how digital technology changes the essential attributes of rural areas; thirdly, existing studies mostly adopt a single method for evaluation, lacking the use of an integrated system approach. Based on this, this study, after reviewing the theoretical boundaries of the concept of digital village construction and the theoretical basis of digital empowerment, constructs an index system for measuring and evaluating the construction level of digital villages in the Yangtze River Delta region; and uses the entropy weight-Topsis method and the obstacle degree model integrated system approach to measure the trend of the construction level of digital villages in the Yangtze River Delta region and identify the key constraints, providing theoretical references for promoting the high-quality development of digital village construction in the Yangtze River Delta region. To achieve the above research goals, the second part of the paper is methods, the third part is case analysis, and the fourth part is conclusions.

2 METHODOLOGY

This section provides a comprehensive overview of measurement, evaluation, and identification methods, including method procedures, data collection, data processing, data models, and data applications.

2.1 Method Flow

This paper has developed a data-driven comprehensive evaluation method for the level of regional digital rural development, aiming to measure, evaluate, and identify the key influencing factors of such development. The main research methods include: Data collection involves constructing an evaluation index system for regional digital rural development from four dimensions: digital infrastructure, digitalization of rural economy, digitalization of rural governance, and digitalization of rural life. Data processing employs the minimum-maximum normalization method to non-dimensionalize the indicators, and the entropy method is used to determine the weights of each indicator. Data models sequentially use the entropy method to comprehensively quantify the evaluation of regional digital rural development; and the obstacle degree model is used to identify the key factors that constrain its development. Data application involves scientifically evaluating the development level and its dynamic evolution trend based on the analysis results, and then proposing targeted improvement strategies to promote practical development.

2.2 Data Collection

The paper uses the entropy method to measure the digital countryside. Considering the basic current situation of digital countryside construction and the availability of data, it mainly constructs an evaluation index system for the level of digital countryside construction from four dimensions: digital infrastructure, digitalization of rural economy, digitalization of rural governance, and digitalization of rural life. The specific index system is shown in Table 1.

2.3.2 Determining indicator weights using the entropy method

To objectively quantify the relative importance of individual indicators, the entropy method was adopted to assign differentiated weights to standardized indicator datasets. The detailed calculation procedures are specified as follows. Firstly, the information entropy value H_j was calculated (see Equation 2). A higher value of $1-H_j$ implies greater information utility of a given indicator, thereby granting the indicator a larger weight in the comprehensive evaluation system. Subsequently, the weight of each indicator was computed in accordance with Equation 4.

$$H_j =-\frac{1}{\ln n}\sum_{i=1}^{n} f_{ij} \ln f_{ij} \tag{2}$$

$$f_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \tag{3}$$

$$w_j = \frac{1-H_j}{\sum_{j=1}^{m}(1-H_j)} \tag{4}$$

Table 1 Evaluation Index System for Digital Rural Construction Level

Target layer	Criterion layer	Indicator layer	Indicator description and attribute	Indicator weight
Level of digital rural construction	Digital infrastructure (Y1)	Coverage rate of rural logistics(X1)	Rural delivery route (km)(+)	6.2355%
		Investment in logistics infrastructure(X2)	Fixed asset investment in transportation, storage, and postal services (CNY 100 million)(+)	5.6901%
		Internet infrastructure construction(X3)	Rural broadband subscribers (households)(+)	9.1350%
		Rural meteorological observation station(X4)	Agrometeorological observation stations (units)(+)	7.5793%
	Digitization of the rural economy (Y2)	Rural e-commerce(X5)	Number of Taobao villages (units)(+)	21.0579%
		Talent support for digital rural construction(X6)	Professional technical personnel in the public sector (persons)(+)	7.3299%
		Digital technology services(X7)	Employment in information transmission, software, and IT services (persons)(+)	6.5580%
		Capital investment in e-commerce infrastructure(X8)	Local fiscal expenditure on transportation (CNY 100 million)(+)	2.6012%
		Level of digital financial development(X9)	Digital financial inclusion index(+)	3.7665%
	Digitization of rural governance (Y3)	Funding for digital rural governance(X10)	Local government expenditure on community affairs (CNY 100 million)(+)	3.5336%
		Level of e-government development(X11)	Provincial online government service capability(+)	1.2836%
	Digitization of rural livelihoods (Y4)	Television penetration rate(X12)	Rural TV program population coverage rate (%)(+)	1.4735%
		Radio penetration rate(X13)	Rural radio program population coverage rate (%)(+)	1.5704%
		Information service consumption level(X14)	Rural per capita transport & communication expenditure (CNY)(+)	3.3928%
		Information technology services(X15)	Total telecom service volume (CNY 100 million)(+)	16.1146%
		Smartphone penetration rate(X16)	Mobile phones per 100 rural households (units)(+)	2.6781%

2.4 Data Modeling

2.4.1 Entropy-weighted TOPSIS method

This study selects the entropy-weighted TOPSIS method for the comprehensive assessment of digital rural construction levels. The detailed calculation steps are presented below.

