Research on Ecological Agriculture Transformation Strategies in the Context of Rural Livability in the Digital Economy Era

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ABSTRACT This paper constructs a comprehensive evaluation index system covering the digital economy, rural livability, and ecological agriculture transformation, with attention to the sustainable cultivation of raw textile fibers. Based on statistical and field survey data from the Yangtze River Delta region of China from 2018 to 2023, the entropy method and coupling coordination degree model are used for empirical analysis. The results show that digital technology significantly optimizes agricultural production factor allocation: smart agriculture application scenarios increased from 120 to 850, fertilizer and pesticide application intensities decreased by 55 kg/ha and 3.3 kg/ha, respectively, and agricultural labor productivity increased by 26,000 yuan/person. A livable rural environment also promotes ecological agriculture transformation, with ecological agriculture accounting for 28.5% of total agricultural output value in highly livable areas. The coupling coordination degree of the three systems increased from 0.425 to 0.842, indicating a shift from moderate imbalance to good coordination. The findings support a digital-agricultural transformation path enabled by IoT, remote sensing, wireless sensor networks, and electromagnetic-wave communication infrastructure.

INDEX TERMS digital agriculture,ecological transformation,coupling coordination,remote sensing,wireless sensor networks

I. INTRODUCTION

AGAINST the background of the global digital economy and the in-depth development of the national rural revitalization strategy, the transformation of traditional agriculture and the value of rural development are undergoing profound adjustments, directly impacting the sustainable cultivation and processing of natural textile fibers. This shift necessitates a digital integration of raw material production with modern textile manufacturing standards, ensuring that rural industrial structures evolve to support high-quality, ecologically sound textile outputs. On the one hand, digital technologies—specifically big data, the Internet of Things (IoT), and artificial intelligence—provide the necessary impetus to overcome traditional agricultural resource constraints while enhancing production efficiency and environmental resources and enhance the efficiency of agricultural production; on the other hand, the proposal of the goal of building "livable, workable, and beautiful villages" means that rural development has transcended the characteristic single-dimensional economic growth and is starting to move in the direction of comprehensive pursuit of multi-dimensional values such as ecological environment, infrastructure and public services.

The main contributions of this paper are as follows: First, it constructs a three-dimensional comprehensive evaluation index system integrating three dimensions of the digital economy, livable environment of the rural area, and ecological agricultural transformation, which provides a methodological basis for the systematic measurement on the development level of the three; Second, it introduces a coupling coordination degree model to empirically reveal the dynamic evolution characteristics and stage-specific patterns of the synergistic relationship among three in the Yangtze River Delta region from 2018 to 2023; Finally, based on the empirical analysis results, it gives a therapeutic strategy framework aimed at promoting the positive interaction.

The structure of this paper is as follows: Part Two reviews relevant literature on agricultural transformation, digital economy, and rural development; Part Three details the research area, data sources, evaluation index system construction, and coupling coordination degree model; Part Four presents and discusses in depth the reconstructive effect of digital economy on the allocation of ecological agricultural elements, the supporting role of rural livable environment, and the empirical results of the coupling coordination degree among the three; Part Five summarizes the research conclusions and proposes targeted strategy suggestions.

II. RELATED WORK

As a core issue of global sustainable development, agricultural transformation has been the subject of extensive empirical research in academia due to its complexity and multidimensionality. Jayne et al. [1] used descriptive statistics and comparative analysis to explore the dynamic changes of farms of different sizes and their driving factors. Deng et al. [2] used a coupling coordination degree model to quantitatively assess the spatiotemporal evolution characteristics of the coordinated development of the two between 2010 and 2019. Arya [3] used literature review and comparative analysis to sort out the process, common characteristics and differentiated patterns of agricultural transformation in major Asian countries based on historical perspective and macro data. Gosnell [4] explained how this method can provide a more comprehensive understanding by analyzing the transformation case of ranchers in the western United States who have been involved for a long time to regenerative agriculture practices. Yunindanova [5] analyzed the potential impact on each link of the agricultural value chain and, in combination with the current situation of Indonesian agriculture, explored the preparations required for transformation.

