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INNOVATION IN THE PATH OF CLEANER PRODUCTION AUDIT MECHANISM FROM THE PERSPECTIVE OF CIRCULAR ECONOMY IN WASTE MANAGEMENT

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ABSTRACT
Facing climate change and resource constraints, cleaner production (CP) and the circular economy (CE) are essential for achieving China's "dual carbon" goals. While CP and CE form a mutually reinforcing coupling through material flow synergy and waste management synergy, conventional cleaner production audits (CPA) remain limited to enterprise-level scope with fragmented waste management, failing to capture systemic resource circulation opportunities. To address this gap, the research proposes an innovative CPA mechanism integrating CE principles for enhanced waste management. The mechanism introduces three innovative pathways: (1) methodological transformation from enterprise-level to industry/park-level overall audit; (2) process optimization through refined waste and material flow management; and (3) evaluation criterion reconstruction integrating waste management and resource recovery indicators. This approach provides theoretical foundations and practical pathways for implementing CE-oriented waste management, contributing to SDG 12 (Responsible Consumption and Production), SDG 9 (Sustainable Industrial Development), SDG 13 (Climate Action), and China's "Dual Carbon" objectives. While empirical validation through case studies remains a priority for future research, the proposed framework establishes a comprehensive methodological foundation for transforming conventional CPA practices toward circular economy principles.

1. INTRODUCTION

In the context of global climate change and increasingly prominent resource and environmental constraints, improving waste management efficiency and promoting resource recovery have become key tasks for countries to achieve sustainable development (Geng et al., 2019; Varsha et al., 2025). The global economy currently consumes approximately 100 billion tonnes of raw materials annually, with less than 6.9% being recycled and reused (Circle Economy, Circularity Gap Report 2025). Consequently, this linear economic model not only exacerbates resource depletion but also poses serious threats to ecosystems. China, as the world's largest developing country, has clearly put forward the dual carbon goals (carbon peak and carbon neutrality), which require a fundamental transformation from the traditional linear economic model to a circular model centered on waste reduction, reuse, and recycling (Jiang, 2025). The transition to a circular economy (CE) is estimated to have the potential to reduce global greenhouse gas emissions by 25 billion tonnes by 2030 and significantly alleviate resource pressure (Circle Economy, Circularity Gap Report 2025).

Cleaner production (CP), as a crucial means of pollution prevention and resource conservation, has been promoted in China for over two decades. Since the enactment of the CP Promotion Law in 2002, remarkable accomplishments have been made in energy conservation and emission reduction across the country (Chen et al., 2023; Zhang et al., 2023). Since 2016, over 40,000 enterprises nationwide have conducted mandatory cleaner production audits (CPA), with total investment in CP transformation exceeding RMB 270 billion and more than 610,000 CP schemes proposed. Moreover, remarkable achievements have been made in pollution reduction and carbon emission mitigation. According to available statistics, the implementation of CP transformations has resulted in the reduction of approximately 5.16 billion tons of wastewater, 370,000 tons of chemical oxygen demand (COD), 51,000 tons of ammonia nitrogen, 688,000 tons of sulfur dioxide (SO_2), and 567,000 tons of nitrogen oxides (NO_2). Additionally, through the conservation of electricity, coal, natural

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gas, and other energy sources, the cumulative reduction in carbon dioxide (CO_2) emissions has reached approximately 4.37 billion tons (Ministry of Ecology and Environment, 2022). Nevertheless, conventional CPA primarily focus on individual enterprises, lacking systematic coordination in waste management and resource recovery at the industrial or park level (Li et al., 2025). This leads to problems such as fragmented waste recycling, low resource recovery efficiency, and difficulties in forming synergistic effects with regional CE systems. For instance, in typical industrial parks, a substantial proportion of potential waste exchange synergies remain unrealized due to persistent institutional barriers and inadequate audit mechanisms (Sokka et al., 2020; Fraccascia et al., 2020).

