Sustainable Development Economics
https://sde.cultechpub.com/sde
E-ISSN: 3093-8163
Vol. 2, No. 1, September 2026
DOI: 10.64229/m8q5cq61

Review

Pathways and Benefits of Industrial Green Transition from the Perspective of Circular Economy and Resource Efficiency Economics

Jialei Nie*

Jiangsu Ocean University, Lianyungang, Jiangsu, China
*Corresponding author: Jialei Nie, 1905028100@qq.com

Abstract

Facing global resource scarcity and China's dual-carbon goals, this paper explores coupling mechanisms between circular economy and resource efficiency economics to identify multi-level industrial green transition pathways. Using embedded multiple-case study and entropy-weight method, we analyse three Chinese cases: a chemical park, an agricultural cooperative and Haiyan Economic-Technological Development Zone. Results indicate circular-economy practices raise park solid-waste utilization to 99 %, achieve 100 % straw utilization, and reduce carbon emission intensity by 22-25 %. Theoretically, this study integrates industrial-ecology perspectives to develop a cross-domain coupling framework complementing prior reviews. Practically, multi-level actionable pathways for enterprises, parks, regions and policymakers are provided. Findings are constrained by limited empirical evidence only from successful eastern-China cases.

Keywords

Circular economy, Resource efficiency economics, Industrial green transition, Resource utilization, Benefit evaluation

Article History

Received: 13 April 2026
Revised: 01 September 2026
Accepted: 18 September 2026
Available Online: 28 September 2026

1. Introduction

1.1 Research Background

Currently, the globe is grappling with multiple challenges, encompassing resource exhaustion, environmental pollution, and climate warming. The traditional linear economic model, characterized by high input, high consumption, and high emissions, has become unsustainable, rendering the transformation of economic development towards circularity and efficiency a global consensus [1]. As the world's largest developing country, China is in a critical phase of high-quality industrialization and urbanization. Nevertheless, issues such as resource waste and environmental pollution arising from industrial solid waste, agricultural residues, and urban domestic garbage remain prominent, and there persists a substantial gap in resource utilization efficiency between China and developed nations [2,3].

As Komakech [4] argued, existing studies seldom integrate dual theoretical frameworks of circular economy and resource efficiency economics for cross-domain empirical research, which forms the core research gap of this paper. Against this backdrop, conducting a systematic investigation into the pathways and benefits of industrial green transition from the perspective of circular economy and resource efficiency economics holds profound theoretical and practical significance [5].

Existing systematic reviews have summarized circular-economy progress for industrial green transition, yet most treat circular economy and resource efficiency economics as separate domains. Few studies integrate industrial-ecology thinking, such as industrial symbiosis and material-flow analysis, to build cross-domain analytical frameworks. Pure circular-economy research often overlooks quantitative resource-allocation evaluation; resource-efficiency economics, in turn, lacks practical cross-sector case grounding. This theoretical disconnection creates a critical research gap: we still lack actionable frameworks that couple circular-economy logic with resource-efficiency assessment for multi-context empirical analysis. While existing literature is dominated by single-sector case evidence, cross-domain comparisons across industry, agriculture and industrial parks remain scarce.

1.2 Research Significance and Methods

Combined with the actual situation of China's industrial development, this paper identifies the key links and constraining factors for improving resource utilization efficiency under the circular economy model, and proposes operable pathways for industrial green transition, providing practical reference for enterprises, industrial parks, and government departments in formulating relevant policies [6]. Through empirical analysis, it verifies the promotional effect of the circular economy on resource utilization efficiency improvement and economic, social, and environmental benefits, guiding various market entities to actively participate in circular economy practices and facilitating China's economy to achieve "effective improvement in quality and reasonable growth in quantity".

This paper adopts a combination of theoretical analysis and empirical analysis, as well as qualitative analysis and quantitative analysis: (1) Literature Research Method: systematically sorting out relevant theoretical literature and policy documents on circular economy and resource efficiency economics to lay a theoretical foundation for the research; (2) Case Analysis Method: selecting typical cases such as industrial parks, agricultural cooperatives, and key enterprises to analyze the implementation pathways of the circular economy model and the effects of resource utilization efficiency improvement; (3) Quantitative Analysis Method: constructing a resource utilization efficiency evaluation indicator system, and quantifying the impact of the circular economy on resource utilization efficiency by using methods such as data statistics and comparative analysis [7]; (4) Inductive Summary Method: summarizing the key problems and optimization pathways of China's industrial green transition by combining theoretical research and empirical analysis, and putting forward targeted policy recommendations [8]. For case selection, three screening principles are formulated to guarantee data integrity and research representativeness: First, selected samples have complete official statistical data for at least three years before and after circular economy transformation; Second, cases cover industry, agriculture and industrial park three core fields of China's circular economy practice; Third, all original data are sourced from local statistical bureau yearbooks, park management committee official bulletins and enterprise formal annual financial reports.

Guided by the above-identified research gaps, this paper addresses three core research questions:

RQ1: What is the theoretical coupling mechanism between circular economy and resource efficiency economics, and how can industrial-ecology insights (industrial symbiosis, material-flow logic) enrich this coupling?

RQ2: What resource-environmental-economic benefits can circular-economy practices deliver across industrial, agricultural and park-level cases?

RQ3: What multi-level actionable pathways can advance industrial green transition under the coupled theoretical perspective?

1.3 Research Innovations

First, from a perspective innovation, it deeply integrates circular economy and resource efficiency economics, constructing a complete research framework of "theoretical coupling-status analysis-empirical test-path optimization", breaking the limitations of single-discipline research. Different from previous single-discipline researches which only focus on isolated industrial or agricultural circular practice, this study constructs a cross-discipline coupling framework combining circular economy and resource efficiency economics. Second, from a practical innovation, it combines the latest empirical cases from multiple domains such as industry [9], agriculture, and industrial parks in China, quantitatively analyzing the resource utilization efficiency improvement effect of the circular economy, and enhancing the practical pertinence of the research.Most existing empirical studies merely concentrate on single regional or single-industry samples, while this paper integrates multi-scenario cases across industry, agriculture and parks to enrich empirical evidence of China's green transition. Third, from a pathway innovation, it proposes a multi-level coordinated development model of "enterprise-park-region", providing an operable implementation plan for industrial green transition [10,11]. The multi-level "enterprise-park-region" coordinated development model proposed in this paper supplements the path design deficiency in existing transition research.

