Proceedings of the 10th International Conference on Economic Management and Green Development
DOI: 10.54254/2754-1169/2026.36096

Research on Economic and Environmental Benefit Evaluation of Eco-Friendly Material Application and Recycling Technology Integration under Closed-Loop Supply Chain

Qiqi Liu

School of Economics and Management, Chongqing Jiaotong University, Chongqing, China
1810588520@qq.com

Abstract. Against the backdrop of carbon peaking and carbon neutrality goals, closed-loop supply chains serve as a critical pathway to realize a circular economy. Nevertheless, the collaborative operation mechanism between eco-friendly material application and recycling technologies remains unclear. This paper conducts an analysis taking Apple Inc. as the research case. Combined with green design theory, the study finds that the adoption of materials such as recycled aluminum streamlines processes at the source, forms positive feedback with disassembly technologies, and achieves the organic integration of carbon emission reduction and supply chain resilience improvement. The research verifies that the integrated operation of the two is constrained by high costs and technical adaptability issues, yet it can balance economic and environmental benefits. The findings provide practical references for the green transformation and upgrading of manufacturing industries.

Keywords: closed-loop supply chain, eco-friendly materials, economic benefits

1. Introduction

Constrained by global climate warming and depletion of earth resources, the linear economic model of "extraction-manufacturing-disposal" has become unsustainable. According to statistics from the United Nations Environment Programme, tens of millions of tons of electronic waste are generated worldwide each year, with a recycling rate of less than 20%. Under the strategic requirement of achieving carbon peaking and carbon neutrality, the traditional operational modes of China's manufacturing industry face severe challenges, which also create opportunities for green development. A closed-loop system acts as a connecting link between green design and end-of-life recycling. Closed-loop supply chains place greater emphasis on resource recycling, where materials flow backward to production terminals after manufacturing to form circular cycles. Conventional recycling models are commonly plagued by bottlenecks including mixed materials hard to sort and inferior performance of recycled materials. In view of the above challenges, establishing a unified analytical framework that integrates the research and application of eco-friendly materials with advanced recycling equipment is a powerful solution to the aforementioned dilemmas, as well as a

DOI: 10.54254/2754-1169/2026.36096

strategic option for enterprises to enhance core competitiveness. This research breaks the past separation between material science and supply chain management studies, constructing a three-in-one material supply chain analytical perspective covering "materials-technology-management". It analyzes replicable paths for small and medium-sized enterprises to implement green transformation driven by benchmark enterprises in the industry, and offers certain judgment references for governments to formulate policies advancing circular economy development.

Overseas research on closed-loop supply chains commenced after the 1990s. Guide & Van Wassenhove [1] systematically elaborated the management challenges of CLSC for the first time, pointing out that product recycling and remanufacturing constitute the core of value recovery. Fleischmann et al. [2] delivered a foundational review on quantitative reverse logistics models. Savaskan et al. [3] established a game framework for different recycling entities led by manufacturers, which has become the benchmark for subsequent CLSC channel research. Hao et al. [4] took electric vehicle power batteries as the research object and quantified the emission reduction effects of recycling on energy consumption and greenhouse gas emissions during production, shifting CLSC research from an efficiency-oriented dimension to a sustainability-oriented dimension. Design for Disassembly (DfD) and the selection of recyclable materials with high recoverability have emerged as new research growth points in recent years.

Domestic CLSC research started around 2006. Wang Yuyan et al. [5] first introduced game theory into CLSC pricing research in *Chinese Journal of Management Science*. Wang Wenbin and Da Qingli [6] systematically investigated CLSC decision-making and coordination under reward-penalty mechanisms. Sun Hao and Da Qingli [7] studied differentiated pricing by incorporating channel power and risk aversion. Recent domestic studies have refined research perspectives into two major branches: ① Green Design / Design for Environment (DfE): Yao Fengmin et al. published successive papers in *Control and Decision* [8] and *Computer Integrated Manufacturing Systems* [9], arguing that the improvement of manufacturers' green design levels expands market demand and product recycling rates but may not bring economic benefits to manufacturers themselves. This conclusion provides a theoretical interface for this paper's research on "material-technology integration". ② Power Battery & Recycling Technology: Wu Wenqi and Zhang Ming [10] studied CLSC decision-making for power batteries under carbon cap-and-trade policies and government subsidies in *Chinese Journal of Management Science*. Li Xiaobing et al. [11] discussed recycling pricing considering consumer heterogeneity in the same journal. The research team led by Fu Yao [12] realized closed-loop upgrading recycling of waste PET plastics via acetic acid chemical depolymerization. Huang Yunzheng et al. [13] sorted out combined processes for waste lithium batteries including "pretreatment – physical/chemical/biological recycling – echelon utilization", laying an engineering foundation for this paper's analysis of material-technology coordination.