Currently, the CPA system is confronted with three fundamental challenges in adapting to the requirements of the CE. First, there is a mismatch in audit scope. conventional CPA is confined within the boundaries of individual enterprises, while the CE demands consideration of cross-organizational material flows (General Office of the Ministry of ecology and environment, 2022; de Oliveira et al., 2023). This discrepancy gives rise to what scholars refer to as the "island effect" in CP, where individual enterprises achieve internal optimization, yet the systematic resource circulation loops remain unclosed (Fraccascia et al., 2020). Second, there exists a deficiency in methodologies. Existing CPA lack standardized approaches for tracking waste streams across different enterprises and industries. The absence of material flow analysis frameworks tailored for industrial symbiosis makes it difficult to identify and quantify opportunities related to the CE (Gupta et al., 2021). Third, there is a gap in the evaluation system. Current performance indicators mainly center on in-enterprise pollution control and energy efficiency, failing to incorporate metrics that reflect CE performance—such as cross-facility resource productivity and waste valorization rates (Ferrante et al., 2025; de Oliveira et al., 2023). Leading countries in CE development, including Germany and Japan, have established extended producer responsibility systems and industrial symbiosis promotion mechanisms, thereby substantially enhancing their national resource efficiency and reducing environmental pollution (Kripalani et al., 2025; Environmental Research & Education Foundation, 2025; Helena Dickinson, 2024; Alev et al., 2020). However, these experiences cannot be directly applied in China due to differences in industrial structure, governance systems, and development stages. Therefore, developing an innovative path of CPA mechanism from the perspective of CE in waste management that suits China's national conditions not only holds theoretical value but is also crucial for achieving the dual carbon goals.

Despite growing recognition of CE principles in waste management, a critical research gap persists: existing CPA lack systematic frameworks for tracking cross-enterprise resource flows and quantifying inter-organizational circularity performance. This study addresses this gap by constructing an innovative CPA framework that operationalizes CE principles within waste management. By integrating theories of industrial ecology, institutional analysis, and environmental management, we develop a tool to advance system-level circularity through auditable enterprise actions. The analysis proceeds through a critical review of current CPA limitations and the presentation of a new CPA framework from the perspective of CE. The research provides theoretical contributions by bridging CE and CPA scholarship, and practical value by offering policymakers an actionable roadmap to boost resource efficiency through audit mechanism innovation.

2. THEORETICAL BACKGROUNDS

2.1 CP and the CE

CP and the CE are core pathways driving the green transformation of industry. The two approaches form a complementary system in the fields of waste management and resource utilization, characterized by "source control–system closure". Clarifying their conceptual boundaries and coupling logic provides the theoretical foundation for establishing a CE-oriented CPA mechanism.

CP (Cleaner Production): Guided by the concept of "holistic prevention", CP takes reducing pollutant emissions, conserving resources, and improving production efficiency as its core objectives, and implements comprehensive control throughout the production process (covering raw material procurement, product design, and production packaging and transportation) (UNEP, 2001). Its key measures include process optimization, clean energy substitution, and internal resource recycling, with the goal of minimizing waste generation at the source and laying a foundation for subsequent waste management and resource recovery.

CE (Circular Economy): Centered on the "3R Principles" (Reduction, Reuse, Recycling), CE extends the scope of resource management beyond individual enterprises to the entire industrial chain and regional system (ISO, 2023). It focuses on building closed-loop of waste recycling and resource recovery systems, realizing the transformation of waste into renewable resources through multi-level coordination across enterprises, industries, and regions, and ultimately achieving the dual goals of waste minimization and resource utilization maximization (Ellen MacArthur Foundation, 2013).

