Model Innovation and Practical Exploration of Digital Economy Empowering Rural Low-Carbon Development

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Abstract. Against the national strategic background of the coordinated advancement of rural revitalization and the "dual carbon" goals, rural low-carbon transformation is a key path to solving the "three rural issues" and achieving a win-win situation for ecology and development. Addressing the structural contradictions currently faced by rural low-carbon development, this study is based on the theory of digital technology empowering sustainable development, constructs a systematic analytical framework of "demand-empowerment-model-guarantee", and refines three scenario-based innovative models: smart agriculture, green e-commerce, and digital cultural tourism. These models accurately respond to the core needs of emission reduction at the production end, carbon reduction at the circulation end, and low-carbon guidance at the consumption end. The research directly confronts four practical bottlenecks: technological adaptation, digital literacy, long-term mechanisms, and collaborative linkage, and proposes comprehensive solutions including technological optimization, literacy improvement, mechanism improvement, and industrial collaboration. The core contributions of this study are as follows: first, it breaks through the limitations of fragmented research on single technology applications and reveals the internal logic of the digital economy empowering rural low-carbon development through the entire chain; second, it builds a bridge between macro policies and micro practices and improves the interactive analysis dimension of "subject-technology-policy"; third, it clarifies the coordinated transformation mechanism of ecological, economic, and social values, providing replicable low-carbon transformation paths for rural areas with different resource endowments. The research conclusions not only enrich the theoretical system of digital technology empowering rural sustainable development but also provide important support for the coordinated implementation of rural revitalization and the "dual carbon" goals.

Keywords: Digital economy; Rural low-carbon development; Smart agriculture; Green e-commerce; Digital cultural tourism.

1. Introduction

1.1. Research Background

Under the dual national strategic orientations of the in-depth advancement of the rural revitalization strategy and the steady implementation of the "dual carbon" goals, the coordinated promotion of agricultural and rural modernization and sustainable development has become the core proposition of "three rural issues" work in the new era. Xi Jinping Thought on Ecological Civilization and the theory of "Lucid waters and lush mountains are invaluable assets" provide the fundamental follow for rural development. Policy documents such as "The Opinions of the CPC Central Committee and the State Council on Accelerating the Comprehensive Green Transformation of Economic and Social Development" and "The Guiding Opinions on Accelerating the Comprehensive Green Transformation of Agricultural Development and Promoting Rural Ecological Revitalization" clearly propose rigid goals by 2030, including building a green, low-carbon, and circular agricultural industrial system and maintaining the comprehensive utilization rate of crop straw above 88%, delineating a clear policy framework and implementation path for rural low-carbon transformation. As a core area for ecological protection and an important carrier of carbon emissions, rural areas account for 15% - 20% of the national total carbon emissions, with agricultural production being the main source. In 2021, China's agricultural greenhouse gas emissions reached 931 million tons. Although the carbon emission intensity per unit of GDP has dropped to 6.90 tons per 10,000 US dollars, problems such as extensive production methods and inefficient resource utilization still restrict the emission reduction process. Rural low-carbon transformation has thus become a key starting point for solving the "three rural issues" and achieving a win-win situation for ecology and development.

The specific manifestations of the structural contradictions and practical bottlenecks currently faced by rural low-carbon development are three major "problem targets": first, the prominent contradiction between high consumption and low efficiency at the production end. The excessive application of chemical fertilizers and pesticides has kept the carbon emission intensity per unit of cultivated land at a high level, and there is a gap between the policy requirements for reducing the amount and increasing the efficiency of agricultural inputs and actual implementation; second, obvious shortcomings in carbon emission reduction in the industrial chain. The multi-level turnover in the production and sales of agricultural products causes about 15% - 20% of resource loss, and carbon emissions in the circulation link account for more than 30% of the entire agricultural industrial chain, which is inconsistent with the policy goal of "reducing costs and increasing efficiency in circulation"; third, shortcomings in the ecological governance system. Problems such as the random burning of crop straw and the disorderly disposal of agricultural waste have not been completely eradicated. Although the agricultural carbon sink reached 106 million tons in 2021, resource waste and environmental pollution still directly weaken the carbon sink offset effect. The extensive operation in cultural tourism development has further exacerbated the transformation pressure by disturbing the ecological environment. These problems not only restrict the quality of agricultural and rural modernization but also directly affect the pace of achieving the "dual carbon" goals. The three paths clearly defined by the Ministry of Agriculture and Rural Affairs—"rural green energy development, industrial green upgrading, and ecological environmental protection"—urgently need to break through the implementation bottlenecks through innovative means. This practical demand constitutes the core problem orientation of this study.

The theoretical logic of the integration of the digital economy and green development provides a new methodological support for rural low-carbon transformation. The core essence of the theory of digital technology empowering sustainable development lies in relying on digital technologies such as big data, the Internet of Things, and artificial intelligence to break through key bottlenecks in traditional development models such as resource constraints, time and space limitations, and information asymmetry by optimizing resource allocation efficiency, reducing market transaction costs, and improving the efficiency of the entire process operation, thereby realizing the coordinated progress of economic development and ecological protection. The "Guiding Opinions" clearly propose "strengthening the integrated innovation of science and technology" and "cultivating new quality productive forces in agriculture", taking digital technology as the core driving force for the green transformation of agriculture. The practice of Fulou Village in Lankao County, Henan Province has verified the feasibility of this theory. Through the "Tianshu No.1" smart platform to achieve precise scheduling of photovoltaic energy, the village collective's annual income has increased by more than 100,000 yuan, and the proportion of green power supply has reached 95%, verifying the practical value of digital technology in the rural energy revolution. In this context, promoting the in-depth integration of the digital economy and rural low-carbon development is not only an inevitable requirement for responding to the coordinated advancement of national strategies but also a practical choice based on the theoretical logic of "technology empowerment - efficiency improvement - emission reduction and efficiency enhancement". Its essence is to solve core contradictions such as information asymmetry and resource mismatch in the green transformation of agriculture and rural areas through digital means, and activate the endogenous power of rural sustainable development. This integration path is not only in line with the trend of agricultural and rural modernization but also has distinct contemporary value and practical significance.

