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Research on Innovative Environmental Management Models of Leading Agricultural Industrialization Enterprises in Liaoning Province

JingYa Wang

University of Science and Technology Liaoning, 114051, Anshan, China

KEYWORDS

Agricultural industrialization;
Leading enterprises;
Innovation in environmental management models;

ABSTRACT

Under the background of the 'dual carbon' goals and the green transformation of agriculture, the innovation of environmental management modes in leading agricultural enterprises in Liaoning Province has become a key factor in promoting regional agricultural sustainable development. Based on theories such as circular economy and technological innovation, this paper addresses issues such as passive environmental protection and insufficient technology application in enterprises in Liaoning Province, and designs a three-level environmental management innovation model of 'internal enterprise closed loop – industry chain collaboration – regional resource sharing.' An empirical test is conducted using Sanyou Agriculture as a case study. The data show that after implementing this model, the enterprise significantly outperformed the industry average in environmental performance, economic performance, and technological adaptability, achieving a win-win situation of 'enhanced efficiency through environmental protection.' The research findings not only enrich the theoretical framework at the intersection of agricultural economics and environmental management but also provide practical references for the green transformation of leading agricultural enterprises in Liaoning Province and for relevant policy-making.

1.INTRODUCTION

1.1Research background and significance

Against the backdrop of intensifying global climate change and tightening resource constraints, green, low-carbon, and circular development has emerged as a core issue reshaping the global industrial landscape. As a fundamental sector of the national economy, the green transformation of agriculture is directly tied to the ecological security and sustainable development foundation of regions and even the entire country. The implementation of China's "dual carbon" strategy—carbon peaking by 2030 and carbon neutrality by 2060—has laid out a clear path for the low-carbon and ecological transformation of traditional agriculture, while also imposing higher requirements on the environmental governance capabilities of agricultural production and operation entities.

As key hubs connecting smallholder farmers to large markets, leading agricultural industrialization enterprises are core carriers of the modern agricultural management system. Their level of environmental operation not only determines their own potential for sustainable development but also profoundly influences the green transformation of the entire agricultural industrial chain. Liaoning Province, a major grain-producing area in Northeast China and an advantageous region for characteristic agricultural products, boasts a solid industrial foundation for leading agricultural industrialization enterprises in sectors such as grain processing, animal husbandry, and specialty edible fungi and vegetable cultivation. However, their environmental operation practices exhibit obvious lag. In reality, most leading agricultural enterprises in the province remain at the

* Corresponding author. E-mail address:1037126783@qq.com

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level of "passive compliance" in environmental protection, lacking the strategic awareness to deeply integrate environmental management with industrial upgrading. Meanwhile, the penetration rate of green innovation tools such as circular agriculture technologies and digital environmental protection systems is relatively low, and the technical adaptability and systematization of environmental operation models are insufficient. This not only restricts the improvement of enterprises' own economic benefits and brand value but also slows down the province's agricultural transition to a green and low-carbon paradigm, creating a prominent contradiction with the demand for high-quality agricultural development under the background of the revitalization of Northeast China's old industrial bases. In this context, exploring an environmental operation model for leading agricultural industrialization enterprises that suits Liaoning's regional characteristics has become an inevitable choice to address the coordinated challenge of agricultural ecological protection and industrial efficiency improvement.

Theoretically, this study holds significant academic value. First, it systematically sorts out core theories including value creation-oriented environmental management theory, environmental operation paradigm transformation theory, and green culture-environmental operation interaction theory, and establishes a theoretical application framework in the context of agricultural industrialization. This fills the theoretical gap in existing research on environmental operation of meso-level entities (provincial leading agricultural enterprises) and promotes the improvement of the theoretical system at the intersection of agricultural economics and environmental management. Second, through literature integration, theoretical deduction, and coupling analysis with Liaoning's regional characteristics, it constructs an analytical paradigm for environmental operation model innovation that aligns with Liaoning's agricultural industrial endowments, providing a reference analytical framework for theoretical research on environmental operation of leading agricultural enterprises in similar regions.

In practical terms, the value of this study is reflected in dual empowerment. On one hand, taking Liaoning Sanyou Agricultural Biotechnology Co., Ltd. as a typical case, it diagnoses the existing pain points in its environmental operation and constructs an environmental operation model featuring "technological innovation-driven, internal circular closed-loop, and regional resource coordination". This provides a replicable and promotable practical model for leading specialty agricultural product processing enterprises in Liaoning, helping them transform "environmental protection investment" into "value output" and achieve a win-win situation of both environmental and economic performance. On the other hand, the research results can serve as a decision-making reference for local agricultural authorities to formulate agricultural green transformation policies and optimize environmental protection support mechanisms for leading enterprises, driving Liaoning's agricultural sector to realize the simultaneous improvement of ecological benefits and industrial competitiveness under the "dual carbon" goals.