2.2 Coupling relationship between cleaner production and circular economy

CP and CE are not mutually independent; rather, they form a deeply integrated system characterized by "front-end reduction and back-end recycling" (Figure 1). Recent research demonstrates CP-CE coupling through the sustainable energy conversion of lignocellulosic and urban waste via modified downdraft gasification, producing clean fuel within a circular economy framework while reducing waste disposal burdens and environmental pollution (Saravanakumar et al., 2026). Studies further indicate that waste-to-hydrogen technologies utilizing municipal solid waste and biomass as feedstocks embody CP-CE coupling via material valorization and clean energy generation. Substituting diesel with hydrogen in fuel-cell vehicles from 2025 to 2045 is projected to substantially reduce 8.00-14.43 million tonnes of CO_2 and 2.30-4.09 million tonnes of CO emissions (Rahman et al., 2025). This structure creates

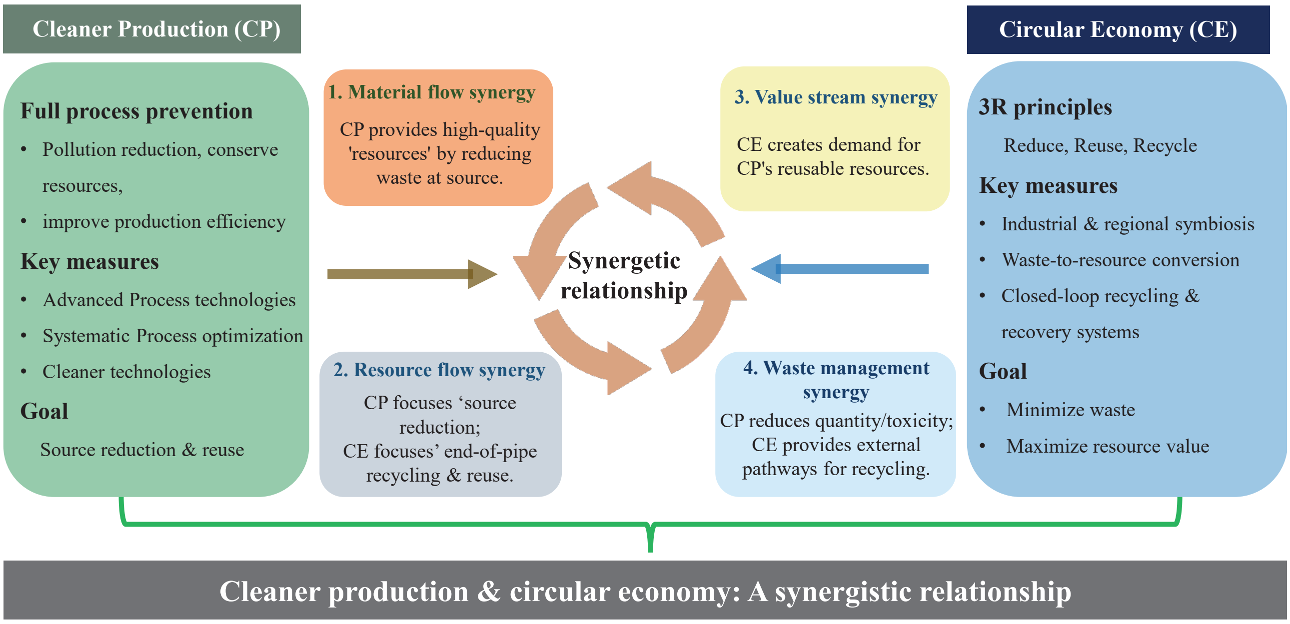

FIGURE 1: Coupling relationship between CP and CE.

a synergistic, mutually reinforcing effect in the fields of waste management and resource recovery, which is specifically manifested in two dimensions: material flow synergy and waste management synergy (Geng et al., 2012).

Material flow synergy: CP optimizes material utilization efficiency within enterprises, reducing waste generation at the source and thereby alleviating the pressure of subsequent waste treatment and provides high-quality "recyclable raw materials" for the CE system. In turn, CE expands channels of resource recovery, enabling waste from one enterprise to be reused as raw materials for another, which further promotes enterprises to deepen CP practices (Lieder & Rashid, 2016).