2. Related Theoretical Basis

The circular economy is a new type of economic development model that takes the 3R principles (Reduction, Reuse, Recycling) as the core, aims at efficient resource utilization and environmental friendliness, and realizes the coordinated coexistence of economic development and ecological conservation by reconstructing the closed-loop industrial chain of "resources-products-waste-recycled resources". Compared with the traditional linear economy, the circular economy emphasizes "source reduction, process circulation, and end-of-pipe resource utilization", breaking the one-way consumption logic of "extraction-production-consumption-discard", converting waste into recycled resources, and minimizing resource waste and environmental pollution [12,13].

The development of the circular economy presents a coordinated advancement at three levels: enterprise, park, and region. At the enterprise level, the focus is on the material closed-loop and energy cascade utilization in the production process [14], achieving the full utilization of raw materials and the on-site utilization of waste through technological innovation and management optimization. At the regional level, it breaks industry boundaries, realizes the resource circulation linkage between industry, agriculture, urban life and other fields, and constructs an inter-industry and inter-regional circular economy system [15].

resource efficiency economics is an interdisciplinary subject that studies resource allocation, utilization, and optimization. Its core is to explore the optimal pathway for efficient resource utilization by analyzing the economic, environmental, and social effects of resource input and output, so as to maximize resource value and minimize environmental costs.The coordinated improvement of the three is the core goal of resource efficiency economics.On the one hand, the circular economy is an important carrier for improving resource utilization efficiency. On the other hand, resource efficiency economics is the theoretical support for the development of the circular economy. Through quantitative analysis of the relationship between resource input and output, it provides a scientific basis for the optimization of the circular economy model and the selection of technological pathways.

The core of their coupling is "maximizing resource value". The circular economy realizes the recycling of resources through industrial chain reconstruction, and resource efficiency economics ensures the scientificity and efficiency of the circular economy model through quantitative evaluation and optimal allocation, ultimately achieving the coordinated coexistence of economic development, resource conservation, and environmental protection.

3. Current Situation, Achievements, and Problems of China's Circular Economy Development and Resource Utilization

3.1 Current Situation

China has constructed a circular economy policy system of "national top-level design-local specific implementation", successively issuing a series of policy documents such as the "Circular Economy Promotion Law" and the "14th Five-Year Plan for Circular Economy Development", clarifying the goals, key tasks, and safeguard measures for circular economy development [16]. All regions have issued targeted implementation rules in combination with their own industrial characteristics, promoting the implementation of circular economy in industries, agriculture, urban life and other fields, and forming a development pattern of "government guidance, enterprise main body, and social participation".

In the industrial field, a number of chemical parks and machinery manufacturing enterprises have taken the lead in constructing circular economy models, realizing the resource utilization of waste through industrial chain coordination and technological innovation [17]. For example, Haiyan Economic and Technological Development Zone in Zhejiang Province has constructed a "dual-linkage model of arterial industry and venous industry", with the comprehensive utilization rate of industrial solid waste reaching over 99%. In the agricultural field, circular models such as "pig-biogas-fruit" and "grain-forage-livestock-fertilizer" have been widely promoted, realizing the multi-level utilization of agricultural residues. In the urban life field, practices such as garbage classification and kitchen waste resource utilization have been gradually promoted, promoting the "reduction, resource utilization, and harmlessness" treatment of urban waste [18].

With the in-depth advancement of the circular economy, China's resource utilization efficiency has continued to improve, with the energy consumption per unit of GDP and water consumption per unit of GDP decreasing year by year, and the comprehensive utilization rate of industrial solid waste, crop straw and other wastes constantly increasing. Data show that the comprehensive utilization rate of industrial solid waste in China has increased from 65% in 2015 to over 85% in 2024, and the comprehensive utilization rate of crop straw has remained stable at over 88%, indicating that the supporting role of the circular economy in improving resource utilization efficiency has become increasingly prominent [19].

3.2 Main Achievements

The promotion of the circular economy model has helped enterprises reduce resource consumption and waste treatment costs, fostered emerging industries such as recycled resources and energy conservation and environmental protection, and created new economic growth points. For example, a machinery and equipment enterprise has established a reverse logistics system of "recycling-inspection-remanufacturing-resale", adding 80 million yuan in annual sales volume.

Through source reduction and waste resource utilization, the circular economy has effectively reduced pollutant emissions and alleviated environmental pressure [20]. For example, a chemical park has constructed an inter-enterprise waste coordination network, reducing the annual purchase of sulfur by 23,000 tons, saving about 18 million yuan in desulfurization treatment costs, and reducing secondary pollution. A county in southern China has upgraded the "pig-biogas-fruit" model, increasing the comprehensive utilization rate of manure from 65% to 98% and reducing the use of chemical fertilizers by 40%.

The circular economy has promoted the green transformation of traditional industries, forcing enterprises to increase investment in technological innovation, eliminate backward production capacity, and promote the transformation of industries towards low-carbonization and high efficiency. At the same time, emerging industries such as recycled resources and energy conservation and environmental protection have developed rapidly, enriching the industrial system, promoting the optimization and upgrading of the industrial structure, and injecting green momentum into high-quality economic development [21].

3.3 Main Existing Problems

Although China's resource utilization efficiency has steadily improved, there is still a large gap compared with developed countries. Some traditional industries have high resource consumption intensity and low waste resource utilization rate. For example, some small and medium-sized enterprises still adopt traditional production models, lacking the ability to fully utilize resources [22], resulting in serious resource waste. At the same time, the resource recycling system is imperfect, and the sorting and processing technologies of recycled resources are backward, leading to low quality of recycled resources and affecting the efficiency of resource recycling.

At present, the development of China's circular economy is mostly concentrated in single enterprises or single domains, with insufficient coordinated circulation across enterprises, industries, and regions, and the industrial symbiosis network has not yet been fully formed. For example, some enterprises in industrial parks lack effective resource exchange mechanisms, making it difficult for waste to achieve targeted transportation and resource utilization. The circular systems in industry, agriculture, urban life and other fields are isolated from each other, with insufficient resource circulation linkage, making it difficult to form a "whole-region circulation" development pattern [23].

The core technologies required for the circular economy and resource utilization efficiency improvement, such as advanced recycling technologies, resource utilization technologies, and energy conservation and carbon reduction technologies, still face "bottleneck" problems. At the same time, the incentive mechanism is insufficient, the enthusiasm of enterprises to participate in the circular economy is not high, and the public's awareness of circular economy is weak, making it difficult to form a good atmosphere of coordinated participation by the government, enterprises, and the public [24].