1.2.Literature Review and Research Gaps

Foreign academic research on leading agricultural industrialization enterprises initially focused on the evaluation of enterprises' comprehensive development level and regional adaptability analysis, and in recent years has gradually extended to the dimensions of competitiveness deconstruction and development potential research. In the aspect of regional adaptability evaluation, ang Ying and Yadong Fan (2010) took leading agricultural industrialization enterprises in Heilongjiang Province as research samples, constructed a comprehensive evaluation system from dimensions such as industrial layout rationality, interest linkage mechanism improvement, and resource integration capability, analyzed the development characteristics and core constraints of leading enterprises under the background of cold-region agriculture, and provided a basic analysis framework for the cultivation and development of leading agricultural enterprises in high-latitude regions [1]. In the field of enterprise competitiveness research, GUO Yubing et al. (2023) selected 28 leading agricultural industrialization enterprises in Shanxi Province as research objects, built a competitiveness evaluation model covering dimensions such as industrial driving capacity, resource allocation efficiency, and technological innovation level, clarified the competitiveness shortcomings of different types of leading enterprises through empirical analysis, and put forward cultivation paths and optimization strategies for core leading enterprises, providing practical references for improving the competitiveness of regional leading agricultural enterprises [2]. Overall, foreign research in this field mostly takes

specific regions as samples, forming a research paradigm of "evaluation system construction - development bottleneck diagnosis - optimization strategy proposal", but there is still a lack of special exploration on the environmental operation dimension of leading enterprises.

The enabling effect of digital technology on agricultural industrialization has been a research hotspot in the field of foreign agricultural economy in recent years, and scholars have conducted in-depth discussions from the dual perspectives of productivity innovation and industrial sustainable development. In terms of improving agricultural green productivity, the research of Zeng F et al. (2024) confirmed that rural digitalization can achieve a leap-forward improvement in agricultural green total factor productivity through paths such as optimizing the allocation of production factors, reconstructing agricultural production processes, and improving the efficiency of resource recycling. The research also pointed out that the enabling effect of digitalization on agricultural green transformation has regional and industrial format heterogeneity, and the enabling effect is more significant in the fields of characteristic agricultural product planting and processing [3]. In the dimension of rural industrial sustainable development, Gao S et al. (2023) combined digital empowerment, rural entrepreneurship, and deep learning technology to construct a logical framework for digital technology-driven sustainable development of rural industries, empirically tested the core value of digital technology in expanding industrial boundaries, reducing production energy consumption, and strengthening industrial chain collaboration, and also revealed practical bottlenecks restricting the landing of digital technology such as technical thresholds and data security [4]. These studies have clarified the enabling path of digital technology for agricultural industrialization, but have not deeply coupled digital technology with the environmental operation model of leading agricultural enterprises, and lack the design of digital environmental operation schemes for leading enterprises.

Foreign research on environmental operation started early, forming a research system centered on the evaluation of environmental management system effectiveness and the measurement of enterprise ecological carrying capacity. At the level of the practical value of environmental management systems, Sroufe R (2003) through empirical research on enterprises in multiple industries, confirmed that a sound environmental management system can significantly optimize enterprise environmental management practices and production and operation processes, which can not only reduce the intensity of enterprise pollutant emissions but also effectively control production costs by improving resource utilization efficiency. The research also clarified the adaptability differences of environmental management systems in enterprises of different scales and formats [5]. In the agricultural field, Yi Ling Liu and Song Qing Li (2014) constructed an ecological carrying capacity evaluation system for leading agricultural industrialization enterprises, designed quantitative indicators from dimensions such as resource consumption, pollution emissions, and ecological contributions, and clarified the core influencing factors of the ecological carrying capacity of leading agricultural enterprises through empirical research, filling the theoretical gap in the quantitative evaluation of the ecological carrying capacity of agricultural enterprises [6]. However, existing research mostly focuses on a single dimension of environmental operation, failing to form a systematic environmental operation model covering the enterprise interior, industrial chain, and region, and there is an obvious gap in research on the adaptability of environmental operation of leading agricultural enterprises in cold regions.

Based on the above research results of foreign literature and combined with the practical needs of the development of leading agricultural industrialization enterprises in Liaoning Province, there are still three significant theoretical and practical gaps in the field of environmental operation of leading agricultural industrialization enterprises.

First, the systematic lack of research perspectives; existing research mostly focuses on a single dimension of environmental operation, for example, Sroufe R (2003) only focuses on the practical effectiveness of the internal environmental management system of enterprises, and Yi Ling Liu et al. (2014) focuses on the single indicator measurement of enterprise ecological carrying capacity, failing to build a multi-dimensional collaborative environmental operation theoretical framework of "enterprise interior - industrial chain - region", which is difficult to meet the systematic environmental governance needs of leading agricultural industrialization enterprises as the chain leaders of the industrial chain. Second, the blank of the cold-region dimension in regional adaptability; although ang Ying et al. (2010) paid attention to the development characteristics of leading agricultural enterprises in cold

regions, they did not extend to the field of environmental operation; and existing environmental operation technologies and schemes are mostly designed based on temperate or tropical agricultural endowments, without fully considering the regional characteristics such as winter low-temperature constraints in Northeast cold regions and the rigid demand for black soil protection. The adaptability research of cold-region-specific agricultural waste recycling technology, low-temperature cultivation energy-saving technology, etc., is blank, leading to the serious lack of landing of existing models in Liaoning Province and other Northeast cold regions. Third, the insufficient synergy of technology integration; although Zeng F et al. (2024) and Gao S et al. (2023) confirmed the enabling value of digital technology for agricultural green transformation, they did not cross-integrate digital technology with theories such as circular economy and industrial chain integration, nor did they form a practical path for environmental operation of leading agricultural enterprises driven by digital technology, making it difficult to solve the practical problems of insufficient application of green technology and low digitalization level of environmental operation of leading agricultural enterprises in Liaoning Province.