Waste management synergy: CP focuses on "source reduction" of waste, while CE focuses on "end-of-pipe recycling" and "systematic reuse" of waste. The combination of the two forms a "source reduction-recycling-reuse" full-chain waste management model, avoiding the limitations of single-stage management and improving the overall efficiency of waste management (Sousa-Zomer et al., 2018).

3. LIMITATIONS OF CONVENTIONAL CLEANER PRODUCTION AUDIT IN WASTE MANAGEMENT

The conventional CPA in China predominantly concentrate on individual enterprises, exhibiting significant limitations in effectively supporting waste management and resource recovery (Sokka et al., 2020).

Narrow scope of audit: The conventional CPA only covers the internal production process of the enterprise, ignoring the connection of waste and resources with upstream and downstream enterprises in the industrial chain (Li et al., 2016). For example, a chemical enterprise may reduce its own wastewater discharge through CP. However, the slag or solid waste it generates often cannot be effectively recycled due to a lack of coordinated planning with downstream treatment or recycling facilities. This disconnect not only leads to secondary pollution but also results in suboptimal resource recovery rates, undermining the systemic benefits of CP (Lyu et al., 2022).

Inadequate management of waste and material flows: The conventional CPA pays more attention to the quantitative reduction of pollutants but lacks refined tracking and analysis of waste generation stage (the type, quantity, and composition of waste generated in each production stage). This makes it difficult to identify the key stages of waste generation and formulate targeted waste reduction and recovery plans (Huang et al., 2024).

Incomplete evaluation criteria: The assessment of CP performance primarily relies on indicators such as pollutant emission reduction and energy savings, while largely excluding metrics specifically related to waste management and resource recovery. This incomplete evaluation system creates a skewed incentive structure, where enterprises prioritize emission reduction in isolation but neglect resource recovery from waste. This focus prevents a deeper integration of corporate CP activities with the broader goals of the regional CE system, limiting the transition towards a more sustainable industrial paradigm (Peng et al., 2016).

Systemic collaboration deficit: A fundamental weakness lies in the absence of mechanisms to foster cross-enterprise collaboration. The audit process does not incentivize or guide enterprises in forming industrial symbiosis networks, where one entity's waste could become another's raw material. This lack of a systemic perspective confines the environmental and economic benefits of CP within factory boundaries, missing significant opportunities for collective resource efficiency gains across industrial parks or regions (Dang, 2021).

Institutional and governance barriers: Beyond internal enterprise behavior, conventional CPA is severely constrained by systemic institutional and governance barriers. Fragmented regulatory oversight, characterized by siloed policies across different agencies, often imposes conflicting mandates on enterprises. This makes the implementation of holistic audits administratively prohibitive (Zhang et al., 2023; Geng et al., 2012). This structural complexity is further exacerbated by the significant absence of market-pull policy incentives, such as green credits or fiscal rewards; without these, audits remain a compliance-push cost center rather than a strategic value driver (Zhang et al., 2021). Consequently, weak enforcement and the lack of standardized monitoring allow these audits to degenerate into a superficial "check-the-box" exercise, where the absence of rigorous third-party verification decouples regulatory compliance from genuine environmental performance (Peng et al., 2016).

4. PATH INNOVATION OF CP AUDIT MECHANISM BASED ON CE (FOCUS ON WASTE MANAGEMENT)

To address the limitations of conventional CPA, this study proposes three innovative pathways underpinned by the CE concept. Guided by this concept, a novel CPA framework focused on enhancing waste management and resource recovery efficiency has been formulated, as illustrated in Figure 2.