With et al. [6] called for the protection of the hydrological connectivity and habitat heterogeneity to be considered in agricultural planning. Sarker et al. [7] found that successful agricultural transformation has a significant positive contribution to economic growth as well as poverty reduction but the strength of the contribution is affected by factors such as initial conditions, institutional quality and non-agricultural sector linkages. Deininger [8] et al. discussed the evidence, driving factors, and effects of agricultural structural transformation in LMICs. Teng and Montesclaros [9] stressed on the importance of international cooperation, adaptive integration of the local knowledge and comprehensive planning linking agriculture to other sectors such as tourism and health. Pan et al. [10] empirically analyzed the net effect of agricultural transformation on food self-sufficiency of households and channels of action if any. This paper discusses the reconstruction of rural livability elements and ecological agricultural transformation interaction through digital technology so as to offer a more modern and consistent strategic framework.

III. METHODS

A. STUDY AREA AND DATA SOURCES

This study selects the Yangtze River Delta region of China as a typical research area. This region boasts a high level of economic development, well-developed digital infrastructure, and is at the forefront of rural construction and agricultural modernization in China, making it representative and pioneering. The research period is set from 2018 to 2023, a period coinciding with the explosive growth of the digital economy and the critical period for the implementation of the rural revitalization strategy. Data sources mainly include three aspects: First, statistical yearbook data, primarily from the China Statistical Yearbook, China Rural Statistical Yearbook, and relevant statistical yearbooks of various provinces and cities in the Yangtze River Delta, used to obtain macroeconomic and agricultural data such as GDP, total agricultural output, fertilizer and pesticide application, and total machinery power; second, government work reports and communiqués, from official documents issued by agricultural and rural affairs departments and ecological environment departments at all levels of government, used to extract policy indicators such as investment in rural infrastructure construction and the completion rate of rural living environment improvement; and third, questionnaire surveys and field research data. The research team conducted a field survey using a structured questionnaire titled 'Rural Digital Transformation Survey' (N=500 valid responses from 50 villages, response rate 92%). The questionnaire design focused on internet usage and e-commerce adoption. These micro-data were normalized using min-max scaling and integrated with the macro-statistical yearbook data through a weighted index aggregation method to ensure cross-scale consistency. All data were standardized and missing values were filled by interpolation to ensure the continuity and integrity of the data and lay a solid data foundation for subsequent quantitative analysis [11-12].

B. CONSTRUCTION OF EVALUATION INDEX SYSTEM

To scientifically measure the level of rural livability and ecological agricultural transformation in the digital economy era, this study, adhering to the principles of systematicity, scientific rigor, operability, and data availability, constructed a comprehensive evaluation index system encompassing three dimensions. The first dimension is the digital economy development level indicator. These nine specific indicators were selected based on the 'Digital Rural Development Strategy Outline' to ensure policy relevance. To address potential multicollinearity—particularly between fiber optic access and 5G coverage—we conducted a preliminary correlation analysis and determined that each indicator captures a distinct stage of digital adoption (fixed vs. mobile). The entropy method was then applied to assign weights based on the unique information contribution of each non-redundant variable. Digital infrastructure is measured by the number of mobile phones per 100 people, the fiber optic broadband access rate in administrative villages, and the 5G base station coverage rate. Digital industrialization is measured by the number of digital agricultural industrial parks and the proportion of revenue from agricultural software and information technology services. Industrial digitalization is measured by the transaction volume of agricultural e-commerce, the number of smart agriculture application scenarios, and the proportion of online retail sales of agricultural products.

The second dimension is the rural livability environment indicator, which covers three secondary indicators: ecological environment livability, infrastructure improvement, and public service convenience. Ecological environment livability includes the rate of harmless treatment of domestic waste, the rate of domestic sewage treatment, and the village green coverage rate; infrastructure improvement includes the rate of hardened village roads, the rural drinking water safety coverage rate, and the logistics and distribution network coverage rate; public service convenience includes the coverage rate of village-level comprehensive service centers, the proportion of standardized compulsory education schools, and the standardization rate of medical and health institutions. Finally, there are the performance indicators for the transformation of ecological agriculture. This dimension includes three secondary indicators: resource utilization efficiency, ecological and environmental benefits, and agricultural output quality. Resource utilization efficiency is measured by the effective utilization coefficient of agricultural irrigation water, fertilizer application intensity (inverse indicator), and pesticide application intensity (inverse indicator); ecological and environmental benefits are measured by the comprehensive utilization rate of straw, agricultural film recycling rate, and the proportion of certified green and organic agricultural product area; agricultural output quality is measured by agricultural labor productivity, land output rate, and the proportion of ecological agricultural output value [13-14].