In response to the above research gaps, this study forms innovative breakthroughs in three aspects: in terms of subject focus, this study locks on leading agricultural industrialization enterprises in Liaoning Province as meso-level subjects, constructs an environmental operation model suitable for the provincial regional agricultural industrial pattern, thereby filling the gap in theoretical and practical research on environmental operation at the meso level, and opening up the connection channel between macro-policy implementation and micro-subject practice; in terms of regional adaptability, based on the climatic characteristics of Northeast cold regions and the demand for black soil protection, develop cold-resistant edible fungi cultivation technology, cold-region waste high-efficiency conversion technology and other cold-region-specific agricultural recycling technologies, design environmental operation schemes that fit regional endowments, and solve the technical adaptability problem of agricultural green transformation in cold regions; in the dimension of theoretical integration, construct a three-level environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing", realize the cross-field integration of circular economy, industrial chain integration and cold-region agricultural technology innovation theories, and form a provincial agricultural leading enterprise green transformation solution with both theoretical depth and practical value.

2.Theoretical Basis and Concept Definition

2.1Leading Agricultural Industrialization Enterprises

According to the relevant identification standards of the Ministry of Agriculture and Rural Affairs, leading agricultural industrialization enterprises refer to agricultural enterprises that take the production, processing, and circulation of agricultural products as their core business, realize large-scale and intensive operation through models such as "enterprise + farmer" and "enterprise + cooperative + farmer", have a significant driving effect on agricultural industrial development, and are recognized by governments at all levels. Its core characteristics include: large operation scale, strong industrial chain integration capability, close interest linkage with farmers, and a prominent role in driving regional agricultural economic development. Leading agricultural industrialization enterprises in Liaoning Province mostly focus on fields such as grain processing, animal husbandry, and characteristic agricultural product development, and are the core subjects of regional agricultural modernization and green transformation.

2.2.Innovation of Environmental Operation Modes

2.2.1.Academic Controversy and Conceptual Analysis

At present, the academic circle has not yet formed a unified consensus on the definition of environmental operation model innovation, and the core of the controversy focuses on two levels: innovation dimension and value orientation. From the perspective of innovation dimension, some scholars believe that environmental operation model innovation should focus on the technical level. For example, Dong Xiaodong et al. (2014) proposed that its core is the embedding of low-carbon technology and recycling technology in the production link, which is the green iteration of the enterprise's technical system; another part of

scholars emphasizes the collaboration at the industrial chain dimension. Zhang Changjiang et al. (2020) pointed out that environmental operation model innovation needs to cover the upstream and downstream of the industrial chain, and realize the maximization of ecological benefits through the integration of the entire chain of resources, and the technological innovation of a single enterprise is difficult to achieve systematic environmental improvement. From the perspective of value orientation, some studies advocate "ecology first" as the core, taking environmental performance as the primary assessment indicator of model innovation; while scholars such as Gan Changsheng (2025) adhere to the dual value orientation of "environment - economy", believing that environmental operation models separated from economic performance do not have a sustainable promotion foundation.

2.2.2.Concept Definition of This Study

Combined with the development characteristics and research needs of leading agricultural industrialization enterprises in Liaoning Province, this study defines environmental operation model innovation as: taking circular economy as the underlying logic, technological innovation as the core support, and industrial chain integration as the implementation path, leading agricultural industrialization enterprises break through the traditional environmental management model of "passive compliance", integrate internal and external resources of the enterprise, and form a new type of operation structure and operation mechanism that "converts environmental constraints into development momentum". Its core connotation includes three aspects: first, the meso attribute of the innovation subject, focusing on provincial leading agricultural industrialization enterprises as the chain leader of the industrial chain; second, the systematicness of the innovation dimension, covering three levels: enterprise interior, industrial chain, and region; third, the synergy of innovation goals, ultimately realizing the dual goals of sustainable enterprise development and regional ecological protection, specifically reflected in practical forms such as the application of circular economy models, digital technology empowering environmental management, and green integration of the entire industrial chain.

Dong Xiaodong et al. (2014) based on Kuhn's "Structure of Scientific Revolutions" theory proposed that the enterprise operation paradigm needs to iterate with changes in external environmental constraints. In the context of low-carbon economy and "dual carbon" goals, enterprises need to shift from the traditional paradigm of "economy first" to the environmental operation paradigm of "environment and economy coordination". This theory provides a paradigm transformation perspective for the research: leading agricultural industrialization enterprises in Liaoning Province need to break through the traditional operation thinking of "emphasizing production over environmental protection", fully integrate environmental factors into all links such as strategic planning, production and operation, and industrial chain integration, and complete the systematic transformation of the operation paradigm.

2.3.Industrial Chain Integration Theory

The industrial chain integration theory emphasizes optimizing the division of labor and cooperation by integrating upstream and downstream resources of the industrial chain, and improving the overall efficiency and competitiveness of the industry. Agricultural industrial chain integration covers the coordinated linkage of links such as means of production supply, agricultural production, agricultural product processing, and circulation and sales. Combined with environmental operation goals, green industrial chain integration needs to integrate environmental protection requirements into all links to achieve efficient resource utilization and environmental risk management and control. This theory provides path guidance for the innovation of environmental operation models of leading agricultural industrialization enterprises in Liaoning Province - by integrating regional agricultural resources, building a green industrial chain of "planting - processing - waste recycling - sales", and improving the systematicness and synergy of environmental operation.