2.4.1.1 Construction of the weighted decision matrix

To improve the objectivity of digital rural evaluation and accurately distinguish the heterogeneity among various indicators, this study introduced a weighting concept. The entropy method was utilized to construct a weighted evaluation matrix, as illustrated in Equation (5).

$$V=\begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix}=\begin{bmatrix} z_{11}.w_1 & z_{12}.w_2 & \cdots & z_{1n}.w_n \\ z_{21}.w_1 & z_{22}.w_2 & \cdots & z_{2n}.w_n \\ \vdots & \vdots & \vdots & \vdots \\ z_{m1}.w_1 & z_{m2}.w_2 & \cdots & z_{mn}.w_n \end{bmatrix} \tag{5}$$

where z_{ij} denotes the standardized indicator value, and w_j represents the corresponding indicator weight.

2.4.1.2 Determination of positive and negative ideal solutions for indicators

Let V^+ denote the maximum value of the *j*-th indicator across all weighted evaluation samples, namely the optimal solution defined as the positive ideal solution. Similarly, let V^- represent the minimum value of the *j*-th indicator, corresponding to the inferior solution as the negative ideal solution. The relevant calculation formulas are presented in Equations (6) and (7).

$$V^+ = \{max\, v_{ij} \middle| i = 1,2,\cdots,m\} \tag{6}$$

$$V^- = \{min\, v_{ij} \middle| i = 1,2,\cdots,m\} \tag{7}$$

2.4.1.3 Calculation of Euclidean distances to the positive and negative ideal solutions

Let D_i^+ and D_i^- denote the distances from each evaluation object vector to the positive and negative ideal solutions, respectively, as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^+)^2} \qquad (i = 1,2,\cdots,m) \tag{8}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^-)^2} \qquad (i = 1,2,\cdots,m) \tag{9}$$

2.4.1.4 Calculation of closeness degree C_i

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{10}$$

The closeness degree quantifies the proximity of the digital rural construction level of each evaluated sample to the positive ideal solution (i.e., the optimal scheme), with values ranging from 0 to 1. A higher value of C_i closer to 1 indicates a superior digital rural construction level of the research sample; conversely, a value closer to 0 signifies a lower construction level. The magnitude of the closeness degree enables the quantitative assessment and hierarchical ranking of digital rural development across all evaluated samples.

2.4.2 Obstacle degree model

The evaluation of digital rural construction serves dual purposes: to objectively assess developmental levels and identify core restrictive factors hindering quality improvement, thereby supporting the formulation of targeted policy implications. Accordingly, further obstacle factor analysis is essential for in-depth mechanism exploration. This method adopts three critical indicators for quantitative calculation: the factor contribution degree (F_j), which reflects the influence intensity of the j-th indicator on digital rural development; the indicator deviation degree (O_{ij}), which measures the gap between the actual indicator value and the expected developmental benchmark; and the obstacle degree (M_j), which quantifies the negative constraint effect of individual or categorical indicators on digital rural construction. The relevant calculation formulas are displayed below.

$$F_j = r_i \times w_{ij} \tag{11}$$

where r_i denotes the weight of the *i*-th subsystem in the comprehensive evaluation model, and w_{ij} represents the weight of the *j*-th indicator contained within the *i*-th subsystem.

$$O_{ij} = 1 - x_{ij}^{'} \tag{12}$$

Where O_{ij} denotes the deviation degree of the *j*-th indicator in the *i*-th region, and $x_{ij}^{'}$ represents the standardized individual indicator value.

$$M_j = F_j \times O_{ij} / \sum_{i=1}^{n} F_j \times O_{ij} \times 100\% \tag{13}$$

where n represents the number of indicators in the system. A larger value of M_j indicates a higher degree of obstacle posed by that basic indicator to the level of digital rural construction. Sorting the values in descending order allows the primary and secondary obstacle factors to be identified.

where n denotes the total number of indicators contained in the evaluation system. A larger M_j value signifies a stronger inhibitory constraint of the corresponding basic indicator on digital rural construction. Ranking these values in descending order facilitates the identification of primary and secondary obstacle factors.

2.5 Data Application

This research focuses on the measurement, evaluation and identification of the level of digital rural construction driven by data. The specific data application process is shown in Figure 1. The main steps are as follows:

The first step is to construct a comprehensive evaluation dataset. Following the definition of the digital countryside, an evaluation index system is established from four dimensions: digital infrastructure, digitalization of rural economy, digitalization of rural governance, and digitalization of rural life. A comprehensive database is constructed to dynamically monitor and reflect the actual situation of the level of digital countryside construction.

The second step is to measure the construction level and identify the key influencing factors. The entropy weight method is used to objectively assign weights to each indicator based on the differences in the degree of influence of the indicators. The TOPSIS method is combined to conduct a comprehensive quantitative evaluation of the level of digital countryside construction, forming a time series quantitative result of regional construction level. Further, the obstacle degree model is used to identify the key limiting factors that constrain the improvement of the level of digital countryside construction.