Against this background, this paper targets the effect of integrating eco-friendly materials and recycling technologies from the closed-loop supply chain perspective, attempting to fill the existing research gap in this field.

2. Mechanism analysis of eco-friendly material application and recycling technology integration

The utilization of eco-friendly materials is not isolated; strong coupling relationships exist between eco-friendly materials and recycling technologies. This chapter logically analyzes the interaction mechanism between recycling technologies and eco-friendly materials within closed-loop supply chains.

DOI: 10.54254/2754-1169/2026.36096

2.1. Promotion mechanism of eco-friendly materials on recycling technology efficiency

Traditional electronic products adopt mixed plastics of various types, hard-to-separate adhesives, or coatings containing toxic and hazardous substances, leading to high difficulty and costs in recycling and disposal. The adoption of eco-friendly materials fundamentally mitigates recycling difficulties at the product design source.

Material homogenization delivers higher sorting efficiency. For instance, product casings that extensively adopt a single type of recycled aluminum alloy instead of diverse composite materials eliminate elaborate material identification and separation steps during recycling, enabling direct smelting. Non-toxicity lowers technical barriers: eco-friendly materials generally contain no heavy metals such as lead and mercury, so recycling processes do not require costly tail gas treatment devices, and ordinary physical disassembly and crushing technologies can meet processing standards. Modular design matched with standardized materials allows automated disassembly robots to easily identify and separate target components, drastically increasing processing volume per unit time.

2.2. Feedback effect of recycling technologies on the popularization of eco-friendly materials

Advanced recycling technologies serve as supporting guarantees for the large-scale application of eco-friendly materials.

On one hand, high recycling rates eliminate potential risks restricting the promotion of eco-friendly materials. Many eco-friendly materials such as biodegradable plastics pose contamination risks if mixed into ordinary plastic recycling streams. High-precision near-infrared (NIR) sorting technologies enable accurate material classification to guarantee pure recycling streams, encouraging enterprises to boldly adopt new eco-friendly materials.

On the other hand, material performance restoration technologies boost market acceptance of recycled materials. Recycling technologies are not limited to simple product crushing; they also include in-depth processing techniques such as impurity removal and molecular chain restoration. When recycling technologies can produce recycled materials with performance equivalent or close to virgin raw materials, downstream recycled material manufacturers are willing to purchase recycled feedstock. Upstream eco-friendly material developers therefore gain stable sales channels to conduct further research, development and production, forming a positive market incentive cycle.

2.3. Collaborative operation mode within closed-loop supply chains

Under the collaborative target model of closed-loop supply chains, material-technology integration restructures the logistics, information flow and capital flow of the entire supply chain. Information flow: Material scientists input physicochemical property data of new materials into information pools for recycling engineers, supporting targeted disassembly process development. Meanwhile, recycling terminals feed back material compatibility problems generated during disassembly to the design end to facilitate iterative product research and development. Logistics: Recycling plants directly transport recycled materials to product manufacturing factories, shortening logistics distances within closed-loop supply chains and cutting transportation energy consumption. Capital flow: Cost savings brought by reduced material expenses and lower environmental compliance risks are partly allocated to research and development investment in recycling technologies and partly converted into corporate profits. The internal capital cycle achieves self-sustaining operation within the closed-loop system.

DOI: 10.54254/2754-1169/2026.36096

3. Case analysis and benefit evaluation – a case study of Apple Inc.

As the world's highest market-value technology enterprise, Apple Inc. [14] leads the entire industry in environmental protection practices and achievements. Faced with massive global electronic waste pressure, Apple put forward an ambitious environmental target: to achieve full carbon neutrality across its supply chain and full product life cycle by 2030. To reach this goal, Apple constructed a closed-loop supply chain ecological system centered on material innovation and technological innovation from the consumer end. The company vigorously promotes the utilization of recycled materials including recycled aluminum, recycled tin and recycled rare earth elements. Meanwhile, it independently developed multiple generations of iPhone disassembly robots (Liam, Daisy, Dave) and built large-scale material recycling laboratories. This chapter conducts analysis based on publicly released *Environmental Progress Report* and partial relevant statistical data.