2.4.Technological Innovation Theory

The technological innovation theory holds that technological progress is the core driving force for industrial upgrading and enterprise development. In the field of environmental operation, green technological innovation (such as low-carbon production technology, recycling technology, digital environmental protection technology, etc.) is the key to improving environmental performance. Studies by Yu Sidong et al. (2025) and Fu Bo et al. (2025) have confirmed

that innovative means such as "Internet +" and digital technology can empower the quality and efficiency improvement of agricultural industrialization. This theory provides technical dimension support for the research: leading agricultural industrialization enterprises in Liaoning Province need to break through the technical bottlenecks of environmental operation through green technology research and development and application, and promote the iterative upgrading of environmental operation models.

2.5.Theoretical Integration Framework

This study constructs a three-dimensional theoretical integration framework of "circular economy as the underlying logic + industrial chain integration as the implementation path + technological innovation as the core support". Each theory does not act independently, but intersects and collaboratively supports the construction of the three-level environmental operation model. The specific logic is as follows:

(1) Circular economy theory lays the core criteria of the model

The core principles of circular economy, "reduce, reuse, and recycle", delineate the underlying logical boundary of the three-level environmental operation model. At the level of the internal enterprise closed loop, it guides enterprises to build a material and energy circulation chain of "resources - products - renewable resources" to realize the nearby resource utilization of waste; at the level of industrial chain collaborative circulation, it requires chain leader enterprises to extend the circular concept to the upstream and downstream, creating a full-chain circular system of "green supply - clean processing - low-carbon circulation"; at the level of regional resource sharing and circulation, it promotes the overall utilization of waste across enterprises and industries, realizing the efficient circulation of resources at the regional level and solving the problem of the limited circulation scope of a single subject.

(2) Industrial chain integration theory clarifies the model implementation path

The industrial chain integration theory provides an expansion path of "from single point to system" for the three-level model. For the single-point breakthrough of the internal enterprise closed loop, this theory guides enterprises to first integrate resources in internal production, processing, waste treatment and other links; on this basis, relying on the chain leader status of leading enterprises, integrate upstream farmers/cooperatives, downstream distributors and other industrial chain subjects to realize industrial chain collaborative circulation; finally extend to the regional level, integrate resources across industries and subjects, build a regional sharing platform, complete the model expansion from micro to meso, and ensure the systematicness and synergy of environmental operation.

(3) Technological innovation theory consolidates the model landing support

The technological innovation theory provides technical feasibility guarantee for the three-level model. In view of the special regional conditions of Northeast cold regions, the technological innovation theory guides enterprises to develop adaptive technologies such as low-temperature-resistant cultivation and high-efficiency conversion of waste mushroom sticks to solve the technical pain points of the internal enterprise closed loop; at the level of industrial chain collaboration, support enterprises to introduce clean production technologies such as Internet of Things monitoring and waste heat recovery to realize precise environmental management and control of the entire chain; at the level of regional resource sharing, help build a digital resource allocation platform, improve the efficiency and accuracy of regional resource integration, and ensure the transformation of the three-level model from theoretical design to practical landing.

The cross-integration of the three theories forms a complete theoretical system of "logical guidance - path planning - technical support", providing a comprehensive theoretical basis for the construction and verification of the three-level environmental operation model of leading agricultural industrialization enterprises in Liaoning Province, avoiding the limitations and fragmentation problems of the application of a single theory.

3.Design of Environmental Operation Model Innovation from the Perspective of Circular Economy

Based on the core principles of circular economy of "reduce, reuse, and recycle", combined with the industrial endowment of leading agricultural industrialization enterprises in Liaoning Province and the regional ecological needs of Northeast cold regions and major grain-producing areas, this study constructs a three-level progressive

environmental operation innovation model system of "internal enterprise closed loop - industrial chain collaborative circulation - regional resource sharing", and the specific design is as follows:

3.1.Internal Enterprise Closed-Loop Circulation Model: Focusing on Single-Point Breakthrough of "Resources - Products - Renewable Resources"

To address the pain points of resource waste and ineffective control of waste emissions in the enterprise production link, with the core goal of "cost reduction, efficiency improvement, and environmental load reduction", build an internal material and energy circulation system for enterprises to realize the nearby resource utilization of waste, reduce the dependence on external resources, and enterprises of different industrial types can form differentiated circulation paths:

(1) Circulation sub-model for grain processing enterprises

Build a closed loop around the "full value chain development of rice/corn", forming a circulation link of "raw grain - main products - by-products - renewable resources - waste - energy/fertilizer". Specifically, rice husks can be burned for power generation through biomass boilers, meeting 30%-50% of the enterprise's production electricity demand; the ash residue generated from power generation is mixed with rice bran meal to process into organic carbon-based fertilizer, which is fed back to the enterprise's cooperative planting base, forming an internal resource closed loop of "processing - energy - planting".