The third step is based on the quantitative evaluation results, from aspects such as infrastructure construction, core development goals and institutional guarantees, propose countermeasures and suggestions to promote the improvement of the level of rural digitalization construction.

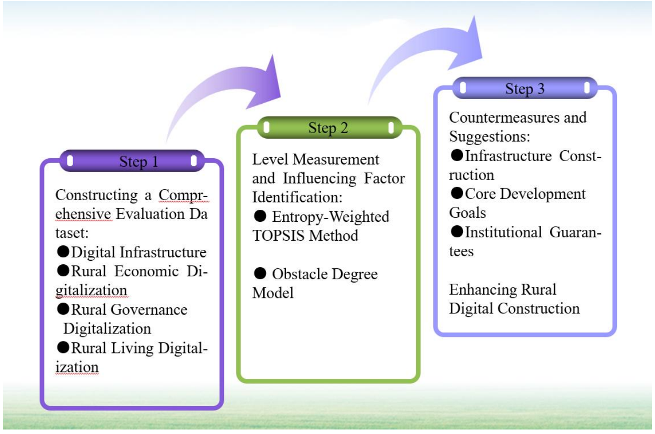

Figure 1 Flowchart of Data Application in Digital Rural Construction

3 CASE STUDY

3.1 Background of the Case Study

The Yangtze River Delta region (including Shanghai, Jiangsu, Zhejiang, and Anhui provinces) is one of the regions with the highest economic development levels in China. In 2024, this region achieved a regional GDP of 33.17 trillion yuan, accounting for approximately 24.7% of the national total. As a core area of national economic and social development, the Yangtze River Delta region not only shoulders the pioneering and exemplary mission of promoting the deep integration of urban and rural areas and exploring the path to common prosperity, but also faces practical challenges such as uneven digital development within the region, insufficient integration of technology and rural industries, and an incomplete long-term mechanism. Systematically assessing the actual level of digital rural construction in this region can not only provide a scientific reference for accurately identifying development shortcomings, optimizing policies and resource allocation, but also help summarize and extract regional practical experiences with operational feasibility and promotion value, further promoting the efficient flow of urban and rural elements, alleviating digital inclusiveness risks, and effectively stimulating the internal development momentum of rural areas, thereby providing the "Yangtze River Delta model" for the national digital rural construction.

3.2 Results

By applying the entropy value - TOPSIS method, the temporal and spatial evolution trend of the digital rural construction level in the study area was comprehensively evaluated; further, the obstacle degree model was utilized to identify the key driving factors that hinder the improvement of the digital rural construction level in the region. The specific results are as follows:

3.2.1 Results of the temporal and spatial evolution trend of the overall digital rural construction level in the Yangtze River Delta region

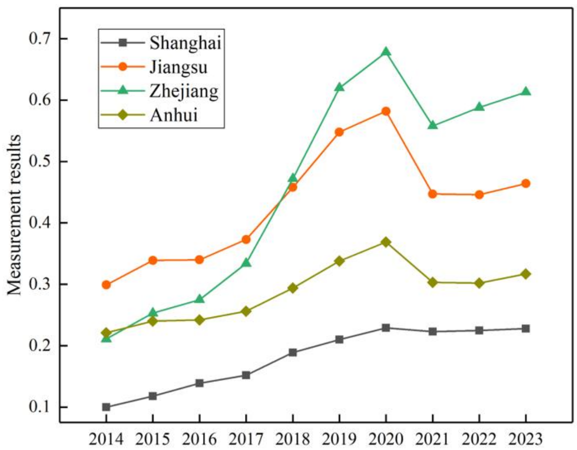

Figure 2 Evaluation Results of Digital Rural Construction Level in the Yangtze River Delta

From the trend shown in Figure 2, it can be observed that from 2014 to 2023, the digital village construction levels of all provinces in the Yangtze River Delta region showed an increasing trend, but there were significant differences in the growth rate and development path. Among them, Jiangsu and Zhejiang were overall leaders, Anhui was in the middle position of catching up, and Shanghai had a relatively low starting point but maintained steady progress. Specifically: Jiangsu Province began at 0.299 in 2014. Except for a phased adjustment in 2021, it maintained an upward trend in the other years, and by 2023, it had recovered to 0.464, approaching the level before the adjustment, demonstrating its solid foundation, complete system, and strong ability to resist fluctuations. Zhejiang Province had particularly significant growth rates, especially after 2018, it accelerated upward, reaching a peak of 0.678; although the adjustment in 2021 was large, it recovered quickly, and by 2023, it had rebounded to 0.613, reflecting its clear market-driven nature, rapid trial and error, and continuous growth development characteristics. Anhui Province gradually increased from 0.221 to 0.317 in 2023, still having a significant gap compared to Jiangsu and Zhejiang, but its growth rhythm was stable, in line with its status as a major agricultural province and the function of undertaking industrial transformation and promoting agricultural digitalization. Shanghai had an overall lower level, with 0.228 in 2023, consistent with its small rural area proportion and the focus of digital construction on urban modern agriculture and rural revitalization demonstration projects. The formation of the differences in the digital village construction levels in the Yangtze River Delta region mainly resulted from the following factors: Jiangsu and Zhejiang provinces had developed county economies and had good rural industrial foundations, with large digital investments, especially earlier layout in e-commerce, smart logistics, and digital agriculture fields, thus having a higher overall level and rapid growth. As a major agricultural province, Anhui Province has continuously made efforts in the industrial transfer of the Yangtze River Delta and promoting agricultural digital transformation, with a stable growth rate, but due to the overall economic level and infrastructure conditions, it still has a gap compared to Jiangsu and Zhejiang. Shanghai's rural area is small, with digital construction focusing on urban modern agriculture and high-quality demonstration projects, reflecting a "small but exquisite" development path.