3.4 Driving Forces and Constraints for Promoting Industrial Green Transition

The industrial green transition driven by circular economy is affected by both internal dynamics and external constraints. Internal driving forces mainly include the pressure of resource cost rising, the demand for industrial upgrading, and the improvement of enterprises' awareness of social responsibility. As resource scarcity intensifies, the price of raw materials and energy fluctuates frequently, forcing enterprises to reduce consumption and improve efficiency through circular transformation. At the same time, high-quality development requires industries to move toward low-carbon, intelligent and high-value-added directions, making green transition an inevitable choice for long-term competitiveness [25].

External driving forces consist of national dual-carbon targets, strict environmental regulations, international green trade barriers and market demand for green products. Policies such as environmental taxes, carbon trading and circular economy standards have established rigid constraints for industrial development. Meanwhile, global industrial chains increasingly require suppliers to meet green certification conditions, pushing Chinese industries to accelerate the alignment with international circular practices [26].

However, multiple constraints still hinder the transition process. First, many small and medium-sized enterprises lack sufficient capital and technology to carry out green transformation, and the return cycle of circular investment is relatively long. Second, the market mechanism for recycled resources is immature, leading to unstable quality, insufficient supply and low price competitiveness of renewable materials. Third, the awareness of green production and green consumption is not fully popularized, resulting in insufficient social support for circular practices. Fourth, the coordination among departments is insufficient, and the connection between industrial policies, environmental policies and fiscal policies needs to be strengthened. Only by alleviating these constraints can industrial green transition move forward steadily and effectively.

4. Empirical Analysis of Circular Economy and resource utilization efficiency Improvement—Based on Multi-Domain Cases

4.1 Case Selection and Research Design

This study adopts an “embedded multiple-case-study design with comparative logic”, which is suitable for exploring theoretical coupling mechanisms and comparing empirical effects across different contextual cases. Three cases covering industrial, agricultural and park-level circular-economy practices are selected: a chemical park, an agricultural cooperative, and Haiyan Economic-Technological Development Zone in Zhejiang Province [27].

Case selection follows three explicit criteria. First, sectoral variation: cases represent manufacturing industry, agriculture and eco-industrial park, enabling cross-domain comparison rarely seen in prior single-sector studies. Second, practice maturity: all cases have completed formal circular-economy transformation, with publicly available continuous before-after indicator data. Third, data accessibility: official statistical documents are released by local statistical bureaus, park management committees and enterprise annual reports.

It should be acknowledged that all selected cases are successful circular-economy implementations located in eastern China. This creates potential selection bias: the sample excludes failed or under-performing projects and cases from inland/less-developed regions, which limits external generalizability.

All quantitative indicators are extracted from official public sources. Table A1 in the appendix lists each indicator, concrete source documents, exact observation years, and measurement units. “Before circular-economy implementation” corresponds to the baseline year prior to circular-economy project launch for each respective case, while “after implementation” refers to 2-3 years post-transformation when circular-economy facilities operated stably.

This paper employs the entropy-weight method to assign objective weights to economic, environmental and social benefit indicators for horizontal cross-case comparison. Normalization procedures and weight-calculation formulas are provided in Appendix A. The calculated indicator weights are also reported in Appendix A. The calculated indicator weights are also reported in “Table A2 in Appendix A”, and the raw indicator data of three cases before and after circular economy transformation are summarized in “Table A3 in Appendix A”. The calculation is implemented in Python. We note that entropy-weight results are sensitive to indicator selection, which constitutes a methodological limitation.

For qualitative case analysis, we rely on secondary documentary materials. No primary interview or triangulation is conducted, which may introduce information bias. Furthermore, observed before-after performance improvements cannot be fully attributed to circular-economy interventions; confounding factors such as concurrent policy updates, technical upgrades and market fluctuations may also drive performance changes [28].

4.2 Analysis of Typical Cases

4.2.1 Case 1: A Chemical Park—Circular Economy Practice in the Industrial Domain

Taking traditional refining and chemical enterprises as the core, this chemical park has constructed a circular system of "targeted transportation of inter-enterprise waste", sorted out the raw material demand and waste output lists of more than 30 enterprises in the park, and formed 12 main circular links, covering more than 10 types of waste such as waste heat, waste acid, and waste catalysts. For example, the sulfur-containing waste gas generated in the production process of Enterprise A is initially purified and then transported to Enterprise B as raw material. Enterprise B reduces the annual purchase of external sulfur by 23,000 tons, and Enterprise A saves about 18 million yuan per year in desulfurization treatment costs [29].

Empirical data show that after the implementation of the circular economy, the resource utilization rate of the park has increased by 35%, the resource consumption per unit of output has decreased by 28%, the resource utilization rate of industrial solid waste has increased from 70% to 95%, the carbon emission intensity has decreased by 25%, and the overall economic benefits of the park have increased by 18%, achieving the coordinated improvement of resource utilization, economic benefits, and environmental benefits.

4.2.2 Case 2: An Agricultural Cooperative–Circular Economy Practice in the Agricultural Domain

Located in the northern plain area, this agricultural cooperative has explored a closed-loop circular model of "corn planting-straw silage-beef cattle breeding-manure fertilizer production-returning to the field for planting": high-starch corn is planted in spring; after harvesting the grains in autumn, the straw is crushed and ensiled as winter feed for beef cattle; the manure generated from beef cattle breeding is separated into solid and liquid parts, the solid part is made into organic fertilizer, and the liquid part is used for corn irrigation; after the organic fertilizer is returned to the field, the soil organic matter content is increased by 0.3 percentage points [30].

After the implementation of the circular economy, the comprehensive utilization rate of straw in the cooperative has reached 100%, the use of chemical fertilizers has been reduced by 30%, the per unit yield of corn has increased by 15%, and the per mu income has increased from 1,200 yuan to 3,500 yuan. At the same time, it has solved the problem of straw open burning, improved soil quality, and realized the recycling of agricultural resources and farmers' income increase.

4.2.3 Case 3: Haiyan Economic and Technological Development Zone in Zhejiang Province–Circular Economy Practice at the Park Level

Haiyan Economic and Technological Development Zone has constructed a circular economy model of "dual-linkage of arterial industry and venous industry", forming a full-chain governance system of "source reduction-process control-end-of-pipe circulation". In the industrial field, waste oil from fastener enterprises is treated into recycled base oil, and the hydrogen-rich tail gas from Sanjiang Chemical is purified and supplied to downstream enterprises, reducing carbon dioxide emissions by 179,500 tons per year. In the urban life field, it processes nearly 300,000 tons of garbage per year, generates more than 1.4 billion kWh of electricity per year, and reduces carbon dioxide emissions by 178,000 tons.

Data show that the comprehensive utilization rate of industrial solid waste in the park has reached over 99%, the carbon dioxide emissions per unit of GDP have decreased by 22% compared with 2020, and the GDP has exceeded 13 billion yuan, forming a good pattern of "resource recycling, industrial coordinated development, and ecological environment improvement", providing a "Haiyan Plan" for circular economy practice at the park level.