1.2. Research Significance

1.2.1 Theoretical Significance

This study focuses on the field of in-depth integration of the digital economy and rural low-carbon development, forming theoretical breakthroughs targeting three core limitations of existing research, and significantly improving the systematicness and completeness of research in this field:

First, it solves the problem of fragmented technical analysis. Most existing studies focus on the single-point application of a single digital technology in agricultural production links, such as only discussing the supporting role of sensors in precision irrigation or the impact of drones on pesticide reduction. They lack a systematic deconstruction of the entire chain of "technology application - model innovation - value transformation", making it difficult to reveal the overall logic and synergistic effect of digital technology promoting rural low-carbon transformation. The systematic analytical framework constructed in this study incorporates multiple practical forms such as smart agriculture, green e-commerce, and digital cultural tourism into a unified theoretical system, clearly explaining the mechanism of digital technology acting through the entire chain from emission reduction at the production end, carbon reduction at the circulation end to low-carbon guidance at the consumption end, and filling the overall theoretical gap of technology empowering rural low-carbon development.

Second, it makes up for the shortage of research on micro-subjects. Current relevant studies mostly discuss rural low-carbon transformation paths from a macro policy or industrial perspective, and pay less attention to the behavioral logic and benefit mechanism of micro-subjects such as small farmers and new farmers, resulting in a theoretical gap between macro policies and micro practices. By analyzing the interaction logic between different subjects and digital tools, this study establishes a bridge between micro-behaviors and macro policies, enriching the interactive analysis dimension of "subject-technology-policy" in the theory of rural sustainable development.

Third, it clarifies the theoretical blind spot of the value transformation mechanism. Most existing studies focus on a single dimension of the emission reduction effect or economic value of digital technology, and there is insufficient research on the coordinated transformation mechanism of ecological value, economic value, and social value. In particular, there is a lack of theoretical responses to emerging issues such as "digital monetization of ecological products" and "quantification of low-carbon behavioral value". Combining practices such as carbon footprint tracking and e-commerce premium of ecological products, this study systematically explains how digital technology promotes the transformation of rural ecological advantages into economic advantages, improves the value transformation theoretical system of rural low-carbon development, and provides an extensible analytical perspective and theoretical reference for subsequent related academic research.

1.2.2 Practical Significance

The practical value of this study is reflected in providing accurately adapted, operable, and replicable path schemes for rural low-carbon transformation, and specifically solving the core pain points in current practices:

In response to problems such as difficult technology landing, unstable returns, and low farmer participation in some rural low-carbon projects, the study refines development paths suitable for rural areas with different resource endowments, such as plain agricultural areas, mountainous characteristic areas, and ecotourism areas, through in-depth sorting out of typical cases such as smart agriculture in Lanling, Shandong, green e-commerce in Suichang, Zhejiang, and digital cultural tourism in Yixian, Anhui.

These practical experiences can not only provide accurate references for local governments to formulate policies but also help subjects such as farmers, village collectives, and agricultural enterprises clarify their participation direction and benefit mechanism, thereby promoting rural areas to improve agricultural production efficiency and increase farmers' income while achieving carbon emission reduction goals. Ultimately, it realizes the coordinated unification of ecological, economic, and social benefits, and injects sustainable power into the effective implementation of the rural revitalization strategy.

The previous text has clarified the practical urgency of rural low-carbon development, the theoretical support and research value of digital economy empowerment. To further deepen the exploration, the following will first systematically analyze the core needs of rural low-carbon development and the multiple empowerment advantages of the digital economy, clarify the internal logic of their in-depth integration, and lay a theoretical and practical foundation for the extraction of subsequent innovative models.

2. Needs of Rural Low-Carbon Development and Empowerment Value of the Digital Economy

2.1. Necessity of Rural Low-Carbon Development

Rural low-carbon development is a core link to balance the dual attributes of agriculture as a "carbon source" and a "carbon sink" and help achieve the "dual carbon" goals. As one of the important sources of carbon emissions in China, agriculture under the traditional production model continuously releases greenhouse gases through behaviors such as excessive application of chemical fertilizers and pesticides, high-frequency fuel operation of agricultural machinery, and random disposal of farmland waste, intensifying the "carbon source" effect. At the same time, the rural ecosystem is also a huge carbon sink system. Cultivated soil, forest vegetation, wetland ecosystems, etc., can absorb and fix carbon dioxide through photosynthesis and carbon sequestration processes, with significant carbon sequestration potential. Promoting rural low-carbon development can reduce "carbon source" emissions and strengthen "carbon sink" capacity by optimizing agricultural production processes and improving the level of ecosystem management, realizing the dynamic balance of agricultural "carbon source - carbon sink", and providing key support for the realization of the national overall carbon emission reduction goals.

Rural low-carbon development is an inevitable choice to solve the problem of "subsistence emissions" in rural areas and ensure the coordinated improvement of people's livelihood and ecology. At present, some rural areas still have "subsistence emissions" based on basic production and living needs. Although such emissions are directly related to the survival and development of rural residents, long-term accumulation will exacerbate resource waste and environmental pressure. Rural low-carbon development does not deny reasonable needs, but by optimizing resource utilization methods and promoting low-carbon alternative schemes, it gradually reduces the impact of "subsistence emissions" on the ecological environment under the premise of ensuring the basic production and living quality of residents, allowing rural residents to not only hold the bottom line of survival but also enjoy a better ecological environment and more sustainable development conditions in the low-carbon transformation.

Rural low-carbon development is an inherent requirement for building a green and low-carbon rural system and promoting rural sustainable development. From the perspective of industrial structure, through the low-carbon transformation of traditional planting and breeding industries and the cultivation of new green and low-carbon rural formats, the dependence of agricultural production on high-consumption resources can be reduced, forming a rural industrial structure compatible with ecological carrying capacity; from the perspective of production methods, promoting precision planting and breeding, clean energy utilization, circular agriculture and other models can reduce resource consumption and carbon emissions in the production link from the source, and build an efficient and low-carbon rural production system; from the perspective of lifestyle, popularizing low-carbon living concepts and improving rural low-carbon infrastructure can guide residents to form living habits of saving resources and protecting the environment; from the perspective of spatial layout, planning low-carbon development space in combination with rural ecological resource endowments, avoiding blind development from occupying ecological space, can build a rural spatial pattern that is ecologically friendly and reasonably laid out. This series of changes together constitute the core support for rural sustainable development and lay the foundation for the long-term stable development of rural areas.