3.2.2 Results of the spatiotemporal evolution trend of the digital village construction level subsystem in the Yangtze River Delta region

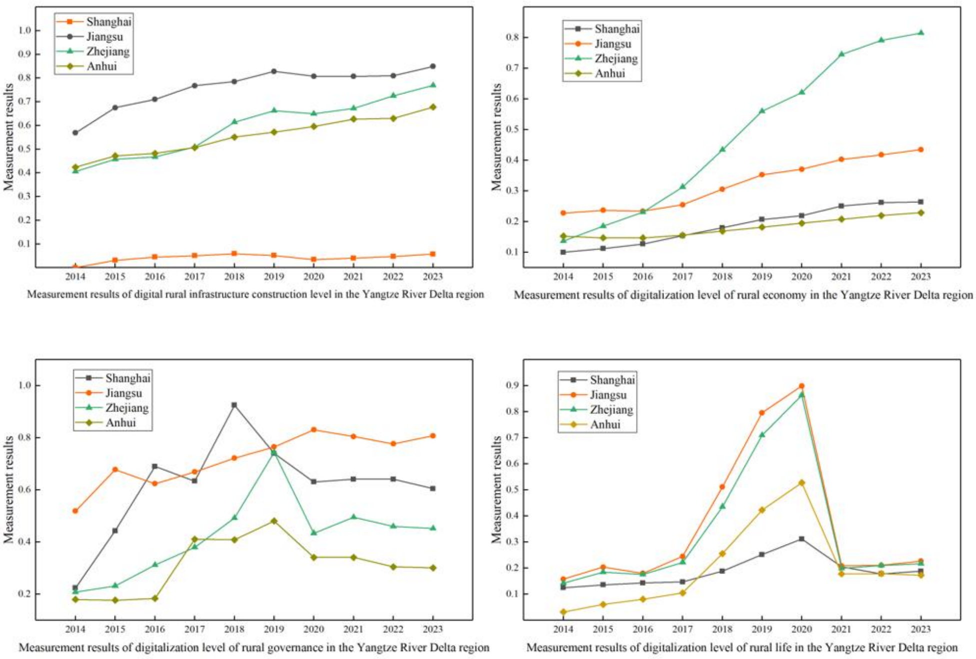

Figure 3 Subsystem-Level Measurement Results of Digital Rural Construction in the Yangtze River Delta

Figure 3 presents the evaluation results of each subsystem of the digital rural construction in the Yangtze River Delta region. The detailed analysis is as follows:

3.2.2.1 Digital infrastructure level

From Figure 3, it can be observed the evolution trend of digital infrastructure construction in the Yangtze River Delta region from 2014 to 2023. The overall trend has been upward since 2014, with significant growth rates in Jiangsu, Zhejiang, and Anhui provinces, while Shanghai has maintained a relatively stable level with a significantly lower level. The digital infrastructure construction level in Jiangsu Province steadily increased from 0.569 in 2014 to 0.849 in 2023, with a significant growth rate from 2017 to 2019. After 2020, there were slight fluctuations, but it remained at a high level, reflecting its advantages in system promotion capabilities and solid foundation. Zhejiang Province demonstrated the strongest growth momentum, with a particularly significant increase after 2018, from 0.614 to 0.769 in 2023, with an increase of nearly 90%, reflecting clear policy guidance and active market response. Anhui Province gradually increased from 0.424 to 0.678, with an increase of approximately 60%, indicating its active pursuit of the opportunities of the Yangtze River Delta integration while continuously increasing investment in digital infrastructure. In contrast, Shanghai's data remained within a narrow range of 0.03 to 0.06, reflecting the relatively lower priority of digital infrastructure construction in its rural development. These differences are closely related to the economic development stage, rural structure characteristics, and policy orientation of each province. Jiangsu Province and Zhejiang Province, relying on their strong fiscal strength and high economic development levels, have systematically promoted the layout and upgrading of hardware facilities such as rural network coverage and data centers; Anhui Province, as a traditional agricultural province, has continuously strengthened information infrastructure construction under the dual promotion of "Digital Anhui" and rural revitalization policies, gradually narrowing the gap with advanced regions in the Yangtze River Delta; Shanghai, due to its limited rural area and a more urban-oriented function positioning in rural areas, has a relatively lower proportion of digital infrastructure in the overall evaluation system.