4.1 Methodological transformation: from enterprise-level audit to industry/park-level overall audit

Taking key industries (e.g., iron and steel, petrochemical) and industrial parks as audit objects, the CE-oriented CPA expands the audit scope to cover the entire industrial chain or regional waste and resource system. This breaks the island effect of conventional single-enterprise audits and aligns with the systemic requirements of CE (Velenturf et al., 2021).

Industry-Level Audit: Establish an inter-enterprise audit team composed of enterprise representatives, industry associations, and environmental institutions. The team maps the material flow and waste flow network of the entire industry, identifies bottlenecks in waste recycling, including inconsistent waste standards between upstream and downstream enterprises, lack of waste recycling technology, and formulates industry-wide CP improvement plans

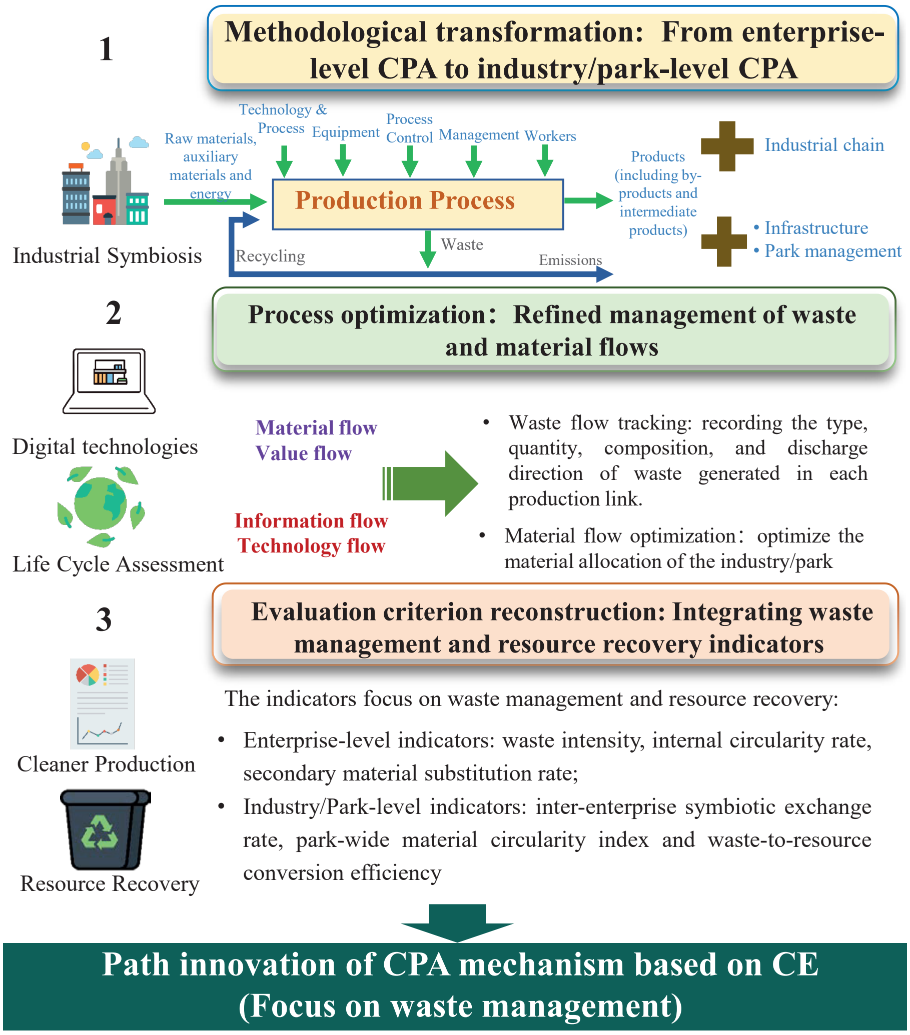

FIGURE 2: Innovative CPA pathways based on the CE (focus on waste management).

(Chen et al., 2024). For example, in the iron and steel industry, the audit promotes the recycling of blast furnace gas between iron and steel enterprises and power plants, and the reuse of steel slag in the cement industry, thereby realizing cross-enterprise waste resourceization.