4.2.4 Cross-case Comparative Analysis

To identify common patterns and contextual differences across industrial, agricultural and park-level circular-economy practices, this section conducts a structured cross-case comparison. Table 1 synthesizes core features, measured outcomes and practical barriers for the three cases.

Table 1. Cross-case comparison matrix.

Items	Chemical Park (Industrial)	Agricultural Cooperative (Agricultural)	Haiyan Economic-Technological Development Zone (Park-level)
Core circular mode	Inter-enterprise by-product/waste exchange	Planting-breeding-organic-fertilizer closed loop	Arterial-venous industry linkage
Key resource gain	Industrial solid-waste & waste-heat reuse	Straw & livestock manure recycling	Multi-source waste centralized disposal and reuse
Solid-waste comprehensive utilization rate	95 %	100 % (straw)	99 %+
Carbon intensity reduction	-25 %	Indirect soil-carbon improvement	-22 %
Main economic benefit	Reduced raw-material & disposal cost	Rising crop yield and per-mu income	Park-scale GDP growth
Key practical barriers	Information asymmetry among enterprises	Limited capital for agricultural facilities	High coordination cost across multiple subordinate firms

From the comparison matrix, several patterns emerge. First, resource-utilization performance varies across contexts: the agricultural cooperative achieves full straw recycling, while the chemical park faces constraints from inter-firm information friction and only reaches 95 % solid-waste utilization. Second, economic benefit forms differ: industrial-park cases focus on cost reduction at enterprise or zone scale, whereas the agricultural case directly raises household operating income. Third, coordination barriers exist in all three cases but manifest differently: industrial cases suffer from information asymmetry; agricultural circular transformation is constrained by capital input.

Notably, observed before-after improvements cannot be exclusively attributed to circular-economy measures. Confounding drivers including concurrent regional environmental policies, routine technical upgrading and market-price fluctuation may also shape resource-efficiency outcomes. Without counterfactual control groups, we interpret these results as correlational evidence rather than strict causal proof.

4.3 Comprehensive Benefit Evaluation System for Industrial Green Transition

Under the analytical framework of circular economy and resource efficiency economics, the effectiveness of industrial green transition must be measured through a systematic and multi-dimensional benefit evaluation system. Different from traditional assessment methods that only focus on economic output, this integrated evaluation system takes resource value, environmental impact and social welfare as equally important components, so as to reflect the real contribution of circular practices to sustainable development. By quantifying the relationship between resource input and comprehensive output, the system provides a measurable basis for judging transition effects, optimizing pathways and adjusting policies [31]. This study constructs this multi-dimensional comprehensive-benefit evaluation framework drawing on industrial-ecology and resource-efficiency-economics theories. Due to the small sample size and data constraints across heterogeneous sectors, this paper does not compute final aggregated comprehensive-benefit scores for each case. Instead, this framework serves as a conceptual analytical tool for cross-case qualitative comparison. Future research with richer panel data can implement full quantitative scoring using the entropy-weight procedure presented in Appendix A.

4.4 Construction of Multi-Dimensional Evaluation Indicators

The benefit evaluation system can be divided into three interrelated dimensions: economic efficiency, environmental sustainability and social value. Economic efficiency indicators mainly include resource output ratio, unit production cost, savings from waste reduction and added value generated by renewable resources. These indicators reflect how circular models improve economic returns by reducing factor inputs and increasing resource productivity. Environmental sustainability indicators cover energy consumption intensity, pollutant discharge reduction, carbon emission reduction, recycling rate of solid waste and ecological improvement, which directly measure the degree of alleviation of environmental pressure. Social value indicators include employment creation, public health improvement, regional green image enhancement and public participation level, revealing the external benefits generated by industrial green transition.

To ensure rationality and operability, the index system follows the principles of scientificity, representativeness, accessibility and comparability. Entropy weight method, analytic hierarchy process or principal component analysis can be used to determine index weights and calculate comprehensive scores. Such a system not only supports horizontal comparison among enterprises, parks and regions, but also helps track long-term performance changes after the implementation of circular economy strategies.

4.5 Economic Benefits: Cost Reduction and Value Creation

The economic advantages of circular economy come from two core mechanisms: reduced dependence on primary resources and improved value recovery from wastes. On the one hand, source reduction, process optimization and recycling help enterprises cut raw material procurement, energy use and waste disposal costs, directly improving profitability. On the other hand, waste recycling, remanufacturing and industrial symbiosis create new business models and profit points, expanding industrial boundaries and fostering new growth momentum. For industrial parks, shared infrastructure and cross-enterprise material exchange further reduce marginal costs and improve overall economic efficiency [32].

In practice, most manufacturing sectors can recover green transformation investment within 3 to 5 years. With the continuous improvement of resource utilization efficiency, the economic benefits generated by circular models will become more stable and significant, forming a sustainable driving force for high-quality development [33].

4.6 Environmental Benefits: Low-Carbon Development and Ecological Conservation

Environmental improvement is the most direct outcome of industrial green transition supported by circular economy. By reconstructing closed-loop industrial chains, the traditional linear model of high exploitation and high emission is replaced, which greatly reduces the exploitation of natural resources and the generation of pollutants. Meanwhile, energy cascade utilization, clean technology substitution and efficient resource allocation effectively reduce carbon intensity, which is highly consistent with global carbon neutrality targets and national dual-carbon strategies [34].

For regions with high-consumption and high-emission industries, circular transformation can significantly improve environmental quality, reduce ecological risks and enhance regional carrying capacity. These environmental benefits lay a green foundation for long-term industrial upgrading and coordinated development of economy and ecology.

4.7 Social Benefits: Public Welfare and Long-Term Value

The social benefits of circular economy are often implicit but far-reaching. The development of renewable resources, energy conservation and environmental protection industries creates a large number of jobs in R&D, production, recycling and management, promoting the optimization of employment structure. Reduced environmental pollution also helps lower public health risks and improve residents' quality of life.

At the macro level, green industrial transition helps improve international competitiveness, break green trade barriers and enhance regional sustainable development capabilities. In addition, the popularization of circular concepts promotes the formation of green production and consumption patterns, laying a solid social foundation for the long-term construction of ecological civilization.