C. EVALUATION MODEL CONSTRUCTION

This study employs the entropy method to determine the weights of each indicator, thus avoiding the interference of subjective factors in the evaluation results. The entropy method calculates information entropy based on the degree of difference between the observed values of each indicator, thereby determining the weights and objectively reflecting the relative importance of each indicator in the comprehensive evaluation system. Specifically, firstly, the raw data is standardized to eliminate the influence of dimensions; different standardization formulas are used for positive and negative indicators. Secondly, the information entropy and difference coefficient of each indicator are calculated. The larger the difference coefficient, the stronger the indicator's ability to distinguish the evaluation, and the higher its weight. Finally, the weights of each individual indicator and the comprehensive score of each system are calculated. Based on this, to further explore the coordinated development relationship among the digital economy, rural livable environment, and ecological agricultural transformation, a coupling coordination degree model is introduced. Coupling degree reflects the degree of interdependence and mutual constraint between systems, while coordination degree considers the level of positive interaction and mutual promotion between systems during the development process. First, construct a comprehensive evaluation function for the three systems, then calculate the coupling degree between the two systems and the three systems, and finally, by introducing the coupling coordination degree model, calculate the coordination degree (D value), and divide the coordination level into six levels according to the size of the D value: severe imbalance, moderate imbalance, barely coordinated, intermediate coordinated, good coordinated and excellent coordinated, so as to intuitively reflect the development status and interaction relationship of the three in different periods and different regions [15].

IV. RESULTS AND DISCUSSION

A. ANALYSIS OF THE RESTRUCTURING EFFECT OF THE DIGITAL ECONOMY ON THE ALLOCATION OF ECOLOGICAL AGRICULTURAL FACTORS

The digital economy significantly restructures the allocation of ecological agricultural resources, as evidenced by data from the Yangtze River Delta (2018-2023), which greatly enhances the efficiency and accuracy of ecological agriculture resources. The improvement in the digital infrastructure has removed the information silos in traditional agriculture, and the flow of factors of production such as land, labour, capital and technology, through use of better combinations, on a larger scale has become feasible. Empirical data shows that with the year-on-year increasing fibre optic broadband access rates and 5G base station coverage in administrative villages, the rural labour productivity has experienced a significant upward trend. This confirms that digital technology through reduction in information search and transaction costs have fostered the deepening and specialisation of agricultural division of labor.

Table 1 is the correlation results of some indicators of digital agriculture and output benefits from the ecological agriculture of the Yangtze River Delta region 2018-2023. Observing the data in the table, we can see that the number of the smart agriculture application scenarios rapidly increased from 120 in 2018 to 850 in 2023. At the same time, the effective utilization coefficient of agricultural irrigation water also increased from 0.580 to 0.645, which also indicated that the water resource utilization effect has been improved significantly. This trend reflects the fact that the common use of digital technologies such as Internet of Things and sensors in agricultural production help monitor the precision of the needs of crops and climate through irrigation, thereby conserving water resources. Furthermore, the fertilizer application intensity decreased from 320 kg/ha in 2018 to 265 kg/ha in 2023, and pesticide application intensity decreased from 12.5 kg/ha to 9.2 kg/ha, while agricultural labor productivity increased from 32,000 yuan per person per year to 58,000 yuan. This inverse relationship clearly shows the inherent logic that digital technology brings to the transformation of ecological agriculture: the excessive use of chemical inputs can be controlled by digital management methods of precision fertilization and intelligent pesticide application, which not only reduces the risk of non-point source pollution and the ecological environment is protected, but also achieves the synchronous growth of economic benefits by reducing costs and improving quality.