3.2.2.2 The digitalization level of rural economy

As shown in Figure 3, from 2014 to 2023, the digitalization level of rural economy in the three provinces and one municipality of the Yangtze River Delta region has been continuously rising, but there are significant differences in the growth rates. Among them, Zhejiang Province performed particularly well, especially during the period from 2017 to 2021, with a significant growth rate. After 2021, although it slightly slowed down, it still remained at a relatively high level, reaching 0.815 by 2023, indicating that the rural digital economy in Zhejiang Province has entered a stage of large-scale and systematic deepening, demonstrating strong development vitality and the effectiveness of rural industrial structure transformation. Jiangsu Province and Shanghai Province had relatively stable growth, rising from 0.228 and 0.1 to 2023's 0.435 and 0.264, reflecting a steady and orderly advancement path. Anhui Province started at a lower level and had relatively slow growth, rising from 0.153 to 0.229, overall still at a relatively low level, reflecting insufficient development momentum of rural digital economy and the continuous widening gap with Jiangsu and Zhejiang. These development differences are closely related to the economic structure, policy orientation, and rural industrial foundation of each province. Zhejiang Province, with its solid digital economy foundation, rapid development of new business forms such as rural e-commerce and live-streaming sales, as well as the coordinated promotion of "digital village" and "common prosperity" policies, has led the digitalization performance of rural economy. Jiangsu Province relies on developed county economies and a complete rural industrial system, and the digital transformation process has been continuously and steadily advanced. Shanghai Province, due to the relatively low proportion of agriculture in the economic total, the digitalization of rural economy mainly focuses on characteristic scenarios such as urban agriculture and high-quality tourism, and the overall driving effect is limited. Anhui Province, with a relatively late start in rural digital economy development, still lacks strong infrastructure, talent reserves, and capital investment, and the growth momentum needs to be further enhanced.

3.2.2.3 Digitalization level of rural governance

As shown in Figure 3, from 2014 to 2023, the overall digitalization level of rural governance in the Yangtze River Delta region showed a fluctuating upward trend, but there were significant regional differences. Among them, Jiangsu Province had the most stable development trend, while Zhejiang Province and Shanghai Province had relatively large fluctuations. Anhui Province exhibited a "U-shaped" evolution characteristic of first rising and then falling. Specifically, Jiangsu Province steadily increased from 0.519 in 2014 to 0.808 in 2023, although there were fluctuations during this period, the overall level remained at a high level, demonstrating its systematic and continuous progress in rural governance digitalization. Shanghai Province rose rapidly from 2015 to 2018, reaching a peak of 0.925 in 2018, then gradually declined and stabilized at the range of 0.6 - 0.65, reflecting that after the concentrated construction stage, the development of digital governance in Shanghai has gradually slowed down. Zhejiang Province reached a high point of 0.744 in 2019, but then significantly declined, reaching 0.452 in 2023, indicating that during the rapid advancement process, the digital governance construction in Zhejiang Province faced certain sustainability pressure. Anhui Province achieved a relatively rapid improvement from 2017 to 2019, rising from 0.18 to 0.481, but then continued to decline, reaching 0.301 in 2023, indicating that its rural governance digitalization process encountered a certain development bottleneck at a certain stage. The differences in performance among various provinces mainly stem from the differences in governance foundation, policy continuity, and digital application scenarios. Jiangsu Province, relying on a relatively mature governance system, deeply promotes the integration of digitalization and grassroots governance, continuously improves the "grid-based + digital" model, and thus maintains a stable development trend. Shanghai Province, with strong financial and technical support, achieved rapid construction and visible results in the early stage, but as the focus of urban governance shifted, the subsequent investment and advancement pace of rural governance digitalization have slowed down. Zhejiang Province, despite being at the forefront in digital government construction, is constrained by factors such as institutional connection and other mechanisms, resulting in a high-level adjustment. Anhui Province, driven by the policy of the Yangtze River Delta integration, achieved a certain improvement at a certain stage, but due to relatively weak foundations and incomplete long-term mechanisms, the sustainable development momentum is insufficient, leading to a lack of strength.

3.2.2.4 The digitalization level of rural life

As shown in Figure 3, from 2014 to 2020, the overall digitalization level of rural life in the three provinces and one municipality of the Yangtze River Delta region showed a rapid upward trend. However, since 2021, the data in all regions have significantly declined, and then remained at a relatively low level and stabilized between 2021 and 2023, forming a three-stage evolution pattern of "rapid increase - sudden decline - stable at a low level". Specifically for each province and municipality, Jiangsu Province has consistently maintained the lead, reaching a peak of 0.899 in 2020, significantly higher than other regions; although it dropped sharply to 0.209 in 2021, it gradually recovered to 0.227 in 2023, still ranking first among the four regions. Zhejiang Province also reached a high point of 0.863 in 2020, plummeted to 0.199 in 2021, and then slightly recovered to 0.217. Shanghai had a relatively moderate growth, with a peak of 0.312 in 2020, falling to 0.205 in 2021, and stabilizing at 0.188 in 2023. Anhui Province had the lowest starting point, but made significant progress during 2018-2020, reaching 0.528 in 2020, then declined, and was 0.173 in 2023, overall still lagging significantly behind Jiangsu and Zhejiang. The performance differences among the provinces and municipalities are closely related to their development stages, policy support intensity, and rural social structures.