(2) Circulation sub-model for animal husbandry enterprises

With the "full resource utilization of breeding waste" as the core, build a circulation chain of "feed formulation - livestock and poultry breeding - manure collection - biogas project - biogas residue/biogas slurry processing - planting". The biogas produced by anaerobic fermentation of breeding manure can be used for enterprise heating, canteen gas or connected to the local gas pipeline network; biogas residue is processed into commercial organic fertilizer, and biogas slurry is used to irrigate supporting silage corn bases after harmless treatment, which not only solves the problem of breeding manure pollution but also reduces feed procurement costs, realizing a self-sufficient cycle of "breeding - energy - planting".

(3) Circulation sub-model for characteristic agricultural product processing enterprises

For the edible fungi and fruit and vegetable processing industries, design a circulation path of "culture medium/raw materials - products - waste mushroom sticks/fruit residue - renewable resources". Taking edible fungi enterprises such as Liaoning Sanyou Agriculture as an example, waste mushroom sticks can be crushed and mixed with straw and livestock manure to process into organic cultivation substrate or organic fertilizer, which is reused for edible fungi production or sold to surrounding farmers, realizing the closed-loop operation of "production - waste - reproduction", with the waste resource utilization rate reaching more than 90%.

3.2.Industrial Chain Collaborative Circulation Model: Promoting Full-Chain Linkage of "Upstream - Midstream - Downstream"

Taking leading enterprises as chain leaders, integrate upstream and downstream resources of the industrial chain, and implement the circular economy concept throughout the entire process of agricultural production, processing, and circulation, realizing the coordinated linkage of "upstream green supply - midstream clean processing - downstream low-carbon circulation", and solving the limitations of a single enterprise's limited circulation scope and insufficient resource utilization:

(1) Upstream green supply link

Leading enterprises sign green production agreements with cooperatives and family farms through the interest linkage mechanism of "order agriculture + technical guidance", uniformly supply biological pesticides, organic fertilizers, high-quality improved seeds, and provide standardized technical training. For example, Dalian Hanwei Group provides cooperative farmers with green feed formulas and ecological breeding technologies in the egg industrial chain, requiring the unified recycling and treatment of breeding manure, which not only ensures the green and safety of raw materials but also provides a stable source of waste for the entire industrial chain circulation.

(2) Midstream clean processing link

Leading enterprises promote the technological transformation of "reduction and resource utilization" in the processing link, and adopt clean production processes to realize the cascade utilization of energy and the recycling of

water resources. For example, Liaoning Goubangzi Smoked Chicken Group has introduced a waste heat recovery system, which uses the waste heat of processing steam for workshop heating and raw material preheating, greatly reducing production energy consumption.

(3) Downstream low-carbon circulation link

Jointly with terminal sellers to build a circular circulation system of "green packaging - low-carbon transportation - waste packaging recycling". Taking Panjin Dingxiang Rice Industry as an example, it uses degradable corn starch packaging materials, builds packaging recycling outlets with chain supermarkets, and the recycled packaging is crushed and used as feed or organic fertilizer auxiliary materials to feed back to upstream planting; in the transportation link, new energy vehicles or railway transportation are preferred to reduce logistics carbon emissions, forming an industrial chain circular closed loop of "processing - sales - recycling".

3.3.Regional Resource Sharing and Circulation Model: Realizing Cross-Enterprise and Cross-Industry Resource Integration

To address the problems of weak investment capacity in environmental protection facilities of small and medium-sized leading enterprises and scattered regional resources, following the principles of "sharing, efficiency, and intensification", under government guidance and led by leading enterprises, build a regional shared circular economy platform, integrate resources and waste across enterprises and industries, and improve the overall efficiency of regional environmental operation.

(1) Regional waste treatment sharing platform

Led by large leading enterprises such as Liaoning Hefeng Animal Husbandry, build regional organic fertilizer processing centers and biomass energy stations to centrally dispose of livestock manure from surrounding small and medium-sized breeding enterprises and rice husks and rice bran and other by-products from grain processing enterprises, reducing the investment cost of environmental protection facilities for small and medium-sized enterprises and realizing the centralized and resource utilization of regional agricultural solid waste.

(2) Cross-industry circulation platform for black soil protection

Combined with Liaoning Province's strategic positioning as a major grain-producing area, integrate resources in the fields of "planting - breeding - processing - agricultural machinery services", and build a regional circulation system of "black soil conservation tillage - waste returning to the field - organic planting". Specifically, provincial leading grain processing enterprises, together with agricultural machinery cooperatives, implement a conservation tillage model of "straw crushing returning to the field + organic fertilizer application"; breeding enterprises supply manure resources, and processing enterprises provide organic auxiliary materials such as waste mushroom sticks, jointly supplying green fertilizers for the planting link, which not only improves black soil fertility but also realizes the full circulation of regional agricultural waste, reducing chemical fertilizer usage by more than 30%.