TABLE 1. Changes in Digital Agriculture Development and Ecological Benefit Indicators in the Yangtze River Delta Region, 2018-2023

Years	Number of smart agriculture application scenarios (units)	Agricultural irrigation water effective utilization coefficient	Fertilizer application intensity (kg/ha)	Pesticide application intensity (kg/ha)	Agricultural labor productivity (10,000 yuan/person)
2018	120	0.580	320	12.5	3.2
2019	210	0.592	305	11.8	3.6
2020	350	0.605	290	11.2	4.1
2021	520	0.618	280	10.5	4.7
2022	680	0.632	272	9.8	5.2
2023	850	0.645	265	9.2	5.8

Further analysis of the data in Table 1 shows that the intervention of digital technology has changed the ecological agriculture from one based on "experience" to a "data-driven" model. Between 2018 and 2020, because of the still developing digital infrastructure the improvement in ecological benefit indicators was relatively gradual. However, since 2021, with the deep penetration of technologies such as 5G and big data, there is an explosive growth in the application scenarios of smart agriculture, the decline in fertilizer and pesticide application intensity is significantly accelerated, and the improvement in the labor productivity of agriculture is also significantly improved. This indicates that the driving role of digital economy in transformation of ecological agriculture, there is a certain lag effect and threshold effect. Once the years of digital infrastructure reach a certain scale, its impact on the efficiency of allocating factors will increase exponentially. Furthermore, increase in agricultural e-commerce transactions has also contributed to the opposite of the standardised production of ecological agriculture. Online sales put greater demands on traceability and brand quality of agricultural products, which forces the end of production to adapt more ecologically to planting and breeding modes, which in turn creates a virtuous cycle of "market demand guiding production transformation."

B. ASSESSMENT OF THE SUPPORTING ROLE OF A LIVABLE RURAL ENVIRONMENT IN THE TRANSFORMATION OF ECOLOGICAL AGRICULTURE

A livable rural environment is not only a carrier of the life of rural residents, but also an indispensable external support condition to make a transformation of ecological agriculture. A quality living environment, well-developed infrastructure and convenient public services can reduce considerably the external costs of operations in ecological agriculture and make it more appealing to highly skilled human resources and green capital. Analysis results show that there is significant positive correlation between the result of comprehensive evaluation of rural livability environment and the performance of ecological agriculture transformation; the higher livability index of regions will tend to have the higher level of ecological agricultural development. Specifically, the ecological ecological environment is the direct determinant of the production environment quality for the ecological agriculture. Effective treatment of the domestic waste and sewage help to reduce the sources of agricultural non-point source pollution, providing a prerequisite for the production of green and organic agriculture products.

Comparative data related to the performance of ecological agriculture transformation in each of the different livability levels of the Yangtze River Delta region in 2023 can be seen in Figure 1. Based on the comprehensive evaluation score of rural livability, the sample areas were divided into three categories, including high livability, medium livability, and low livability. The data has a clear indication of high livability areas keeping the environmental measure at a lofty index of 98% plus high rates of the rate of harmless treatment of domestic waste, treatment of domestic sewage in 100% plus, and certification of green and organic agricultural products at 35.8%, way ahead the medium and low livability areas at 22.4% and 12.6%, respectively. At the same time, the share of the volume of the value of ecological agricultural production in highly livable areas was 28.5%, and in low livable area - 15.2%. This is a significant regional difference, which means that the good rural livability environment can bring a "brand premium" effect, consumers will be more willing to pay for the value of the ecological agriculture products produced in areas with beautiful environment and orderly governance, so as to induce the producers to take more large-scale ecological agriculture.