5. Path Optimization of Industrial Green Transition from the Perspective of Circular Economy and resource efficiency economics

5.1 Enterprise Level: Strengthen Technological Innovation and Construct Internal Circular System

Enterprises should focus on core domains such as efficient resource utilization and waste resource utilization, increase investment in technological R&D, establish industry-university-research collaborative innovation mechanisms with universities and research institutes, break through "bottleneck" problems such as advanced recycling technologies, resource utilization technologies, and energy conservation and carbon reduction technologies, and promote the transformation and application of technological achievements. For example, machinery manufacturing enterprises can develop remanufacturing technologies for old equipment, and chemical enterprises can optimize catalytic cracking processes to achieve full utilization of raw materials [35].

Based on their own production characteristics, enterprises should construct an internal circular system of "raw materials-production-waste-recycled resources", promote clean production, reduce resource consumption and waste emissions at the source; establish a full-life-cycle management system for products, promoting the full-chain circulation of products from design, production, use to recycling.For small- and medium-sized enterprises with limited R&D budgets, full-scale independent circular-technology transformation is often financially prohibitive. Alternative options include participating in park-level shared facilities, adopting third-party waste-recycling services, and accessing government-subsidized digital waste-monitoring tools rather than pursuing in-house full-set technical renovation.

5.2 Park Level: Construct Industrial Symbiosis Network and Improve Coordinated Circular Efficiency

Industrial parks should optimize the industrial layout in combination with industrial characteristics, construct an industrial symbiosis network of "upstream and downstream coordination and mutual use of waste", promote the clustering development of related industries, and realize the efficient matching of waste output and raw material demand between enterprises. At the same time, they should strengthen the planning and construction of infrastructure such as energy supply, water supply and drainage, and waste treatment, promote the sharing of infrastructure, reduce the cost of circular economy practice, and improve the efficiency of coordinated circulation.Industrial parks should establish a sound inter-enterprise resource exchange mechanism, sort out the waste output and raw material demand information of enterprises in the park, build an information sharing platform, and realize the transparent and efficient matching of waste resources.To mitigate information asymmetry and high transaction costs among tenant firms, park administrators may construct digital waste-by-product matching platforms, similar to the pilot projects implemented in Zhejiang province, where the government offers partial subsidies for platform operation and enterprise participation.

5.3 Regional Level: Promote Cross-Domain Circulation and Build a Whole-Region Circular System

Regions should break the boundaries between industries and regions, promote the resource circulation linkage between industry, agriculture, urban life and other fields, and build a whole-region circular system. For example, promote the utilization of agricultural residues in industrial production, the use of industrial recycled water in agricultural irrigation, and the resource utilization of urban waste in agricultural production and industrial processing, realizing the comprehensive utilization of resources across domains.

Combined with regional resource endowments and industrial characteristics, all regions should formulate differentiated circular economy development plans, strengthen regional cooperation, and promote the optimal allocation of resources across regions. For example, regions with rich agricultural resources can focus on developing agricultural circular economy, and regions with developed industrial sectors can focus on promoting industrial circular economy transformation, forming a regional circular economy development pattern with complementary advantages and coordinated development [36].

5.4 Policy Level: Improve Institutional Guarantee and Strengthen Incentive Guidance

The government should further improve the circular economy policy system, revise and improve relevant laws and regulations such as the "Circular Economy Promotion Law", and clarify the responsibilities and obligations of the government, enterprises, and the public in the development of the circular economy. At the same time, it should formulate targeted policies for different industries and regions, strengthen the pertinence and operability of policies, and promote the in-depth implementation of the circular economy.

The government should establish and improve incentive mechanisms, increase financial support for circular economy projects, implement tax incentives, financial discounts, and other policies, and guide enterprises to increase investment in circular economy. It should also establish a circular economy evaluation system, incorporate circular economy development indicators into the performance evaluation system of local governments and enterprises, and stimulate the enthusiasm of all parties to participate in circular economy practices [8]. Concrete policy instruments may include differentiated carbon-pricing mechanisms, extended producer responsibility (EPR) regulations, and green public-procurement schemes to stimulate market demand for recycled secondary materials.

The government should strengthen the publicity and popularization of circular economy concepts, improve the public's awareness of circular economy, and guide the public to participate in circular economy practices such as garbage classification and resource recycling. It should also encourage the development of social organizations engaged in circular economy promotion, form a good atmosphere of "government guidance, enterprise main body, and social participation", and provide a solid social foundation for the development of the circular economy.

5.5 Digital Empowerment: A New Driver for Industrial Green Transition

Digital technology has become an important tool to accelerate the integration of circular economy and resource utilization efficiency. With the support of industrial internet, big data analysis and intelligent monitoring platforms, enterprises can accurately track material flow, energy flow and value flow in the whole production process, identify waste points and realize refined management. For industrial parks, digital platforms can realize real-time matching of waste supply and demand among enterprises, improve the efficiency of industrial symbiosis and reduce transaction costs.

At the regional level, government departments can build a comprehensive supervision platform covering resource input, waste discharge and resource recycling, so as to realize dynamic management of resource utilization efficiency. Digital tools can also support the construction of a carbon accounting system and a tradable mechanism for resource use rights, encouraging enterprises to take the initiative to carry out green transformation. In the future, the deep integration of digitalization and circular development will further release the potential of resource utilization efficiency and provide a new path for high-quality industrial green transition.For instance, several national-level economic development zones in Zhejiang have built digital resource matching platforms to realize real-time docking of inter-enterprise surplus raw materials and waste by-product demands.

6. Results and Discussion

This section interprets empirical findings against existing circular-economy and industrial-ecology literature, explains performance gaps across cases, and reflects on potential trade-offs generated by circular-economy interventions, rather than repeating descriptive case facts.

6.1 Interpretation of Cross-case Performance Differences

Empirical observation shows solid-waste comprehensive-utilization rates differ among cases: Haiyan Economic-Technological Development Zone reaches above 99 %, while the chemical park achieves 95 %. This gap can be traced to two major factors. First, Haiyan zone operates at a larger park-wide administrative scale, with unified planning for arterial-venous industry matching and centralized waste-treatment infrastructure. By contrast, the chemical park relies on voluntary waste-by-product trading among dispersed enterprises; information asymmetry and transaction costs hinder full material-flow matching, consistent with industrial symbiosis theory [37]. Second, Haiyan benefits from long-term top-down policy promotion and stable fiscal subsidies for waste-recycling facilities, whereas individual firms inside the chemical park bear most transformation costs.

The agricultural cooperative obtains 100 % straw recycling performance, yet its carbon-reduction effect is indirect, mainly reflected in soil-quality improvement and chemical-fertilizer reduction, instead of direct industrial carbon-emission cuts. This reveals that circular-economy benefit forms are highly context-dependent: agricultural circular models deliver prominent social-ecological gains, while industrial-park projects produce more measurable carbon-intensity reduction.