Park-Level Audit: Take the industrial park as a unit, integrate the CPA of all enterprises in the park, and build a centralized waste management and resource recovery system. For example, the park constructs a centralized waste treatment center to classify, treat, and recycle waste from different enterprises; at the same time, it plans the cascade utilization of waste heat and wastewater in the park to maximize the efficiency of waste resourceization (Figure 3, Wen et al., 2025).

Potential barriers: Practical implementation may encounter potential bottlenecks, including data confidentiality concerns regarding proprietary intellectual property (Ji et al., 2020), elevated coordination costs arising from multi-stakeholder synchronization (Li et al., 2025), and data inconsistencies stemming from disparate enterprise systems, which could complicate the integration of fragmented information into a unified regional audit system (Li et al., 2024).

4.2 Process optimization: refined management of waste and material flows

Introduce digital technologies to realize refined tracking, analysis, and management of waste and material flows in the audit process, thereby solving the problem of information asymmetry in conventional audit material flow management (Zhao et al., 2025).

Waste flow tracking: Establish a waste flow accounting system for industries/parks, recording the type, quantity, composition, and discharge direction of waste generated in each production stage (Zhan et al., 2025). Through data analysis, identify waste generation hotspots and formulate targeted waste reduction measures. For example, by implementing an AI-powered dosing system that precisely controls chemical input, a wastewater treatment company successfully reduced its annual sludge production by 10% (Wu et al., 2025).

Material flow optimization: Based on the material flow accounting system, optimize the material allocation of the industry/park, promote the replacement of virgin raw materials with recycled resources, and reduce the generation of non-recyclable waste (Pilipenets et al., 2025). In a typical chemical park, several enterprises have implemented waste cascade utilization strategies to achieve substantial reductions at the source. For instance, enterprise A now directs sludge to boiler co-processing, reducing landfill-bound sludge by approximately 1,000 tonnes annually. Enterprise B has technologically enabled the full valorization of dimethyl ethanolamine distillation residues, converting a waste stream previously destined for incineration into a resource. Complementing these efforts, a steel plant has commissioned a 3-million-tonne low-carbon cement production line to utilize steel slag and other bulk solid wastes, transforming them into valuable raw materials (Wu et al., 2025).

4.3 Evaluation criterion reconstruction: integrating waste management and resource recovery indicators

The performance evaluation system for CP should be reconstructed to integrate both enterprise-level and CE system-level indicators, with a dedicated focus on waste management and resource recovery efficiency (Battiston et al., 2025; Cui et al., 2022). This integrated framework goes beyond singular metrics, enabling a holistic assessment of the synergies between environmental protection and