3.4.Core Supporting Elements of Model Design

To ensure the landing of the environmental operation model from the perspective of circular economy, three core supporting elements need to be matched to solve the key bottlenecks in the model operation. First, technical support; focusing on the characteristics of agriculture in Northeast cold regions, develop low-cost circular technologies suitable for local conditions. At the same time, introduce digital technologies, such as installing intelligent monitoring systems in biogas projects to monitor gas production efficiency and pollutant emissions in real time, improving the accuracy of the circulation process. Second, premium incentives for upstream farmers to participate in green production. Establish a "circulation benefit sharing mechanism", leading enterprises implement "minimum purchase price + 5%-10% green price increase"; regional sharing platforms adopt "fee based on quantity + profit sharing" to reduce the environmental protection costs of small and medium-sized enterprises. Third, standard support; formulate special standards for agricultural circular economy in Liaoning Province, covering "technical specifications for waste resource utilization", "green production standards for the entire industrial chain", "operation and management standards for regional circulation platforms", etc., clarify circulation indicators for different industries such as grain processing and animal husbandry, and ensure the standardized and quantifiable operation of the model.

3.5.Analysis of Model Applicability Boundaries

The three-level environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing" designed in this study is mainly applicable to the following three types of leading agricultural industrialization enterprises in Liaoning Province:

Characteristic agricultural product processing enterprises: such as edible fungi and fruit and vegetable processing enterprises. The waste generated in the production process of such enterprises, such as waste mushroom sticks and fruit residues, has high resource value. They can rely on the internal closed-loop model to realize waste reuse, and at the same time, integrate surrounding resources such as straw and livestock manure through industrial chain collaboration and regional sharing to improve circulation efficiency. The practice of Liaoning Sanyou Agriculture has verified the adaptability of this model.

Grain processing enterprises: such as rice and corn processing enterprises. The by-products generated in their production, such as rice husks and rice bran, can be used for energy and fertilizer utilization through internal closed loops. As the core subject of the regional grain industrial chain, they can take the lead in building industrial chain collaboration and regional sharing platforms, promoting the full-chain circulation of "planting - processing - returning to the field", which is in line with Liaoning Province's industrial positioning as a major grain-producing area.

Large-scale animal husbandry enterprises: such as pig and layer breeding enterprises. They can realize the biogas conversion and organic fertilizer processing of breeding manure through internal closed loops, and at the same time link with surrounding planting enterprises to form an industrial chain circulation of "breeding - energy - planting", and also rely on regional sharing platforms to solve the manure treatment problem of small and medium-sized breeding entities.

4.Case Analysis and Empirical Test

To ensure the representativeness and promotion value of the case study conclusions, this study selects Sanyou Agriculture as the core case object, and its typicality is mainly reflected in three aspects: first, industrial representativeness, the enterprise focuses on the edible fungi processing field in Northeast cold regions, and the edible fungi industry is one of the core formats of characteristic agricultural product processing in Liaoning Province. The pain points it faces, such as "difficulty in adapting to cold-region cultivation and low resource utilization rate of waste mushroom sticks", are consistent with the common predicament of most leading enterprises of the same type in the province; second, subject-level representativeness, Sanyou Agriculture is a provincial leading agricultural industrialization enterprise, with the resource integration capability of the industrial chain leader, covering the entire process of "strain research and development - cultivation production - processing and sales - waste recycling", which is fully in line with the meso-subject positioning of provincial leading agricultural industrialization enterprises focused on this study; third, model adaptability representativeness, the enterprise has fully implemented the three-level environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing", covering all core links from internal intelligent cultivation circulation to regional centralized treatment of waste mushroom sticks, which can provide a complete practical sample for verifying the effectiveness of this model. In addition, to further verify the universality of the model, this study also selects 1 leading grain processing enterprise and 1 leading animal husbandry enterprise in Liaoning Province for supplementary comparison to confirm the adaptability of the three-level model in different agricultural formats.

4.1.Enterprise and Industry Pain Points

The traditional model of Liaoning's edible fungi industry has three core problems: first, the cultivation link relies on manual regulation, and the accuracy of parameters such as temperature and humidity is low, leading to high energy consumption; second, most of the waste mushroom sticks generated in edible fungi production are landfilled, with a resource utilization rate of less than 20%, causing environmental pollution and resource waste; third, under the low-temperature environment in winter in Northeast cold regions, the growth cycle of edible fungi is extended by 30%, and the nutrient loss of the cultivation substrate is fast, affecting yield and quality. Before 2019, Sanyou Agriculture was also restricted by this, with environmental operation investment accounting for only 1.2% of operating income, the annual cost of waste mushroom stick treatment

exceeding 500,000 yuan, and the market share of green products less than 15%.

4.2.Design of Environmental Operation Model

Internally, the enterprise focuses on the entire process of "cultivation substrate - edible fungi production - waste mushroom sticks - renewable resources", creating a closed loop of "resources - products - waste - renewable resources". It independently developed an intelligent edible fungi cultivation system, which monitors and intelligently regulates cultivation environment parameters in real time through sensors; the waste mushroom sticks generated in production are crushed and mixed with straw and livestock manure to process into organic cultivation substrate or organic fertilizer, which is fed back to the enterprise's self-built 200-mu edible fungi planting base and surrounding farmers' farmland, realizing the internal circulation of "cultivation - waste - reproduction".

In view of the characteristics of Northeast cold regions, develop low-temperature-resistant edible fungi cultivation technology and waste mushroom stick high-efficiency conversion technology to solve the problems of "poor low-temperature adaptability and low waste conversion efficiency" in the traditional model; introduce digital technology, deploy Internet of Things monitoring equipment in the cultivation workshop to realize real-time collection and optimization of energy consumption and environmental parameters.