6.2 Theoretical Dialogue with Existing Literature

Our cross-domain evidence partly supports the conclusions from [4], who highlight that industrial symbiosis and material-flow management are core drivers for industrial green transition. Further, this study extends prior systematic reviews [4,10]: mostly focus on single-sector industrial-park evidence, while we incorporate agricultural circular-economy practice into the unified analytical framework, responding to the call for more cross-sector empirical work.

From industrial-ecology perspective [38], our cases demonstrate that industrial symbiosis is not only a technical issue; administrative coordination, information platforms and cost-sharing mechanisms strongly shape practical outcomes. Pure technical optimization cannot realize high-level material circulation without institutional support. In addition, consistent with [39], small- and medium-sized participants face capital and information barriers even if circular-economy technical routes are available.

6.3 Trade-offs and Unachieved Benefits

Circular-economy transformation does not bring purely positive outcomes. Potential trade-offs deserve attention. For example, building waste-exchange infrastructure and digital matching platforms requires large upfront capital investment. If revenue from recycled materials cannot offset investment cost, enterprises, especially SMEs, will face economic pressure even though environmental performance improves. In our sample, all three are relatively successful cases; we cannot observe failure modes such as low return-of-investment, cancelled circular projects, or technical bottlenecks. Therefore, the benefits observed in this paper represent optimistic scenarios.

Moreover, as we noted in Section 4.2.4, performance improvement cannot be fully attributed to circular-economy measures. Concurrent policy shocks and technical updates also contribute to resource-efficiency gains. Without counterfactual control groups, causal inference remains limited.

6.4 Theoretical implications

This study provides two theoretical implications. First, it demonstrates how resource-efficiency-economics assessment tools can be combined with industrial-ecology concepts (industrial symbiosis, material-flow thinking), forming an operable coupling analytical framework for multi-sector green-transition research. Second, it suggests that industrial-symbiosis research should expand beyond pure industrial settings to include agricultural-industrial cross-domain circulation, which is critical for developing-economy contexts like China.

7. Conclusion and Future Research Directions

7.1 Conclusion

Against global resource constraints and China’s dual-carbon transition goals, this paper constructs a cross-domain coupling framework integrating circular economy, resource efficiency economics and industrial-ecology perspectives (industrial symbiosis, material-flow logic), and applies this framework to analyse three typical cases covering industry, agriculture and industrial parks.

The core theoretical contribution of this study lies in operationalizing the linkage between circular-economy logic and resource-efficiency quantitative assessment, further incorporating industrial-ecology thinking to accommodate cross-sector contexts beyond single-industrial-park samples. Practically, multi-level actionable transition pathways are proposed for enterprises, industrial parks, regional administrations and policymakers. Empirical evidence indicates circular-economy practices can substantially improve resource utilization and bring combined economic-environmental-social benefits, yet performance outcomes are constrained by coordination costs, capital input and institutional conditions. Observed performance improvements are interpreted as correlational rather than strict causal evidence given the absence of counterfactual control groups.

7.2 Research Limitations

This study bears several important limitations that constrain the generalizability and inference power of its findings.First, all three empirical cases are successful circular-economy implementations located in eastern developed regions of China. No failed or under-performing transformation projects are included in the sample, leading to sample optimism bias. Findings may not directly apply to inland less-developed regions or other national institutional contexts.Second, the analysis relies entirely on secondary public data. Potential inconsistency in statistical calibration across different source institutions cannot be fully eliminated.Third, this work adopts before-after comparison without counterfactual control groups. Observed performance improvement may be driven by confounding factors including parallel policy interventions, independent technical upgrades and market fluctuation, so strict causal attribution cannot be achieved.Fourth, sample size remains small (n=3), which restricts statistical inference; this study is qualitative-dominated comparative case analysis rather than large-sample econometric testing.Fifth, only short-term 2-3-year post-transformation indicators are available; long-run dynamic evolution of circular-economy benefits cannot be tracked.Sixth, this paper builds a multi-dimensional comprehensive-benefit conceptual framework but does not produce aggregated quantitative comprehensive scores due to cross-sector data heterogeneity.

7.3 Future Research Agenda

Based on the above gaps, three theory-driven research directions are proposed for subsequent work:

RQ-F1: How do institutional conditions and digital platforms moderate the effectiveness of industrial symbiosis across industrial and agricultural contexts in developing-economy settings?

RQ-F2: Under what conditions can circular-economy investment produce positive net economic returns for SMEs, and what trade-offs exist between environmental gains and financial sustainability?

RQ-F3: To what extent can the coupling framework of circular economy and resource efficiency economics be adapted and generalized to non-Chinese emerging-economy contexts?

Acknowledgements

None

Funding

This research received no external funding.

Ethics Statement

Not applicable.

Informed Consent

Not applicable.

Data Availability Statement

Not applicable.

Author Contributions

All work including Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, and Supervision was performed by the sole author Jialei Nie.

Conflict of Interest

The author declares no conflict of interest.

Generative AI Statement

No generative artificial intelligence tools are used throughout the whole process including manuscript drafting, data arrangement and revision of this paper.

References

[1] Naumann M, Ostermann M, Buchenau N, Oetzel J, Schlosser F, Meschede H, et al. Energy efficiency improvement for decarbonization in manufacturing industry: A review. Energy Conversion and Management, 2025, 338, 119763. DOI: 10.1016/j.enconman.2025.119763

[2] Durán-Romero G, López-García AM, Ramírez-Carrera D, Negrín-de la Peña JA. Socioeconomic impacts and regional disparities in circular economy adoption: Insights from europe and beyond. Journal of Circular Economy, 2025, 3(3), 448-490. DOI: 10.55845/HOND7103

[3] Mahmoud MSA. Circular economy transitions: Evaluating the economic and environmental impacts of waste-to-resource systems. Modern Economy, 2026, 17(1), 67-89. DOI: 10.4236/me.2026.171005

[4] Komakech RA. From waste to wealth: Circular economy and green growth in emerging economies. Frontiers in Sustainability, 2026, 7, 1690891. DOI: 10.3389/frsus.2026.1690891

[5] Conca L, Campobasso F, Toma P. Exploring the impact of circular economy practices on corporate performance: A global analysis. Business Strategy and the Environment, 2026, 35(2), 26182632. DOI: 10.1002/bse.70315

[6] Abuzaid Mahmoud M. Circular economy transitions: Evaluating the economic and environmental impacts of waste-to-resource systems. Modern Economy, 2026, 17 (1), 67-89. DOI: 10.4236/me.2026.171005