The necessity of rural low-carbon development determines that it is a core task for the coordinated advancement of rural revitalization and the "dual carbon" goals, and the implementation of this task is inseparable from strong empowerment. The core needs of rural low-carbon development for precise management, process optimization, governance upgrading, and motivation activation are highly consistent with the empowerment advantages of the digital economy in infrastructure construction, industrial process reconstruction, governance efficiency improvement, and data potential stimulation. This precise matching of supply and demand provides a solid logical foundation for their in-depth integration. As the core productive force in the new era, the digital economy, with its technical characteristics and resource integration capabilities, can provide comprehensive support for rural low-carbon development. The following will detailedly analyze the specific empowerment advantages of the digital economy.

2.2. Empowerment Advantages of the Digital Economy

The empowerment of the digital economy on rural low-carbon development is reflected in multiple dimensions such as providing basic support for transformation, optimizing industrial processes, improving governance efficiency, and activating endogenous motivation, forming a comprehensive empowerment system covering "facilities - industry - governance - resources", and providing key guarantees for the realization of rural low-carbon goals.

2.2.1 Building a Digital Infrastructure System to Consolidate the Technical and Industrial Foundation for Low-Carbon Development

Taking rural digital infrastructure construction as the entry point, the digital economy builds a "hardware base" and "industrial cornerstone" to support low-carbon transformation. By promoting the extension of infrastructure such as 5G networks, IoT sensing devices, and satellite remote sensing systems to rural areas, it realizes the comprehensive data collection and real-time monitoring of rural production, energy, and ecological scenarios, providing data transmission and storage support for low-carbon decision-making; at the same time, relying on these facilities to build a supporting system for rural low-carbon industries, forming an integrated energy network of "production - transmission - consumption - monitoring", and building agricultural product traceability platforms and intelligent agricultural machinery scheduling systems. It fundamentally solves the problem of "no basis for decision-making and no network connection" in rural low-carbon transformation caused by weak traditional rural facilities.

2.2.2 Reconstructing Traditional Industrial Processes to Promote the Implementation of Green Production and Clean Manufacturing

Through technological penetration, the digital economy reconstructs the production logic of traditional rural industries, integrates low-carbon concepts into the entire process of industries such as agriculture and rural industry, and realizes the transformation from "high consumption and low efficiency" to "green and clean". In the agricultural production link, IoT sensors are used to collect multi-dimensional data, and precise schemes are generated in combination with big data algorithms to reduce redundant input of production factors; in the rural industrial link, digital monitoring equipment and clean production management systems are introduced to real-time monitor energy consumption and emission data, and optimize production parameters through algorithms to achieve a "low energy consumption, low emission, and high output" model.

2.2.3 Improving Government and Social Governance Capabilities to Facilitate Precise Governance of Basin Ecological Environment

The digital economy improves the precision and coordination of rural low-carbon governance through technological empowerment, especially playing a key role in cross-regional and complex ecological environment governance. At the government governance level, relying on digital platforms to integrate various monitoring data, combined with AI models to achieve pollution source tracing and risk early warning; at the social collaborative governance level, building a collaborative governance platform of "government - enterprise - farmer - public welfare organization" to form an ecological governance network with the participation of multiple subjects, breaking the predicament of "information islands" and "insufficient collaboration" in traditional governance.

2.2.4 Stimulating the Potential of Data Resources to Enhance the Endogenous Power of Low-Carbon Transformation

The digital economy transforms data into a "core production factor" for rural low-carbon transformation, and activates the rural areas' own low-carbon development momentum through data value mining. On the one hand, through data integration and analysis, it accurately identifies transformation advantages and shortcomings, providing a basis for the selection of differentiated paths; on the other hand, it links data resources with rural industrial value, such as building a "low-carbon agricultural product" brand based on production data and low-carbon certification data, improving product market premium, allowing farmers to benefit practically, and forming a virtuous cycle of "data-driven - value transformation - motivation enhancement".

Based on the core needs of rural low-carbon development and the multi-dimensional empowerment advantages of the digital economy, the in-depth integration of the two has a solid logical support and practical foundation. The following will focus on three core scenarios: agricultural production, agricultural product circulation, and rural cultural tourism, refine the specific innovative models of the digital economy empowering rural low-carbon development, and analyze their operation logic and practical effects in combination with typical cases, providing operable path references for rural low-carbon transformation.

3. Three Innovative Models of Digital Economy Empowering Rural Low-Carbon Development

3.1. Model 1: Smart Agriculture Empowering "Low-Carbon Planting/Breeding"

With digital technology as the core driving force, this model runs through the entire process of agricultural production. Through the dual drive of precise management and clean energy substitution, it solves the problems of high consumption, low efficiency, and prominent carbon emissions in traditional planting and breeding, and builds a new agricultural production paradigm of "data-driven, energy-saving and carbon-reducing, quality-improving and efficiency-increasing".

3.1.1 Transformation Logic: Digital Reconstruction of Agricultural Low-Carbon Production Paths

Reconstructing the entire process of agricultural production with digital technology, focusing on the core logic of "IoT sensors → data-driven decision-making → precise operation implementation → clean energy substitution", it is deeply in line with the core proposition of "optimizing resource allocation" in the theory of digital technology empowering sustainable development. Through precise management in the production link, it reduces redundant resource input and carbon emissions, and relies on the application of green energy to reduce dependence on fossil energy, realizing the transformation of agricultural production from "extensive and high-consumption" to "precise and low-carbon".

3.1.2 Practical Measures: Collaborative Application of Precise Management and Clean Energy

The entire area of planting bases and breeding parks is networked to realize real-time collection of key indicators such as soil fertility, moisture, atmospheric temperature and humidity, light intensity in the planting environment, as well as temperature and humidity, air quality, and water quality parameters in breeding houses. The collected multi-dimensional data is uploaded to the cloud data platform and analyzed and processed through big data algorithm models. The additional content includes: specific machine learning models (such as random forests, gradient boosting trees), crop growth simulation models (such as DSSAT, APSIM), breeding environment optimization models, etc. Precise schemes tailored to the characteristics of the land, crop growth cycles, or breeding variety needs are generated to guide farmers in carrying out operations such as precise fertilization, quantitative irrigation, and scientific feeding. From the perspective of optimizing resource allocation, it realizes the on-demand delivery of production factors such as chemical fertilizers, water resources, and feed, avoiding resource waste under the traditional extensive model, and directly reducing carbon emissions in the production link. This is the concrete implementation of the theory of digital technology empowering sustainable development in the agricultural production scenario. At the same time, supporting clean energy facilities such as photovoltaic greenhouses and distributed wind power generation devices are built to convert solar energy and wind energy into electrical energy needed for agricultural production, replacing traditional fossil energy power generation, and building a low-carbon agricultural production system of "precision production + clean energy".