Establish cooperation with 5 small and medium-sized edible fungi enterprises and 3 straw recycling cooperatives in the surrounding area, share intelligent cultivation technology and waste treatment equipment, centrally treat waste mushroom sticks in the region, and the processed organic fertilizer is supplied to surrounding grain growers, forming a collaborative network of "characteristic agricultural product processing - regional resource circulation".

4.3.Empirical Test:Analysis of Model Effectiveness Based on Data

4.3.1.Data Collection and Indicator Design

Focusing on the three dimensions of "environmental performance - economic performance - technical adaptability", collect core data of Sanyou Agriculture in 2019 (before model implementation), 2023 (after model implementation), and 2024 (after optimization), and compare with the average level of similar edible fungi processing enterprises in Liaoning Province to verify the effectiveness of the model. The specific indicators and data are as follows:

Dimension Classification	Specific Indicators	Sanyou Agriculture in 2019 (before model)	Sanyou Agriculture in 2023 (after model)	Sanyou Agriculture in 2024 (after optimization)	Average of similar enterprises in Liaoning Province (2024)
Environmental Performance	Resource utilization rate of waste mushroom sticks	18%	92%	100%	38%
	Energy consumption per unit output (kWh/mu)	8200	5100	4800	7500
	Water resource reuse rate	22%	58%	62%	32%
	Organic fertilizer replacing chemical fertilizer (tons) |	0	3200	4500	950
	Qualified rate of production "three	75%	100%	100%	88%

	wastes" discharge				
Economic Performance	Proportion of environmental operation investment in revenue	1.2%	2.5%	2.8%	2.0%
	Cost of waste mushroom stick treatment	52	18	15	42
	Proportion of green product revenue	14%	48%	55%	28%
	Annual total output value (10,000 yuan)	3200	7500	12000	4800
	Profit rate per unit product	8.5%	15.2%	18.6%	10.2%
Technical Adaptability	Popularization rate of intelligent cultivation technology	0%	100%	100%(full-process digitalization)	28%
	Survival rate of low-temperature cultivation in cold regions	72%	95%	96%	80%
	Technology R&D investment (10,000 yuan/year)	85	260	350	130
	Number of scientific research cooperation institutions	3	8	12	4
	Number of patents owned (items)	2	15	22	6

Table.1. Data Collection

4.3.2.Verification of Model Effectiveness Based on Data

(1) Environmental performance: achieving a leap from "passive emission reduction" to "active circulation", with significantly better results than industry benchmarks

First, waste resource utilization has achieved a full closed loop. From 2019 to 2024, the resource utilization rate of the enterprise's waste mushroom sticks increased from 18% to 100%, 62 percentage points higher than the average level of similar enterprises in Liaoning Province (38%), completely eliminating the soil pollution problem caused by the traditional landfill model. Its core driving force is the "waste mushroom sticks - organic substrate - organic fertilizer" circulation system built by the enterprise, which directly confirms the ecological value of the internal closed-loop model.

Second, resource utilization efficiency has achieved step-by-step optimization. The cumulative reduction in

energy consumption per unit output reached 41.5%, and the water resource reuse rate increased by 40 percentage points, both of which are significantly ahead of the industry average; in 2024, the amount of organic fertilizer replacing chemical fertilizer reached 4,500 tons, 4.7 times the industry average, which not only reduced agricultural non-point source chemical pollution but also conformed to Liaoning Province's policy orientation of black soil protection and development, realizing the coordinated development of enterprise production and regional ecology.

Third, pollution control has achieved both compliance and ecological standards. The qualified rate of production "three wastes" discharge increased from 75% to 100%, and has maintained stable compliance for two consecutive years, 12 percentage points higher than the industry average (88%), highlighting the stability and reliability of the model in pollution control.

(2) Economic performance: environmental investment is transformed into value-added momentum, achieving a win-win pattern of "environmental protection and efficiency improvement"

First, the cost structure has achieved refined optimization. Although the proportion of environmental operation investment in revenue increased from 1.2% to 2.8%, the cost of waste mushroom stick treatment decreased by 71.2%, and the profit rate per unit product increased by 10.1 percentage points; in 2024, the enterprise's total output value exceeded 120 million yuan, an increase of 275% compared with 2019, far exceeding the industry average scale of 48 million yuan, confirming that environmental investment is not a "cost burden" but a core element driving enterprise value creation.

Second, the premium capacity of green products has been significantly improved. The proportion of green product revenue of the enterprise reached 55%, 27 percentage points higher than the industry average. This achievement stems from the enterprise's strategic practice of obtaining organic certification and laying out high-end markets relying on environmental performance advantages; combined with the industry trend of a 52.29% year-on-year increase in edible fungi exports in Anshan in 2024, the market competitiveness of its green products has been further released.

Third, the scale expansion effect has accelerated. The growth rate of the enterprise's total output value from 2023 to 2024 reached 60%, much higher than the industry's average annual growth rate of 25%, indicating that after the model matures, the brand value and cost advantages generated by environmental performance have been transformed into the core driving force for scale expansion, verifying the economic feasibility of the "circular economy + market-oriented" model.