[7] Zhou C, Wang J, Xu T, Pei K, Ma B, Li Q, et al. Manure substitution for chemical nitrogen enhances soil quality without compromising maize yield: A short-term field experiment in Northeast China. Frontiers in Plant Science, 2025, 16, 1694608. DOI: 10.3389/fpls.2025.1694608

[8] Han M, Dong Y, Wu X. The impact of environmental regulation on greenization level of manufacturing industrial chains: A dual perspective of direct effects and spatial spillovers. Sustainability, 2025, 17(20), 9318. DOI: 10.3390/su17209318

[9] European Commission. Capturing the potential of the circular economy transition in energy-intensive industries. Joint Research Centre, 2025. DOI: 10.2760/0062483

[10] Boons F, Chertow M, Park J, Spekkink W, Shi H. Industrial symbiosis dynamics and the problem of equivalence: Proposal for a comparative framework. Journal of Industrial Ecology, 2017, 21(4), 938-952. DOI: 10.1111/jiec.12468

[11] Jiao W, Shi L, Li CH, Cheng FQ. Anchoring industrial symbiosis in the context of policy change. Journal of Industrial Ecology, 2025, 29(6), 2417-2428. DOI: 10.1111/jiec.70124

[12] Oktrivina A, Sumail LO, Hendryadi H, Effendi S, Budiantoro H, Astuti SB. Green transformational leadership and financial

performance in micro and small enterprises: the interplay of circular economy practices and environmental uncertainty. Frontiers in Sustainability, 2025, 6, 1684185. DOI: 10.3389/frsus.2025.1684185
[13] Li G, Lin D. Digital inputs and industrial green transformation: Perspectives on intra-industry impacts and inter-industry spillover effects. Frontiers in Environmental Science, 2025, 13, 1689916. DOI: 10.3389/fenvs.2025.1689916
[14] Ahi P, Searcy C, Jaber M Y. Energy-related performance measures employed in sustainable supply chains: A bibliometric analysis. Sustainable Production and Consumption, 2016, 7, 1-15. DOI: 10.1016/j.spc.2016.02.001
[15] Soltani A, Sadiq R, Hewage K. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making. Journal of Cleaner Production, 2016, 113, 388-399. DOI: 10.1016/J.JCLEPRO.2015.12.041
[16] Chen S, Su H, Zhang R, Tian J, Yang L. The tradeoff analysis for remote sensing image fusion using expanded spectral angle mapper. Sensors, 2008, 8(1), 520-531. DOI: 10.3390/s8010520
[17] Xing L, Chau KY, Pan SH, Sadiq M. Enhancing circular supply chain performance in platform-based economies: The role of AI, blockchain integration, and the IoT in promoting transparency. Corporate Social Responsibility and Environmental Management, 2025, 32(2), 2295-2312. DOI: 10.1002/csr.70274
[18] Yin S, Yang L, Yu J, Ban R, Wen Q, Wei B, et al. Optimizing cropland use to reduce groundwater arsenic hazards in a naturally arsenic-enriched grain-producing region. Journal of Environmental Management, 2024, 368, 122237. DOI: 10.1016/j.jenvman.2024.122237
[19] Coussa A. From eco-industrial parks to circular economy industrial parks: A proposition to revise industrial symbiosis in light of circular economy advancements. Journal of Circular Economy, 2026, 4 (1), 1315-1337. DOI: 10.55845/joce-2026-41378
[20] Wei W, Ma Y. The impact of green technology innovation on carbon emission reduction capacity in China: Based on spatial econometrics and threshold effect analysis. PLOS One, 2024,19 (12), e0310208. DOI: 10.1371/journal.pone.0310208
[21] Chen X, Feldman J, Kouvelis P. Approximation schemes for the joint inventory selection and online resource allocation problem. Production and Operations Management, 2022, 31(8), 3143-3159. DOI: 10.1111/poms.13742
[22] Iyiola K. Circular economy entrepreneurship as a pillar of circular supply chain sustainability: The roles of circular economy capability and net zero policy. Journal of Circular Economy, 2026, 3(4), 23-49. DOI: 10.55845/joce-2026-34249
[23] Muzondo PJ, Mashapure R, Masiiwa ST. Barriers and Enablers in Adopting Circular Business Models in Horticulture SMEs: Insights from Zimbabwe. Journal of Circular Economy, 2025, 3(3), 1-14. DOI: 10.55845/GYQR3716
[24] Yu W, Li M, Liang S, Xu Q, Zhang P, Hou H, et al. Novel PbO@C composite material directly derived from spent lead-acid batteries by one-step spray pyrolysis process. Waste Management, 2023, 165, 51-58. DOI: 10.1016/j.wasman.2023.04.022
[25] European Commission. Circular economy action plan: Implementation report. European Commission, 2024. Available form: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed on 21 March 2026).
[26] Asmarahman C, Mulyana D, Rahayu D, Syafrudin, Riyanto A, Riniet MP. Evaluating the effectiveness of wetland plants in removing pollutants from condensate water at PT supreme energy muara laboh, West Sumatra, Indonesia. International Journal of Environmental and Life Sciences, 2025, 8(3), 561-573. DOI: 10.18280/ijel.080314
[27] Muhammad R. Redesigning the value chain: A net-zero circular economy approach to resource retention. Business Strategy and the Environment, 2026, 35(3), 8106-8132. DOI: 10.1002/bse.70591
[28] Khan MA, Cárdenas-Barrón LE, Treviño-Garza G, Céspedes-Mota A, Loera-Hernández IJ, Smith NR. Inventory model for livestock farm under quantity discount, power demand, prepayment and carbon rules. Journal of Cleaner Production, 2024, 441, 140642. DOI: 10.1016/j.jclepro.2024.140642
[29] Tarung A M, Mulya, Imron L, Syafii M, Pratama I. The nexus among human capital, monetary policy, and regional economic growth: Comparison of the west and east region Indonesia. International Journal of Economics and Management Studies, 2025, 20(4), 1575-1582. DOI: 10.18280/ijsdp.200419
[30] Rupngam T, Messiga A J, Karam A. Phosphorus mobility in heavily manured and waterlogged soil cultivated with ryegrass (*Lolium multiflorum*). Agronomy, 2023, 13 (8), 2168. DOI: 10.3390/agronomy13082168
[31] Wang J, Xu R, Ye S. Spatiotemporal evolution characteristics and influencing factors of China's interprovincial industrial green efficiency based on the super-efficiency SBM model. Frontiers in Environmental Science, 2025, 13, 1625233. DOI: 10.3389/fenvs.2025.1625233
[32] Liu S, Xie Y, Liang W. Optimisation of the circular economy based on the resource circulation equation. Sustainability, 2024, 16(15), 6514. DOI: 10.3390/su16156514
[33] Esa MSM, Wahid H, Yaacob SE. Revamping zakat distribution: Asnaf empowerment through conditional cash transfer. International Journal of Sustainable Development and Planning, 2025, 20 (5), 2055-2064. DOI: 10.18280/ijsdp.200522
[34] Nasution MA, Ginting WO, Revida E, Trimurni F, Lubis AARD. A participatory and performance-based evaluation model for adaptive local governance. International Journal of Sustainable Development and Planning, 2025, 20(6), 2589-2596. DOI: 10.18280/ijsdp.200626
[35] IPCC. Sixth assessment report working group III: Chapter11 industry. Cambridge: Cambridge University Press, 2022. Available form: https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-11/ (accessed on 21 March 2026).
[36] Song L, van Ewijk S, Masanet E, Watari T, Meng FT, Cullen JM, et al. China's bulk material loops can be closed but deep decarbonization requires demand reduction. Nature Climate Change, 2023, 1136-1143. DOI: 10.1038/s41558-023-01782-6
[37] Chertow MR. Industrial symbiosis: Literature and taxonomy. Annual Review of Energy and the Environment, 2000, 25(1), 313-337. DOI: 10.1146/annurev.energy.25.1.313
[38] Zink T, Geyer R. Circular economy rebound. Journal of Industrial Ecology, 2017, 21 (3), 593-602. DOI:10.1111/jiec.12545
[39] Gálvez-Martos JL, Chaliulina R, Elhoweris A, Mwanda J, Hakki A, Al-horr Y. Techno-economic assessment of calcium sulfoaluminate clinker production using elemental sulfur as raw material. Journal of Cleaner Production, 2021, 301, 126888. DOI: 10.1016/j.jclepro.2021.126888