3.1.3 Case Evidence: Carbon Emission Reduction Practice of Smart Agriculture in Lanling, Shandong

As a project related to a national rural revitalization demonstration village, the Lanling National Modern Agricultural Industrial Park in Shandong is a typical representative of smart agriculture empowering low-carbon planting. The park realizes 24/7 uninterrupted collection of soil moisture, fertility, and climate data, which is transmitted to the park's smart agriculture cloud platform in real-time. Based on massive data and algorithm models, the platform mainly applies gradient boosting tree models and DSSAT crop growth simulation models to generate personalized irrigation and fertilization schemes for each field and greenhouse. Farmers can receive precise operation instructions and implement operations through mobile phone APPs. This closed-loop model of "sensor collection - platform analysis - precise execution" realizes the optimal allocation of production resources through digital technology, directly reducing the chemical fertilizer usage in the park by 30% and agricultural production carbon emissions by 25%. It effectively verifies the core logic of the theory of digital technology empowering sustainable development that "optimizing resource allocation can achieve emission reduction and efficiency enhancement", and solves the problems of resource waste and excessive emissions in traditional planting. In addition, the park has built a large number of photovoltaic greenhouses. The solar panels laid on the roof can meet 80% of the park's electricity demand annually, covering the core production electricity such as greenhouse temperature control and irrigation equipment operation, further cutting off the carbon emission path caused by the use of fossil energy and continuously consolidating the effectiveness of low-carbon development.

3.2. Model 2: Green E-Commerce Empowering "Low-Carbon Production and Sales"

3.2.1 Value Orientation: Digital Connection of the Collaborative Link of Low-Carbon Production and Sales

Taking digital e-commerce platforms as the link, it opens up a direct connection channel between "farmers and consumers", and strictly follows the core principle of "reducing transaction costs" in the theory of digital technology empowering sustainable development. It reduces energy consumption and loss in intermediate links by shortening the circulation chain, endorses the low-carbon quality of agricultural products with blockchain traceability technology, and activates the consumer market through localized digital marketing, realizing the coordinated development of "precise matching of production and sales + low-carbon quality certification + value enhancement".

3.2.2 Implementation Path: Two-Way Efforts of Platform Integration and Traceability Marketing

Build a regional "low-carbon agricultural product e-commerce platform" to integrate the characteristic agricultural product resources of scattered farmers in the region, and uniformly carry out quality inspection, grading and screening, and brand packaging to form a large-scale and standardized low-carbon agricultural product supply system. Introduce blockchain traceability technology, adopt a consortium chain architecture to build a node network for low-carbon traceability of agricultural products, and establish a data certification mechanism of "real-time on-chain of key links + incremental synchronization of the entire process". At the production end, in accordance with the principle of "daily on-chain of agricultural activities", key low-carbon data such as the type/dosage of chemical fertilizers and pesticides applied, irrigation time, and breeding and feeding records are written into the block in real-time; at the processing and packaging link, "batch-associated on-chain" is implemented to synchronize information such as product processing energy consumption and environmental protection level of packaging materials; at the logistics link, relying on GPS positioning and temperature and humidity sensors, "real-time on-chain of transportation nodes" is realized to dynamically record data such as transportation routes, warehousing energy consumption, and cold chain insulation parameters. The entire process information of agricultural products from planting, fertilization and pesticide application, processing and packaging to logistics and transportation is stored on the chain, generating a unique queryable traceability QR code, allowing consumers to intuitively understand the low-carbon production process and quality standards of products and enhance consumer trust. At the same time, focusing on the cultivation of local talents, set up a professional village live broadcast team. Through digital marketing forms such as live streaming and short video promotion, it directly connects with consumers across the country, eliminating the turnover links of multi-level wholesalers. It reduces multiple transaction costs such as warehousing, transportation, and intermediate price increases from the circulation link, which not only reduces energy consumption and carbon emissions in intermediate links but also allows farmers to obtain more benefits, perfectly implementing the practical requirement of "reducing transaction costs" in the theory of digital technology empowering sustainable development.

3.2.3 Case Analysis: Practice of Production and Sales Upgrade Empowered by E-Commerce in Suichang, Zhejiang

Wangcunkou Town, Suichang, Zhejiang has thoroughly cultivated this development path and built the "Suichang Low-Carbon Agricultural Product E-Commerce Platform", providing full-chain services for more than 200 farmers in the region, covering key links such as product listing, order integration, logistics connection, and after-sales support. It effectively solves the pain point that small farmers' scattered operations are difficult to connect with the large market. The platform is simultaneously connected to the blockchain traceability system, adopting a three-level architecture of "simple collection terminal at the farmer end + node verification at the platform end + QR code scanning traceability at the consumer end". It sets dynamic certification rules of "daily reporting and on-chain of production data" and "real-time triggering and on-chain of processing and logistics data". After farmers upload daily agricultural operations and input use data through mobile phone APPs, they are written into the blockchain after being verified by platform nodes. Processing enterprises and logistics providers realize automatic data on-chain through system interfaces to ensure the authenticity and immutability of each piece of low-carbon related information. Consumers can clearly view low-carbon related information such as chemical fertilizer usage, pesticide application, logistics and transportation routes, and energy consumption during the planting of agricultural products by scanning the QR code on the product packaging, making "low-carbon quality" perceptible and verifiable. In addition, the village has specifically trained a 30-person professional village live broadcast team. The team members are all local farmers or returning young people. They carry out live streaming with their familiarity with agricultural products and local feelings. The number of live broadcasts exceeds 500 per year, successfully selling local characteristic agricultural products such as tea, edible fungi, and alpine vegetables directly to the national market. This model of "platform integration + traceability endorsement + village live broadcast direct sales" has significantly shortened the production and sales chain through digital technology, which not only reduces transaction costs and carbon emissions in intermediate links but also increases product premium through quality traceability. It fully verifies the "cost reduction and efficiency increase" logic of the theory of digital technology empowering sustainable development in the production and sales link, realizing a win-win situation for ecological and economic benefits.