In areas of high livability the rate of the logistics and distribution network cover is up to 95.8%, which is to say fresh agricultural products have greatly reduced the logistics losses and costs, high-value added organic agricultural products can smoothly enter the high-end market. In contrast, in less livable areas, imperfect logistics network, it is hard to rapidly carry out organic agricultural products work, leaving land out of the area, often sales are low, locally, farmers are not keen on the development of organic agriculture. In addition, the convenience of public services that come along with the livable environment, such as total conditions for medical and educational services, is crucial to retaining young laborers and agricultural technical personnel. The transformation of organic agriculture requires new type of professional farmer's who is technically skilled and are good at management. If the living environment of rural areas is poor and the number of public services is small, it will necessarily cause brain drain, organic agriculture will face the problem of "hollowing out." Therefore, the construction of a livable rural environment, by improving the physical environment and soft services, guarantees a solid foundation of human capital and market circulation basis for the

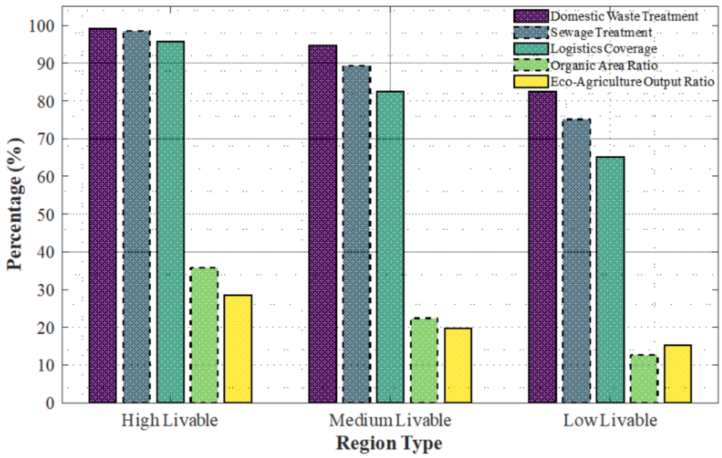

FIGURE 1. Comparison of Ecological Agriculture Transformation Performance in Different Livability Levels of the Yangtze River Delta Region in 2023

transformation of organic agriculture, the two have a highly interdependent relationship and mutual reinforcement.

C. ANALYSIS OF THE COUPLING AND COORDINATION DEGREE BETWEEN DIGITAL ECONOMY, RURAL LIVABLE ENVIRONMENT AND ECOLOGICAL AGRICULTURAL TRANSFORMATION

To further uncover the coordinated development between the digital economy, rural livability and ecological agriculture transformation, this study calculated the data of Yangtze River Delta region from 2018 to 2023 based on the coupling coordination degree model. The results show that the degree of coupling coordination of the three systems has increased in a steady manner year by year, with the coordination level gradually changing from "moderate imbalance" in 2018 to "good coordination" in 2023. This evolution suggests a virtuous cycle of coordinated development; while other factors like national policy shifts and general economic growth contribute to this trend, the digital economy acts as a catalyst by reducing transaction costs and enabling real-time resource optimization. To address potential confounding variables, we observed that the growth rate of the Digital Economy Index (0.312 to 0.880) significantly outpaced general regional GDP growth during the same period, suggesting a specific structural contribution of digitalization to the observed coordination. In the initial stage, because of the stage of digital technology, it was difficult to effectively combine the livable environment resources and the agricultural industry resources, which resulted in no effective interaction among the three systems and a state of imbalance. With the promotion of the strategy of the digital village, digital technology has been gradually applied to such areas as rural governance and agricultural production, and the correlation between the systems has gradually strengthened.

Table 2 shows the specific scores and classifications of the three-system coupling coordination degree from 2018 to 2023. The data in the table shows that in 2018, the coupling coordination degree D value was only 0.425, belonging to the moderate imbalance stage. At this time, the development of the digital economy lagged behind, failing to effectively support the construction of a livable environment and agricultural transformation. In 2019 and 2020, the D value increased to 0.512 and 0.589 respectively, entering the barely coordinated and intermediate coordinated stages. During this period, the widespread adoption of broadband networks and mobile payments activated rural e-commerce, improved the sales environment for agricultural products, and also drove the improvement of rural logistics facilities, enabling a positive interaction between the livable environment and ecological agriculture. Entering 2021, the D value exceeded 0.7, reaching 0.712, and then further jumped to 0.842 in 2023, entering the good coordination stage. During this period, the deep integration of technologies such as big data and cloud computing into the agricultural and rural sectors has enabled precise and intelligent rural governance, significantly improved ecological environment monitoring capabilities, and provided strict regulatory guarantees for ecological agriculture. Preliminary observations suggest that innovations in digital finance may provide potential pathways to alleviate financing constraints; however, further empirical studies focusing on loan accessibility and interest rate data are required to substantiate this specific mechanism.