Jiangsu and Zhejiang have solid economic foundations and systematic digitalization layouts, investing heavily in rural network coverage and smart services, thus having a strong growth momentum. Shanghai, due to its high urbanization level, mainly focuses on community services and intelligent facilities for rural digitalization, with stable but limited growth. Anhui achieved rapid improvement under policy promotion, but due to relatively lagging overall development level, its sustainable growth and ability to withstand fluctuations are still insufficient.

3.2.3 Obstacle degree of digital village sub-construction level in the Yangtze River Delta region

3.2.3.1 Obstacle degree at the criteria layer of digital village sub-construction level in the Yangtze River Delta region

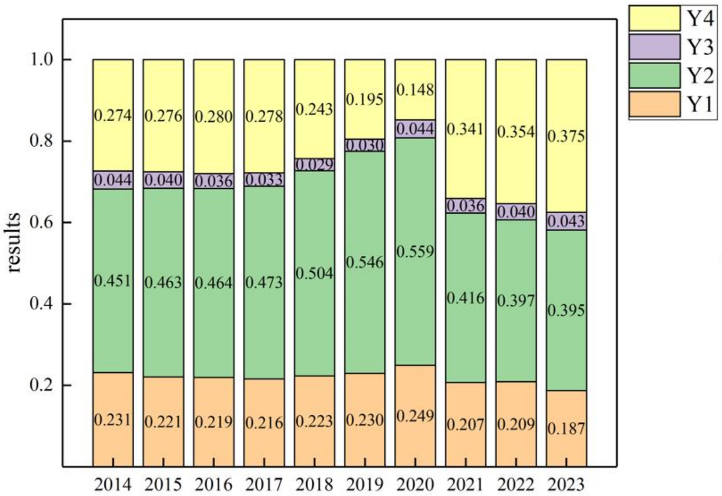

Figure 4 Criterion Layer Obstacle Degree Results of Digital Rural Subsystem Construction Levels in the Yangtze River Delta Region

The obstacles at the criterion level for digital villages in the Yangtze River Delta region as shown in Figure 4 have the following characteristics: The degree of obstacles to rural economic digitalization has shown a fluctuating upward trend overall, increasing from 0.451 in 2014 to 0.559 in 2020. Although it slightly declined after 2021, it still remained at a relatively high level, indicating that economic digital transformation has always been the most significant constraining factor at present. The degree of obstacles to rural life digitalization has continuously decreased before 2020, dropping from 0.274 to 0.148, reflecting that the construction of this dimension had achieved notable progress; however, it rebounded significantly after 2021, exceeding 0.340, indicating that new challenges have emerged during the promotion of life digitalization in recent years. The degree of obstacles to digital infrastructure has shown a downward trend overall, gradually decreasing from 0.231 in 2014 to 0.187 in 2023, reflecting that the construction in this field has continued to invest and the bottleneck constraints have gradually eased. The degree of obstacles to rural governance digitalization has remained at a relatively low level for a long time, indicating that the development of this dimension has been relatively stable and has limited constraining effects. Overall, the obstacle structure for the development of digital villages in the Yangtze River Delta region has gradually evolved from "mainly economic digitalization" in the early stage to "dual constraints of economic and life digitalization", with life digitalization becoming a newly prominent shortcoming. At the same time, the obstacle levels of digital infrastructure and rural governance are relatively low, indicating that the construction in these two areas has achieved phased results.

3.2.3.2 Obstacles in the indicator layer of digital village construction in the Yangtze River Delta region

Based on Table 2, the analysis of the ranking data of the index-level obstacles for the three provinces and one municipality in the Yangtze River Delta region in 2014, 2019, and 2023 reveals that rural e-commerce (X5) has always been the most significant obstacle hindering the construction of digital villages. Among them, Jiangsu Province stands out particularly, indicating that the popularization and continuous operation of e-commerce in rural areas still have widespread shortcomings. Information technology services (X15) except for Zhejiang Province in 2023, ranked among the top two in the obstacle degree in all other provinces and cities over the years, reflecting that the implementation and coverage of digital services in rural areas still face insufficient support and uneven distribution issues. From the perspective of regional internal differences, the obstacles in Shanghai mainly concentrate on rural e-commerce (X5), information technology services (X15), and internet infrastructure construction (X3). Jiangsu Province, in addition to rural e-commerce (X5) and information technology services (X15), digital service technology (X7) also continuously constitutes a relatively high obstacle. Zhejiang Province, except for rural e-commerce (X5) and information technology services (X15), the influence of digital village construction talent support (X6) and digital service technology (X7) has also gradually become prominent. Anhui Province's main obstacles are also mainly concentrated on rural e-commerce (X5) and information technology services (X15), and the constraining effect of digital service technology (X7) is also relatively persistent. Overall, at the indicator level of digital village development in the Yangtze River Delta region, rural e-commerce and information technology services remain the prominent shortcomings faced by all regions. As the construction process progresses, the influence of systematic constraints such as insufficient talent support, limited financial support, and uneven logistics coverage is also increasingly evident.