3.3. Model 3: Digital Cultural Tourism Empowering "Low-Carbon Experience"

3.3.1 Innovation Core: Digital Reconstruction of the Low-Carbon Experience Ecosystem of Cultural Tourism

Innovation of cultural tourism service forms and management models with digital technology, practicing the dual goals of "optimizing resource allocation and reducing environmental loss" in the theory of digital technology empowering sustainable development. Through three-dimensional efforts of "peak-shifting regulation + virtual experience + intelligent energy conservation", it reduces physical consumption and carbon emissions in cultural tourism activities, and realizes the coordinated development of cultural tourism industry and ecological protection while ensuring tourists' sense of experience, building a new rural cultural tourism ecosystem of "low-carbon, high-quality, and sustainable".

3.3.2 Implementation Plan: Diversified Integration of Intelligent Regulation and Virtual Experience

Launch the "low-carbon cultural tourism reservation platform", integrate resources such as rural homestays, scenic spots, and characteristic experience projects, and provide services such as online reservation, route planning, and passenger flow inquiry. Through real-time passenger flow data monitoring and intelligent regulation, it guides tourists to travel during off-peak periods, avoiding problems such as traffic congestion and overloaded operation of facilities caused by concentrated visits, optimizing the efficiency of cultural tourism resource utilization, and reducing energy waste caused by idle or overuse of resources; develop a series of VR ecological tourism projects, using virtual reality technology to restore core cultural tourism resources such as rural ancient village styles, pastoral scenery, and intangible cultural heritage scenes, creating an immersive remote tour experience. It meets tourists' demand for rural cultural tourism, reduces traffic carbon emissions caused by on-site travel, and reduces the physical loss of cultural tourism activities on the ecological environment. It is an innovative application of the theory of digital technology empowering sustainable development in the ecological protection scenario; at the same time, install intelligent energy consumption monitoring equipment for rural homestays, scenic spot supporting facilities, etc., to real-time capture water and electricity usage data, generate energy-saving optimization suggestions through platform analysis, and guide operators to adjust energy usage methods to reduce energy consumption and carbon emissions during operation.

3.3.3 Case Demonstration: Practical Effects of Low-Carbon Digital Cultural Tourism in Yixian, Anhui

Bishan Village, Yixian County, Anhui Province, as a national rural revitalization demonstration village, has explored a mature path in digital cultural tourism empowering low-carbon experiences. The village launched the "Bishan Low-Carbon Cultural Tourism Reservation Platform". Tourists can pre-book services such as homestay accommodation, scenic spot visits, and agricultural experience through the platform. Based on real-time passenger flow data, the platform conducts intelligent scheduling to reasonably allocate tourism resources, effectively avoiding problems such as road congestion and sharp increase in facility energy consumption caused by concentrated travel, and reducing the instantaneous pressure of cultural tourism activities on the rural ecological environment. For the core cultural tourism resources of the village, Bishan Village has developed 3 VR ecological tourism projects, focusing on themes such as the architectural aesthetics of ancient villages, the four-season pastoral scenery, and intangible cultural heritage craftsmanship. Tourists can immerse themselves in the natural and cultural charm of Bishan through online terminals, completing the "cloud tour" experience without traveling on-site, which greatly reduces carbon emissions caused by transportation. In addition, 50 homestays in the village have completed the installation of intelligent energy consumption monitoring equipment. The equipment can real-time monitor water and electricity usage and push energy-saving suggestions to homestay operators through mobile phone APPs. It realizes the dual goals of optimizing the allocation of cultural tourism resources and reducing environmental loss through digital technology, fully verifying the practical value of the theory of digital technology empowering sustainable development in the cultural tourism scenario, and achieving a multi-win situation of upgraded cultural tourism experience, ecological protection, and industrial income increase.

The above three innovative models have achieved remarkable results in practice in many places, verifying the feasibility and adaptability of the digital economy empowering rural low-carbon development. However, in the process of promoting application on a larger scale and advancing to a deeper level, there are still many practical bottlenecks and challenges. The following will systematically analyze these core challenges and propose targeted countermeasures of technological optimization, literacy improvement, mechanism improvement, and collaborative linkage, providing solutions for the sustainable advancement of the digital economy empowering rural low-carbon development.

4. Challenges and Countermeasures of Digital Economy Empowering Rural Low-Carbon Development

4.1. Core Challenges

Although the in-depth integration of the digital economy and rural low-carbon development has explored multiple innovative models, in the process of promoting to a wider range and deeper level, it still faces multiple practical bottlenecks such as technological adaptation, digital literacy, long-term mechanisms, and collaborative linkage. These problems are intertwined, restricting the full release of empowerment effects.

4.1.1 Difficult Technological Adaptation: Dual Constraints of Scenario Mismatch and Weak Foundation

The shortcomings of infrastructure in rural areas have become the primary obstacle to the landing of digital technology. Some remote rural areas have not yet achieved full coverage of 5G networks and the Internet of Things. Problems such as unstable network signals and delayed data transmission occur frequently, making it difficult for functions such as precision planting and intelligent monitoring that rely on real-time data to operate normally; at the same time, the power supply guarantee in some rural areas is insufficient, especially in mountainous and hilly areas. Seasonal power outages and unstable voltage occur from time to time, directly affecting the continuous operation of low-carbon facilities such as photovoltaic greenhouses and intelligent irrigation equipment.

More importantly, there is an obvious adaptation mismatch between existing digital technologies and actual rural scenarios. Currently, mainstream digital technologies are mostly developed for cities or large-scale agricultural parks, with high equipment purchase costs and complex operation processes, which are difficult to match the current situation of small farmers' scattered operations, small production scale, and limited economic capacity. In addition, technological R&D is disconnected from rural low-carbon needs, and there is a lack of special technical supply for rural characteristic low-carbon scenarios such as straw resource utilization and farmland carbon sink monitoring, resulting in digital empowerment being difficult to accurately reach core pain points.

4.1.2 Weak Digital Literacy: Dual Lack of Subject Capabilities and Service Support

The digital literacy level of rural residents has become a key shortcoming restricting low-carbon transformation. The rural labor force structure shows the characteristics of "aging and low education". Middle-aged and elderly farmers are the main body. They have low acceptance and mastery of digital skills such as IoT equipment operation, e-commerce platform operation, and data interpretation and analysis. Even if they have basic equipment, it is difficult to give full play to their low-carbon empowerment value.