(3) Technical adaptability: the collaboration between cold-region technological breakthroughs and digital empowerment builds core competitive barriers

First, the effect of cold-region adaptive technology is prominent. The survival rate of low-temperature cultivation of edible fungi in the enterprise reached 96%, 16 percentage points higher than the industry average, which benefits from the targeted research and development of low-temperature-resistant strains and intelligent temperature control technology, solving the industry pain point of a sharp decline in edible fungi output in winter in Northeast cold regions, and confirming the core conclusion that "technical adaptability is the key premise for the landing of environmental operation models".

Second, innovation capability and achievement transformation efficiency are ahead of the industry. The growth rate of technology R&D investment reached 311.8%, the number of patents owned increased to 22, and the number of scientific research cooperation institutions expanded to 12 (including professional colleges such as Shenyang Agricultural University), all indicators are far ahead of the industry average; in 2024, full-process digital coverage increased production scheduling efficiency by another 15%, further consolidating the enterprise's technical barriers.

Third, the technical scheme has strong industry promotion value. The popularization rate of intelligent cultivation technology reached 100%, 72 percentage points higher than the industry average (28%). The "cold-region digital circulation technology scheme" developed by the enterprise has been included in the 2024 agricultural green technology promotion catalog by the Department of Agriculture and Rural Affairs of Liaoning Province, and has a practical foundation for replication and promotion among similar cold-region agricultural enterprises.

In summary, based on the comprehensive research and judgment of data from three dimensions of environment, economy, and technology from 2019 to 2024, the environmental operation model constructed by Sanyou Agriculture has achieved a coordinated leap in environmental and economic performance through the logical link of "technical adaptability - environmental

circulation - economic value-added", and the results have continued to lead the industry average level. This practice not only verifies the adaptability of the model to leading edible fungi processing enterprises in Liaoning Province but also proves that the environmental operation system with "technological innovation as the core, circular economy as the path, and market orientation as the support" is a feasible paradigm for leading agricultural industrialization enterprises to achieve green transformation and high-quality development.

Conclusion

In the critical stage of the in-depth advancement of the "dual carbon" strategy and the green transformation of agriculture, the environmental operation level of leading agricultural industrialization enterprises in Liaoning Province has become a core variable restricting the sustainable development of regional agriculture. In response to the practical pain points of enterprises in the province such as passive environmental protection and insufficient adaptability of green technology, this study, supported by theories such as circular economy, technological innovation, and industrial chain integration, constructs a three-level innovative environmental operation model of "internal enterprise closed loop - industrial chain collaboration - regional resource sharing", and selects Liaoning Sanyou Agricultural Biotechnology Co., Ltd., a leading enterprise in characteristic agricultural product processing in Northeast cold regions, for empirical testing.

This study first clearly defines core concepts such as leading agricultural industrialization enterprises, environmental operation, and environmental operation model innovation, systematically sorts out the adaptability of theories such as value creation-oriented environmental management, environmental operation paradigm transformation, and green industrial chain integration, and establishes the core logic of environmental operation transformation from "passive compliance" to "value creation". At the model design level, the internal enterprise closed-loop model constructs differentiated circulation paths for different industrial types, grain processing enterprises form a closed loop of "raw grain - processing - energy - planting", animal husbandry enterprises build a self-sufficient cycle of "breeding - biogas - planting", and characteristic agricultural product processing enterprises realize the resource reuse of "cultivation - waste mushroom sticks - regenerated substrate"; the industrial chain collaborative model takes leading enterprises as chain leaders to connect the full-chain greening of upstream green supply, midstream clean processing, and downstream low-carbon circulation; the regional resource sharing model realizes the intensive allocation of resources across enterprises and industries by building sharing platforms such as waste treatment and black soil protection, and at the same time supports the model landing with three supporting elements: technology research and development, income incentives, and standard specifications. The case empirical results of Sanyou Agriculture show that from 2019 to 2024, under the empowerment of the new model, the resource utilization rate of the enterprise's waste mushroom sticks increased from 18% to 100%, the energy consumption per unit output decreased by 41.5%, the water resource reuse rate increased by 40 percentage points, the amount of organic fertilizer replacing chemical fertilizer reached 4,500 tons, and the production "three wastes" discharge achieved 100% compliance; at the economic level, although the proportion of environmental operation investment increased to 2.8%, the cost of waste mushroom stick treatment decreased by 71.2%, the proportion of green product revenue increased to 55%, the annual total output value increased by 275% compared with 2019, and the profit rate per unit product increased by 10.1 percentage points; in terms of technical adaptability, the survival rate of low-temperature cultivation in cold regions reached 96%, intelligent cultivation technology realized full-process coverage, the number of patents owned increased to 22, and the relevant technical scheme has been included in the provincial agricultural green technology promotion catalog, all indicators are significantly better than the average level of similar enterprises in Liaoning Province, successfully achieving the dual goals of "environmental protection and efficiency improvement".

In summary, the theoretical contribution of this study is to improve the theoretical system at the intersection of agricultural economy and environmental management and build an analysis framework for environmental operation of meso-level subjects; the practical value is reflected in providing a replicable green transformation plan for leading agricultural industrialization enterprises in Liaoning Province, and its cold-region adaptive technology and three-level circulation model provide a typical model for the

green revitalization of agriculture in the old industrial base of Northeast China, and also provide a scientific basis for local agricultural authorities to formulate targeted support policies and optimize the regional agricultural ecological governance system.

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