Table 2 Obstacle Degree Results of Indicator Layer for Digital Rural Construction Level in the Yangtze River Delta Region

Year	Shanghai	Jiangsu	Zhejiang	Anhui
	X5(0.2294)	X5(0.329)	X5(0.2734)	X5(0.2572)
	X15(0.1734)	X15(0.2298)	X15(0.1981)	X15(0.1955)
2014	X3(0.0994)	X3(0.0898)	X3(0.09)	X3(0.1014)
	X4(0.0826)	X7(0.0559)	X7(0.0705)	X7(0.0801)
	X1 (0.0679)	X9(0.0546)	X6(0.0589)	X2(0.0581)
	X5(0.2737)	X5(0.4892)	X5(0.2374)	X5(0.3347)
	X15(0.1673)	X7(0.0928)	X15(0.1271)	X15(0.1579)
2019	X3(0.1187)	X15(0.0921)	X6(0.1203)	X7(0.1035)
	X4(0.0985)	X2(0.0655)	X7(0.1162)	X3(0.0824)
	X6(0.0943)	X6(0.0436)	X3(0.1038)	X2 (0.0595)
	X5(0.2687)	X5(0.3829)	X15(0.4812)	X5(0.3367)
	X15(0.21)	X15(0.3752)	X6(0.1342)	X15(0.2591)
2023	X3 (0.1188)	X7(0.0626)	X4(0.1226)	X7(0.0932)
	X4(0.1006)	X4(0.0497)	X7(0.089)	X1(0.103)
	X6(0.0961)	X2(0.0241)	X10(0.067)	X3(0.0577)

3.3 Conclusions and Policy Recommendations

3.3.1 Conclusions

Based on the research analysis and discussion, this paper arrives at the following conclusions: (1) From the overall development trend, the digital rural construction level of the three provinces and one municipality in the Yangtze River Delta has been continuously improving from 2014 to 2023, but with significant gradient characteristics. Jiangsu and Zhejiang have remained in the leading position continuously, Anhui has been steadily following, and Shanghai has a relatively lower starting point but maintains progressive development. (2) In the specific four dimensions, the growth rates and levels of digital infrastructure construction in Jiangsu, Zhejiang, and Anhui are all at a high level, while Shanghai is relatively stable but has a lower level; in the dimension of rural economic digitalization, the performance of Zhejiang is outstanding and has remained at a high level continuously, Jiangsu and Shanghai have a relatively slow growth, and Anhui has a low starting point and a slow growth rate; in the digitalization level of rural governance, it shows a fluctuating upward trend, among which Jiangsu has the most stable trend, the performance of Zhejiang and Shanghai fluctuates greatly, and Anhui shows an "inverted U-shaped" evolution characteristic of rising first, then dropping, and stabilizing at a low level; in the dimension of rural life digitalization, it shows a three-stage evolution characteristic of "rapid increase - sudden decline - stable at a low level", Jiangsu and Zhejiang have always been in the leading position, Shanghai has a relatively stable growth, and Anhui has the lowest starting point but a relatively higher growth rate. (3) From the constraints, in the criterion layer, rural economic digitalization and rural life digitalization are currently the main shortcomings; in the specific indicator layer, rural e-commerce and information technology services are the key bottlenecks affecting the overall development.

3.3.2 Policy recommendations

Based on the research findings and the current situation of the Yangtze River Delta region, the following policy recommendations are proposed to enhance the digital rural development level in the Yangtze River Delta region:

3.3.2.1 Adopt the strategy of "categorized guidance and complementary advantages" to build a new pattern of coordinated development of digital villages in the Yangtze River Delta

Strengthen the leading role of Jiangsu and Zhejiang, systematically summarize their successful practices in areas such as digital infrastructure, rural e-commerce, smart agriculture, and digital governance, and form standardized models and operational mechanisms that can be adopted by the region. Support Shanghai in exploring a unique urban development path, in combination with the needs of rural revitalization in megacities, carry out high-quality pilot projects in digital governance and digital life services, and create demonstration models that deeply integrate with urban functions. Focus on assisting Anhui to make up for its shortcomings, in response to the situation where its digital foundation for rural economy and life is weak and growth is slow, by means of cross-provincial collaboration, technology transfer, and e-commerce empowerment, to strive to enhance its development capabilities and potential.