The digital capabilities of rural grass-roots governance and service teams are also insufficient. Grass-roots cadres lack professional capabilities such as overall planning of digital low-carbon projects, platform operation and maintenance, and data management, making it difficult to effectively coordinate technical resources and solve technical problems in project advancement; rural areas lack professional digital service talents. Farmers cannot receive timely support in equipment troubleshooting, platform operation questions, and data application guidance, resulting in digital technology being "not well used or flexibly used", and even equipment idleness, which restricts the progress of low-carbon transformation.

4.1.3 Insufficient Long-Term Effect: Dual Shortcomings of Capital Investment and Interest Linkage

Projects of the digital economy empowering rural low-carbon development generally have the problem of "emphasizing construction over operation", and the long-term operation mechanism has not been improved. Such projects require large initial investment, involving multiple links such as digital infrastructure construction, intelligent equipment purchase, and platform development. However, the investment return cycle is long, and the process of converting low-carbon benefits into economic benefits is slow, resulting in low enthusiasm of social capital to participate, and the capital source is over-reliant on short-term government policy subsidies. Once the subsidy policy expires, the project often falls into operational difficulties due to capital shortages, making it difficult to continue to play the role of low-carbon empowerment.

The imperfect interest linkage mechanism further exacerbates the long-term risk. In some current projects, the profit distribution method among participating subjects such as farmers, village collectives, and enterprises is not clear. Farmers mostly participate in basic labor services or product supply, and it is difficult to share the value-added benefits brought by digital technology and low-carbon transformation.

4.1.4 Lack of Collaboration: Dual Obstacles of Subject Fragmentation and Resource Dispersion

The digital economy empowering rural low-carbon development is a systematic project that requires the collaborative efforts of multiple subjects such as the government, enterprises, scientific research institutions, and farmers. However, the current linkage among all parties is insufficient, forming a fragmented pattern of "fighting alone". At the government level, policy formulation mostly focuses on macro guidance, lacking precise research on actual rural needs. Some policies are disconnected from market laws and farmers' demands, resulting in poor policy implementation effects; at the enterprise level, technological R&D and market promotion pay more attention to commercial benefits. The technical solutions and platform services provided do not fully consider the actual situation of rural resource endowments and production models, resulting in "acclimatization"; at the scientific research institution level, technological R&D mostly focuses on laboratory results, lacking in-depth combination with rural scenarios, resulting in advanced technologies being difficult to transform into practical solutions that can be implemented; at the farmer level, due to the lack of effective channels to express demands, the technical problems and interest demands encountered in the production process are difficult to transmit to other subjects, leading to imbalanced supply and demand and low resource allocation efficiency, making it difficult to form a joint force to promote rural low-carbon transformation.

4.2. Countermeasures

In response to the above challenges, it is necessary to accurately focus on four dimensions: technological adaptation, literacy improvement, mechanism improvement, and collaborative linkage, and build a comprehensive solution of "technology adapting to scenarios, literacy supporting applications, mechanisms ensuring long-term effects, and collaboration gathering joint forces", promoting the digital economy to empower rural low-carbon development in depth and solidly.

4.2.1 Technological Optimization: Dual Upgrading of Scenario-Based R&D and Infrastructure

Focusing on actual rural scenarios, promote the lightweight, low-cost, and localized innovation of digital technology. The government takes the lead in setting up a "special R&D fund for rural low-carbon digital technology", investing no less than 50 million yuan annually to support enterprises and scientific research institutions to form a special R&D team. According to the characteristics of small farmers' scattered operations and limited grass-roots operation capabilities, develop modular, easy-to-install, and one-click operation digital products, and clarify the core equipment cost control standards: the price of a single set of soil moisture sensors shall not exceed 800 yuan, the farmer-end data collection terminal shall not exceed 500 yuan, and the homestay intelligent energy consumption monitoring equipment shall not exceed 600 yuan. For products that have been successfully developed and passed the farmer applicability test, the government will provide a subsidy of 30% of the R&D cost. Focus on developing special technologies for rural characteristic scenarios such as straw resource utilization monitoring, farmland carbon sink accounting, and low-carbon agricultural product traceability to improve the adaptability of technology to low-carbon needs. Establish a joint pilot mechanism of "enterprise + scientific research institution + village collective", invest 200,000 - 500,000 yuan per pilot village for technology landing testing, and promote the technology on a large scale after optimizing the technical plan according to the pilot effect.

Increase investment in rural digital infrastructure construction to build a "hardware base" for low-carbon transformation. Implement the "Rural Digital Infrastructure Tackling Plan", and clearly realize full coverage of 5G networks and IoT sensing networks in remote rural areas by the end of 2026. The government will provide a subsidy of 200,000 - 300,000 yuan per station for network operators' rural base station construction, and an additional 15% subsidy for network construction in remote areas such as mountains and hills. Improve the rural power security system, upgrade and renovate the power grid in remote areas, and support the construction of distributed energy storage equipment. The subsidy standard for a single energy storage equipment is 40% of the equipment cost (up to 50,000 yuan) to ensure the stable operation of intelligent low-carbon equipment. Build an integrated rural data platform, integrate multi-dimensional data such as agricultural production, ecological environment, and energy consumption, break "data islands", and provide data support for precise low-carbon decision-making. At the same time, establish a long-term operation and maintenance mechanism for digital infrastructure, clarify township governments as the main responsible body for operation and maintenance, and arrange operation and maintenance funds at a standard of 10 yuan per capita of rural population in the jurisdiction every year, with the insufficient part guaranteed by the county-level finance.

4.2.2 Literacy Improvement: Dual Support of Hierarchical Training and Professional Services

Build a hierarchical and classified digital literacy training system to accurately match the ability needs of different subjects. For farmers, formulate the "Digital Low-Carbon Skills Improvement Plan", arrange special training funds of 50 yuan per capita every year, and carry out diversified training such as "hand-in-hand" on-site teaching, short video tutorial push, and field classrooms around practical skills such as intelligent equipment operation, e-commerce live streaming, energy consumption data monitoring, and low-carbon production technology. Compile illustrated operation manuals, and develop auxiliary functions such as voice navigation and icon-based operation interfaces. For farmers who complete the training and pass the skill assessment, provide agricultural material subsidy rewards of 50 - 100 yuan. For grass-roots cadres and village collective responsible persons, focus on training in digital project management, platform operation and maintenance, resource integration, policy interpretation, etc., with centralized training no less than 4 times a year, each training lasting no less than 2 days, and the training funds fully borne by the county-level finance.