TABLE 2. Results of Coupling Coordination Degree Calculation

Years	Coupling coordination degree (D value)	Coordination level	Digital Economy Index	Rural Livable Environment Index	Ecological Agriculture Transformation Index
2018	0.425	Moderate disorder	0.312	0.458	0.405
2019	0.512	Barely coordinated	0.395	0.482	0.458
2020	0.589	Intermediate Coordination	0.488	0.520	0.512
2021	0.712	Good coordination	0.625	0.585	0.608
2022	0.785	Good coordination	0.756	0.642	0.685
2023	0.842	Good coordination	0.880	0.710	0.765

In Table 2 reveals that the digital economy index grew the fastest, increasing from 0.312 in 2018 to 0.880 in 2023, becoming a key indicator that is closely synchronized with the overall coordination improvement.

In contrast, while the rural livability environment index and the ecological agriculture transformation index also maintained growth, their growth rates were relatively slower, increasing from 0.458 to 0.710 and from 0.405 to 0.765, respectively. This indicates that within the current collaborative development mechanism, the spillover effects of the digital economy are gradually being transmitted to the areas of livability environment and agricultural production. However, it is worth noting that as the D value increases, the difficulty of further improving coordination also increases. This requires that future efforts not only rely on breakthroughs in digital technology but also strengthen institutional innovation and mechanism building to promote the universal sharing of digital dividends in rural areas. Furthermore, although the gaps between the three subsystem indices are narrowing, they still exist, particularly the rural livability environment index, which lags behind and to some extent restricts further improvement in overall coordination. Therefore, future strategies should focus on using digital technologies to address shortcomings in livability, such as using digital twin technology for rural planning and using online platforms to improve the efficiency of public service provision, thereby achieving a high-level dynamic balance and synergistic progress among the three systems.

V. CONCLUSION

This study, grounded in the digital economy era, delves into the interactive relationship between rural livability and the transformation of ecological agriculture, focusing on the sustainable cultivation and primary processing of natural textile fibers. By analyzing how digital tools optimize the synergy between environmental health and high-quality textile material production, the research explores collaborative paths for modernizing rural industrial structures through green textile innovations. The following strategic recommendations are proposed to promote the deep transformation of ecological agriculture and the sustainable development of rural areas: First, accelerate the construction of new digital infrastructure to solidify the foundation for digital rural development. Continuously improve 5G network coverage and fiber optic access capabilities in rural and remote areas, promote the deployment of IoT and remote sensing technologies in agricultural production, build agricultural big data centers, break down data barriers, and achieve digital integration across the entire agricultural production, processing, and sales chain. Second, utilize digital technology to improve the governance level of rural livability. Promote the "Internet + Human Settlement Environment Governance" model, utilize technologies such as drone patrols and intelligent sensors to achieve real-time monitoring and early warning of the rural ecological environment, establish a digital waste classification and sewage treatment management system, and create a smart and green rural living environment. Third, construct a digital ecological agricultural industry system. Vigorously develop rural e-commerce, expand sales channels for ecological agricultural products through new models such as live streaming and community marketing, establish a blockchain-based agricultural product quality and safety traceability system to enhance consumer confidence, and utilize digital financial products to solve the problems of difficult and expensive financing for ecological agricultural operators. Fourth, we should focus on cultivating digital literacy and talent. Digital skills training for new-type professional farmers should be conducted to enhance their ability to utilize intelligent devices for developing ecological agriculture, specifically focusing on the precision cultivation and primary processing of high-quality textile fibers. Furthermore, formulating preferential policies to attract compound talents with technical, management, and market expertise to return to rural areas will provide the continuous intellectual support necessary for integrating green textile material production into the digital transformation of ecological agriculture.

AUTHOR CONTRIBUTIONS

The above five authors jointly completed this work.Na Shen and Qian Yang designed the study; all authors conducted the study; Yiting Wang, Zixin Kang and Chenxi Zhai collected and analyzed the data. Na Shen and Qian Yang participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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