3.3.2.2 Identify the key weaknesses and break through the core constraints of digital rural development in the Yangtze River Delta region

Jointly build an e-commerce ecosystem to enhance the digitalization of rural economies. Promote the joint efforts of the three provinces and one municipality to create regional e-commerce brands for agricultural products, integrate logistics and supply chain resources, and focus on helping small and medium-sized farmers and new business entities to integrate into the e-commerce system, effectively breaking through the bottlenecks in rural e-commerce development. Unify service standards and optimize the digitalization of rural life. Extend digital services to education, healthcare, elderly care and other fields, establish a regional integrated service platform and access standards, avoid redundant construction and fragmented operations, and enhance the inclusiveness and sustainability of rural life services. Share governance experience and enhance the digital resilience of rural governance. Summarize and promote the stable digital governance experiences of places like Jiangsu, and promote the establishment of cross-regional data sharing and business collaboration mechanisms to reduce fluctuations in governance effects caused by policy or investment fluctuations and improve the stability of regional overall governance.

3.3.2.3 Strengthen the foundation support and enhance the internal driving force for the development of digital villages in the Yangtze River Delta region

Enhance the digital service capabilities of rural areas, focus on addressing the issue of insufficient supply of rural information technology services, and through conducting targeted training, supporting local technical service teams, guiding enterprises to collaborate with universities for assistance, effectively improve the accessibility and quality of digital services in rural areas. Promote regional data interconnection and sharing. Under the premise of ensuring security and controllability, explore the establishment of a mechanism for sharing and using data in the rural areas of the Yangtze River Delta, gradually break down data silos, reduce redundant investment, and improve the comprehensive utilization efficiency of regional digital infrastructure. Improve the dynamic monitoring and evaluation system. Based on key indicators for the development of digital villages, establish a regular tracking and evaluation mechanism, timely grasp the progress and changes in problems of each region, provide support for policy adjustment and regional collaboration, and promote the transition of digital village construction from individual exploration to overall collaboration.

3.4 Discussion and Management Insights

This paper employs a data-driven approach to quantitatively assess the level of regional digital rural development. Compared with existing literature [19], it has the following advantages: Firstly, the entropy weight-Topsis method is used to comprehensively quantify the level of regional digital rural development and to quantify each criterion layer. Secondly, an obstacle degree model for the digital rural criterion layer and indicator layer is constructed to identify the key influencing factors that constrain the improvement of digital rural development levels. Finally, based on the data-driven approach, a quantitative tool for measuring, evaluating, and identifying regional digital rural development is obtained. From perspectives such as institutional framework, policy effect, collaborative mechanism, and constraints, it provides classified guidance, complementary advantages, and precise policy recommendations for improving regional digital rural development levels based on local conditions.
Considering that the main participants in promoting the improvement of the digital rural development level in regional areas are local governments, based on the above research and conclusions, we obtain the following management insights: (1) Implement a classified guidance and dynamic collaborative advancement strategy. The digital rural construction should be adapted to the development foundation and phased characteristics of different regions, and adopt differentiated advancement paths; by coordinating the flow of cross-regional resources and sharing of experience, a coordinated development mechanism led by the advanced regions should be established to promote the overall construction from an unbalanced state to a collaborative and efficient one. (2) Focus on key weak links for concentrated efforts. The digitalization of rural economy and life remain common shortcomings, especially with rural e-commerce and information technology services being the main constraints. Relevant policies and resources should be prioritized towards these areas, and by focusing on breakthroughs in key bottlenecks, the overall level of digital rural construction can be effectively enhanced. (3) Build a monitoring and early warning and dynamic adjustment mechanism. The development of various dimensions of digital rural areas often presents fluctuation and recurrence characteristics. It is necessary to establish a regular tracking and evaluation system to promptly identify development anomalies and potential risks, enhance the continuity and responsiveness of policy promotion, and ensure the stability and sustainability of the construction process.

4 CONCLUSION

Improving the level of digital rural development has become an important path to address the shortcomings of agricultural and rural modernization, promote the comprehensive implementation of digital China, and achieve high-quality development in rural areas. However, as a dynamic and evolving complex system, the core connotation, element composition, and operational boundaries of digital rural areas still need to be further clarified. Based on this, this paper proposes a data-driven measurement method for the level of regional digital rural development.
The specific innovations are as follows: A dynamic comprehensive evaluation system covering multiple dimensions such as digital infrastructure, digitalization of rural economy, digital governance, and digitalization of rural life has been established. The indicator design takes into account regional differences and hierarchical structures, reflecting both the commonalities of the Yangtze River Delta region's development and the provincial characteristics, while also closely aligning with national policy orientations, thereby enhancing the practical interpretative power and practical guidance value of the indicator system.
Although this research has made certain breakthroughs and innovations based on previous literature, it still has certain limitations. On one hand, this research is based on the status of regional digital rural development, and does not fully consider the effect evaluation of digital rural development in different regions. In the future, it will focus on studying the impact of digital rural development on farmers' income, employment structure, agricultural production efficiency, etc. On the other hand, due to the availability of data and the number of missing values, the research object of this study is concentrated in the Yangtze River Delta region. Although the research results can reveal the status of provincial regional digital rural development, the development of digital rural areas at the city and county levels also shows an

imbalance. In the future research, it will break through the limitation of incomplete data at the city and county levels and focus the research on cities and counties in order to obtain more targeted policy recommendations.

COMPETING INTERESTS

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