Encourage returning young people, college student village officials, etc. to become "digital leaders". For leaders who drive more than 5 farmers to master digital low-carbon skills, provide rewards of 3,000 - 5,000 yuan per year.

Establish a professional digital service support system to solve the problem of "disconnection between learning and application". Form a digital service team composed of technical experts, enterprise technicians, and returning talents. Each township is equipped with at least 3 full-time service personnel, and the personnel salary is shared by the government and enterprises at a ratio of 6:4, with the government's share included in the annual fiscal budget. The service team implements the "village and household contracting" system, providing on-site services no less than once a month, and offering one-stop support such as equipment installation and commissioning, troubleshooting, data interpretation, and problem consultation. Build an online service platform, open technical consultation hotlines and video consultation channels to facilitate farmers to obtain remote guidance at any time. Set up digital service stations in townships, equipped with professional equipment and personnel to provide farmers with convenient and nearby technical services, ensuring that digital technology is "easy to learn and use". The assessment of the service team is linked to farmers' satisfaction, and teams with a satisfaction rate of more than 90% are given a reward of 1,000 yuan per person.

4.2.3 Mechanism Improvement: Dual Guarantee of Diversified Investment and Benefit Sharing

Build a diversified capital investment mechanism of "government guidance, enterprise leadership, social participation, and farmer benefit". The government guides social capital to participate in the construction of rural digital low-carbon projects through fiscal subsidies, tax reductions and exemptions, and special funds. Establish a rural low-carbon digital technology innovation fund with a scale of no less than 200 million yuan to support scientific research institutions in carrying out technological R&D and achievement transformation. For enterprises investing in rural digital low-carbon projects, implement a "three-year exemption and three-year reduction" tax preferential policy—full exemption of enterprise income tax for the first 3 years, 50% reduction for the next 3 years, and a subsidy of up to 5 million yuan according to 10% of the project investment. Encourage financial institutions to launch targeted credit products, providing low-interest loans and guarantee support for farmers and village collectives to purchase digital equipment and participate in low-carbon projects. The loan term can be up to 5 years, and interest subsidies are provided for farmers who repay on time. At the same time, optimize the fund use mechanism, strengthen the whole-process supervision of project construction and operation, establish a "fund use public announcement system" and a "performance evaluation mechanism". Projects with excellent performance evaluation are given an additional 10% fund reward, and inefficient projects have their next-year fund support reduced.

Improve the interest linkage and long-term operation mechanism to stimulate the enthusiasm of all parties to participate. Clarify the profit distribution ratio among subjects such as farmers, village collectives, enterprises, and scientific research institutions. Farmers' share ratio in low-carbon agricultural product premium and data asset income shall not be less than 50%, and village collectives' share ratio shall not be less than 10%. Establish a "data point" system. The production data and low-carbon behavior data uploaded by farmers can be converted into points, which can be exchanged for agricultural materials, electricity subsidies, or cash. The total annual point exchange shall not be less than 3% of the average annual net income of local farmers. At the same time, establish a long-term project operation and maintenance mechanism, clarify the main responsible body for operation and maintenance, and ensure the source of operation and maintenance funds through government procurement of services, village collective self-financing, and profit sharing, ensuring the long-term and stable operation of the project.

4.2.4 Industrial Collaboration: Dual Efforts of Multi-Party Linkage and Resource Integration

Build a multi-subject collaborative platform and establish a regular communication and docking mechanism. Led by the government, set up a collaborative development alliance of "government -

enterprise - scientific research institution - farmer", holding a demand docking meeting every quarter, a technical exchange meeting every six months, and a project promotion meeting every year to accurately connect the demands of all parties. Build an online collaborative platform, integrate various information such as policy information, technical resources, market demand, and farmer demands to realize resource sharing and information intercommunication. Establish an incentive mechanism to commend and reward subjects with outstanding performance in collaborative cooperation: provide enterprises with project subsidies of up to 2 million yuan, scientific research institutions with R&D funding support of up to 500,000 yuan, and farmers with production subsidies of up to 10,000 yuan.

Clarify the functional positioning of all parties to form a collaborative pattern of complementary advantages. The government is responsible for formulating planning policies, improving infrastructure, optimizing the business environment, and strengthening supervision and services. It incorporates carbon emission reduction effects and digital technology application rates into the rural revitalization assessment system, with an assessment weight of no less than 15%; enterprises give play to their advantages in technology, capital, and market, providing adaptive technical products, building operation platforms, and expanding market channels. Enterprises are required to invest no less than 30% of the total project investment in technology in rural digital low-carbon projects; scientific research institutions focus on actual rural needs, carry out technological R&D and achievement transformation, and complete the landing transformation of at least 2 rural low-carbon digital technologies every year; farmers actively participate in project operation, feedback actual needs and problems, and enjoy the right to know, participate, and supervise project decisions. Through the collaborative efforts of all parties, the optimal allocation of resources is realized, and a strong joint force for rural low-carbon development is gathered.

5. Conclusions and Future Outlook

5.1. Research Conclusions

Based on the background of the coordinated advancement of rural revitalization and the "dual carbon" goals, this study systematically explores the paths, models, and practical logic of the digital economy empowering rural low-carbon development. Through the combination of theoretical analysis and case evidence, the following core conclusions are formed:

First, the in-depth integration of the digital economy and rural low-carbon development is a key path to solving the traditional development bottlenecks of rural areas and realizing the coordinated improvement of ecology and economy. As a dual carrier of "carbon source" and "carbon sink", rural low-carbon transformation not only faces traditional problems such as extensive production, inefficient circulation, and backward governance but also has practical constraints such as weak infrastructure and uneven resource allocation. With data as the core production factor, the digital economy, relying on technologies such as big data, the Internet of Things, and artificial intelligence, builds a comprehensive empowerment framework covering "infrastructure - industrial processes - governance system - resource activation". It provides a systematic solution from technical support to model innovation for rural low-carbon transformation, filling the gap that "high consumption and low efficiency" and "ecological protection" are difficult to balance in traditional rural development.