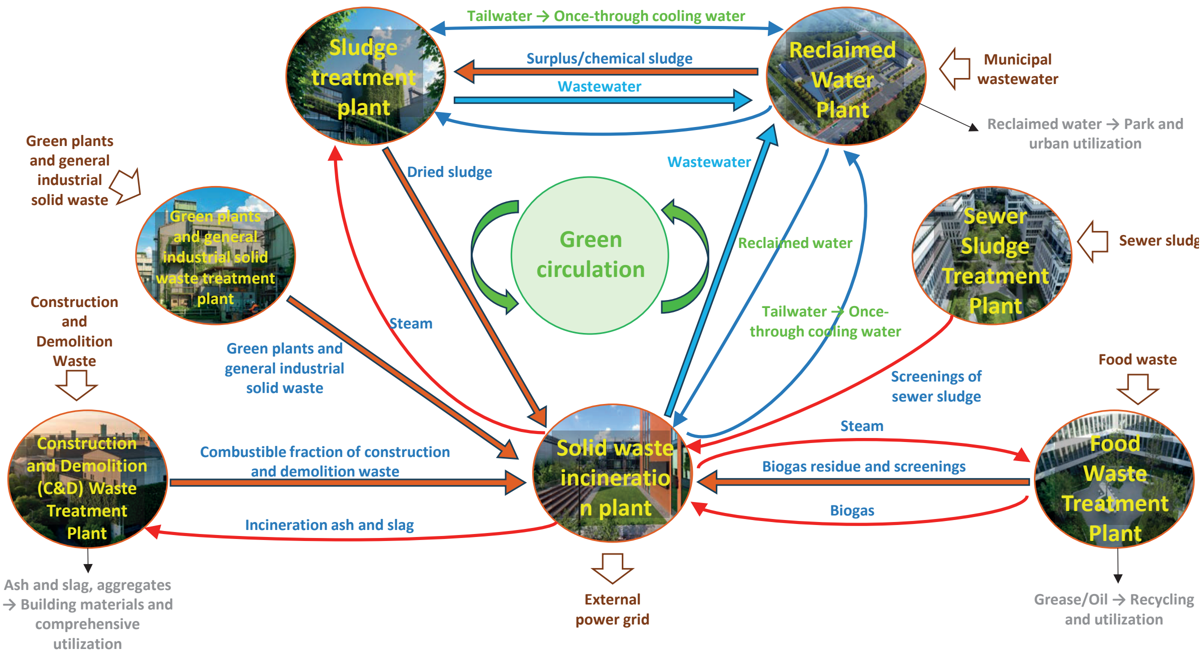

FIGURE 3: Recycling strategy of CE in industrial park (Wen et al., 2025).

economic development. This dual perspective promotes source waste minimization, incentivizes industrial symbiosis and resource circularity, and aligns micro-level production activities with macro-level CE sustainability objectives.

Enterprise-level indicators: From a life cycle perspective (Cui et al., 2022), the key metrics include: (1) waste intensity (i.e., waste generated per unit product), which is measured using material flow accounting covering the entire process from raw material extraction to end-of-life disposal; (2) internal circularity rate, which quantifies the proportion of waste recycled within closed-loop systems; and (3) secondary material substitution rate, which tracks the extent to which virgin materials are replaced by recycled resources. This approach helps identify environmental hotspots beyond individual facility boundaries and across the entire value chain.

Industry/Park-level indicators: Guided by the core principles of CE—closing material loops, slowing resource flows, and narrowing resource input scales (de Oliveira and Oliveira, 2023), the critical metrics include: (1) inter-enterprise symbiotic exchange rate, which reflects the maturity of industrial symbiosis; (2) park-wide material circularity index, which assesses the retention of materials through recycling and energy recovery; and (3) waste-to-resource conversion efficiency, which quantifies the effectiveness of transforming waste into secondary materials or clean energy.

5. CONCLUSIONS

Under the dual constraints of resource scarcity and environmental protection, innovating the CPA mechanism from a CE perspective is imperative for enhancing waste management efficiency, promoting resource recovery, and achieving China's dual carbon goals. This study clarifies the intrinsic coupling relationship between CP and CE in the context of waste management, identifies the limitations of conventional enterprise-level CPA in facilitating waste recycling, and proposes three core innovation pathways: shifting the audit methodology from the enterprise level to industry/park-level assessments, optimizing audit processes through refined waste and material flow management, and reconstructing evaluation criteria to incorporate waste-related indicators.

This proposed green, low-carbon, and circular development model effectively bridges enterprise-level CP practices with regional CE systems, enhancing the overall efficiency of waste management and resource recovery thereby offering a feasible trajectory for the green transformation of key industries. By transforming CPA from an isolated environmental management tool into a systemic driver of the CE transition, this study contributes to China's green industrial upgrading and supports global efforts in tackling climate change and resource scarcity.

Future research should focus on applying this audit mechanism to specific sectors—such as e-waste recycling and construction waste valorization—and exploring the integration of advanced technologies, including artificial intelligence, to further optimize the management efficiency of waste and material flows.

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