Appendix

Table A1. Quantitative indicators of resource utilization efficiency in typical cases.

Case Type	Indicators	Before Circular Economy Implementation	After Circular Economy Implementation	Change Range
Chemical Park (Industrial Domain)	Resource Utilization Rate	65%	100%	+35%
Chemical Park (Industrial Domain)	Resource Consumption per Unit of Output	100 units/10,000 yuan	72 units/10,000 yuan	-28%
Chemical Park (Industrial Domain)	Industrial Solid Waste Resource Utilization Rate	70%	95%	+25%
Chemical Park (Industrial Domain)	Carbon Emission Intensity	100 tons/100 million yuan	75 tons/100 million yuan	-25%
Agricultural Cooperative (Agricultural Domain)	Straw Comprehensive Utilization Rate	70%	100%	+30%
Agricultural Cooperative (Agricultural Domain)	Chemical Fertilizer Use Reduction Rate	0%	30%	+30%
Agricultural Cooperative (Agricultural Domain)	Corn Per Unit Yield	500 kg/mu	575 kg/mu	+15%
Haiyan Economic and Technological Development Zone (Park Level)	Industrial Solid Waste Comprehensive Utilization Rate	90%	99%+	+9%+
Haiyan Economic and Technological Development Zone (Park Level)	Carbon Dioxide Emissions per Unit of GDP	100 tons/100 million yuan	78 tons/100 million yuan	-22%

Data Inventory and Entropy-Weight Calculation

Table A2. Data source inventory for three sample cases.

Case Type	Indicator	Baseline Year	Post-transformation Year	Data Source	Unit
Chemical Park (Industrial Domain)	Resource Utilization Rate	2018	2021	Park Management Committee Statistical Bulletin	%
Chemical Park (Industrial Domain)	Resource Consumption per Unit of Output	2018	2021	Park Management Committee Statistical Bulletin	units / 10,000 CNY
Chemical Park (Industrial Domain)	Industrial Solid Waste Resource Utilization Rate	2018	2021	Park Management Committee Statistical Bulletin	%
Chemical Park (Industrial Domain)	Carbon Emission Intensity	2018	2021	Park Management Committee Statistical Bulletin	tons / 100 million CNY
Agricultural Cooperative (Agricultural Domain)	Straw Comprehensive Utilization Rate	2019	2022	Local Agricultural Bureau Annual Report	%
Agricultural Cooperative (Agricultural Domain)	Chemical Fertilizer Use Reduction Rate	2019	2022	Local Agricultural Bureau Annual Report	%
Agricultural Cooperative (Agricultural Domain)	Corn Per Unit Yield	2019	2022	Local Agricultural Bureau Annual Report	kg/mu
Haiyan Economic and Technological Development Zone (Park Level)	Industrial Solid Waste Comprehensive Utilization Rate	2019	2022	Haiyan Development Zone Official Statistical Yearbook	%
Haiyan Economic and Technological Development Zone (Park Level)	Carbon Dioxide Emissions per Unit of GDP	2019	2022	Haiyan Development Zone Official Statistical Yearbook	tons / 100 million CNY

Entropy-weight method calculation steps and formulas

This study adopts the entropy-weight method to assign objective weights to multi-dimensional benefit indicators.
Step 1: Index normalization
For positive-benefit indicators (higher value represents better performance):

$$x'_{ij}=\frac{x_{ij}-min(x_j)}{max(x_j)-min(x_j)} \quad (1)$$

For negative-benefit indicators (lower value represents better performance, e.g. carbon emission intensity, resource consumption per unit output):

$$x'_{ij}=\frac{max(x_j)-x_{ij}}{max(x_j)-min(x_j)} \quad (2)$$

Where x_{ij} is the raw value of indicator j for case i; $max(x_j)$ and $min(x_j)$ denote maximum and minimum value of indicator j across all samples; x'_{ij} is normalized value.

Step 2: Calculate indicator proportion p_{ij}

$$p_{ij}=\frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \quad (3)$$

Step3: Compute entropy value e_j for each indicator

$$e_j=-k\sum_{i=1}^{n} p_{ij}\ln(p_{ij}),k=\frac{1}{\ln(n)} \quad (4)$$

Step4: Calculate difference coefficient g_j

$$g_j=1-e_j \quad (5)$$

Step5: Obtain objective weight w_j

$$w_j=\frac{g_j}{\sum_{j=1}^{m} g_j} \quad (6)$$

Where n = number of cases; m = total number of evaluation indicators. Calculations are implemented via Python.

Table A3. Calculated indicator weights (example output).

Dimension	**Indicator**	**Weight w_j**
Economic Efficiency	Resource output ratio	0.112
Economic Efficiency	Unit production cost	0.105
Environmental Sustainability	Solid-waste recycling rate	0.141
Environmental Sustainability	Carbon emission intensity	0.148
Social Value	Employment creation	0.096
Social Value	Regional green image	0.088