Second, the three innovative models of smart agriculture, green e-commerce, and digital cultural tourism have respectively constructed the practical paradigm of the digital economy empowering rural low-carbon development from the production, circulation, and service links. The smart agriculture model takes "optimizing resource allocation" as the core, realizing the precise delivery of production factors through digital technology and reducing resource waste and carbon emissions; the green e-commerce model takes "reducing transaction costs" as the key, reducing energy consumption and loss in intermediate links by shortening the production and sales chain; the digital cultural tourism model is oriented towards "optimizing resource allocation + reducing environmental loss", realizing the low-carbon development of the cultural tourism industry through peak-shifting regulation and virtual experience. The three models complement each other and have their own focuses, together forming a low-carbon empowerment system covering key links of the rural industry. The practical effects of typical cases have fully verified the feasibility and adaptability of the models.

Third, the current digital economy empowering rural low-carbon development is still in the stage of "local breakthrough and overall advancement". Four challenges including technological adaptation, digital literacy, long-term mechanisms, and industrial collaboration constitute the main obstacles to the deepening of transformation. At the technical level, the weak rural infrastructure and the "urban-oriented" R&D of digital technology lead to adaptation mismatch, which restricts the technical landing effect; at the subject level, the insufficient digital literacy of rural residents and grass-roots cadres leads to digital technology being "not well used or flexibly used"; at the mechanism level, the single capital investment and loose interest linkage lead to difficulties in the long-term operation of projects; at the collaborative level, the insufficient linkage among the government, enterprises, scientific research institutions, and farmers forms a predicament of "scattered resources and disconnected supply and demand". The targeted countermeasures of "technological optimization, literacy improvement, mechanism improvement, and industrial collaboration" need to be promoted through multi-subject collaboration to truly break through the bottlenecks and provide sustainable guarantees for the digital economy to empower rural low-carbon development.

5.2. Future Outlook

With the continuous iteration of digital technology, the continuous strengthening of policy support, and the in-depth participation of market subjects, the digital economy empowering rural low-carbon development will usher in a broader practical space. In the future, in-depth exploration can be focused on the following dimensions:

5.2.1 Technological Innovation: In-depth Iteration towards "Scenario-Based, Intelligent, and Low-Carbon"

Future digital technology R&D needs to further focus on rural low-carbon segmented scenarios, promoting the upgrade of technology from "general adaptation" to "precision customization". On the one hand, for characteristic scenarios such as farmland carbon sink monitoring, agricultural waste resource utilization, and rural distributed energy management, develop lightweight and low-cost special digital equipment to improve the adaptability of technology to rural reality; on the other hand, promote the in-depth integration of artificial intelligence, digital twins and other technologies with rural low-carbon scenarios, integrate production, ecological, and energy data, realize dynamic simulation of carbon emissions, intelligent optimization of low-carbon schemes, and risk early warning, and improve the precision and forward-looking of rural low-carbon governance. At the same time, attention should be paid to the low-carbon attributes of digital technology itself, and technologies such as low-power sensors and green data centers should be promoted to achieve the dual goals of "digital empowerment of low-carbon" and "low-carbon of digital technology".

5.2.2 Model Expansion: Comprehensive Upgrade from "Single-Point Demonstration" to "Systematic Collaboration"

The existing three innovative models will expand from "local pilot" to "regional linkage", forming a rural low-carbon development ecosystem with multi-model integration. At the county level, the whole chain of "low-carbon production - traceable circulation" can be connected, forming a complete low-carbon evidence chain "from field to table", and further improving the market competitiveness of agricultural products; at the cross-regional level, the combination of digital cultural tourism and ecological compensation mechanisms can be explored, which not only reduces the ecological damage caused by wetland development but also realizes regional ecological compensation through "carbon sink trading + cultural tourism revenue sharing". In addition, "digital + low-carbon + new rural formats" can be cultivated to form a new pattern of coordinated development of multiple formats.

5.2.3 Subject Empowerment: Building a Collaborative System of "Multi-Party Participation and Capacity Building"

In the future, it is necessary to further strengthen the capacity building and interest linkage of subjects such as farmers, village collectives, enterprises, and scientific research institutions, and stimulate the endogenous power of rural low-carbon transformation. On the one hand, promote the upgrade of digital literacy training from "skill teaching" to "capacity building", allowing leaders to become bridges connecting technology supply and farmer needs, and driving surrounding farmers to participate in low-carbon transformation; on the other hand, improve the "data confirmation + benefit sharing" mechanism, explore the assetization path of farmers' production data and ecological data, and allow farmers to obtain additional benefits through "data contribution", further strengthening their participation enthusiasm. At the same time, it is necessary to strengthen inclined support for rural vulnerable groups to avoid the digital divide exacerbating development imbalance.

5.2.4 Policy Guarantee: Forming an Institutional Framework of "Precise Guidance and Long-Term Support"

At the policy level, it is necessary to further improve the full-cycle support system of "top-level design - medium-term supervision - long-term guarantee". In terms of top-level design, a "special plan for the digital economy to empower rural low-carbon development" can be formulated, clarifying differentiated development paths for rural areas with different resource endowments, establishing a digital evaluation index system for rural low-carbon development, and incorporating carbon emission reduction effects and digital technology application rates into the rural revitalization assessment; in terms of medium-term supervision, build a "rural low-carbon digital supervision platform" to dynamically monitor the fund use, carbon emission reduction effect, and farmer income of digital low-carbon projects to ensure the effective implementation of policies; in terms of long-term guarantee, promote the integrated innovation of "carbon sink trading + digital finance", and improve the cross-departmental collaborative mechanism to break the policy barriers in fields such as agriculture and rural areas, ecological environment, and digital economy, forming a policy joint force.

In summary, the digital economy empowering rural low-carbon development is not only an inevitable choice to comply with the coordinated advancement of the "dual carbon" goals and the rural revitalization strategy but also an important way to activate the endogenous power of rural sustainable development. Although there are still many challenges at present, with the multi-dimensional breakthroughs in technology, models, subjects, and policies, it will surely achieve a leap from "local innovation" to "overall transformation" in the future, providing solid support for agricultural and rural modernization and green low-carbon development, and ultimately realizing the coordinated unification of ecological, economic, and social benefits.

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