3.1. Economic benefit evaluation

Apple's practices prove that integrating eco-friendly materials and recycling processes requires enormous short-term investment yet delivers robust economic benefits in the long run.

Direct raw material cost savings in manufacturing. Aluminum serves as the primary casing material for iPhones, whose virgin production consumes massive energy. Apple developed customized aluminum alloys and applied 100% recycled aluminum to new MacBook and iPad products. According to research from the United States Environmental Protection Agency (EPA), recycled aluminum production consumes merely 5% of the energy required for virgin aluminum production. Although Apple has not disclosed specific monetary figures, calculations based on aluminum price fluctuations and production volumes indicate this single measure saves tens of millions of US dollars in raw material procurement costs annually. Rare earth magnets recovered by Daisy robots reduce purchases of high-priced external rare earth resources and hedge price volatility risks in the global rare earth market.

Improved brand premium and market share. Against the prevailing trend of ESG (Environmental, Social and Governance) investment, enterprises' environmental performance significantly influences consumers' purchasing preferences. Apple's carbon neutrality commitments and recycling programs greatly enhance customer brand loyalty. Market survey data shows younger consumer groups are more willing to pay premium prices for eco-friendly products. Apple converts this intangible brand asset into tangible commercial gains, and sustained high product pricing maintains stable high market share.

Reduced compliance costs and access to policy dividends. Countries worldwide have tightened legislation governing electronic waste (such as the EU WEEE Directive), imposing heavy fines on enterprises failing to meet environmental standards. Apple's closed-loop supply chain model satisfies rigid environmental regulatory requirements in advance and avoids legal penalties. Additionally, federal and state governments in the United States offer tax credits and research subsidies to enterprises using recycled materials, generating indirect economic gains for Apple.

Elevated operational efficiency. The Daisy robot can disassemble more than 200 iPhones per hour, far exceeding manual disassembly efficiency. High-speed robotic disassembly recovers larger volumes of core minerals including cobalt and lithium per unit time, lowering enterprises' dependence on external mineral mining, optimizing inventory management and mitigating production suspension risks caused by raw material shortages.

DOI: 10.54254/2754-1169/2026.36096

3.2. Environmental benefit evaluation

Significant carbon footprint reduction. As documented in Apple's *2023 Environmental Progress Report*, aluminum manufacturing once accounted for a large proportion of the carbon footprint of Apple's products. Currently, the adoption of recycled aluminum and hydropower aluminum smelting continuously cuts carbon emission intensity of Apple's products. The company's greenhouse gas emissions have dropped by over 45% since 2015, among which the utilization of recycled materials in supply chains contributes nearly 30% of total emission reductions.

Conservation of critical mineral resources. Electronic devices contain scarce resources such as cobalt, lithium and rare earth elements, which can be extracted from discarded iPhones via Daisy robots. Official reports show Daisy can recover approximately 2 tons of aluminum, 770 kilograms of cobalt, 710 kilograms of copper and 11 kilograms of rare earth elements from recycled iPhones every year. The recycled materials are remanufactured for reuse, reducing equivalent virgin ore mining and protecting ecologically fragile mining areas.

Minimization of electronic waste. Traditional electronic waste disposal methods including incineration and landfilling easily contaminate soil and groundwater. Apple's trade-in program and complete electronic waste disassembly technologies prevent most waste devices from entering landfills. Up to now, Apple has achieved zero solid waste landfill across its global operations, and landfill solid waste volumes within its supply chain decline year by year.

Water and energy conservation. The processing of recycled materials generally consumes less water and energy than virgin material production. For example, recycled paper manufacturing saves half of the water required for virgin pulp production. Apple promotes water-saving production technologies across its supply chain combined with recycled material application, substantially cutting water and energy consumption per unit industrial output value.

Analysis of Apple's case demonstrates that the combined application of eco-friendly materials (recycled aluminum) and innovative recycling technologies (Daisy robots) generates powerful synergies within closed-loop supply chains. Instead of imposing financial burdens on enterprises, such synergy delivers substantial dual economic and environmental dividends through cost reduction, efficiency improvement and brand value enhancement. Nevertheless, Apple's practices rely on abundant capital and robust technology integration capacity, creating high entry barriers for small and medium-sized enterprises.

4. Conclusions and prospects

4.1. Conclusions

Taking closed-loop supply chains as the research perspective, this paper conducts in-depth research on the integration of eco-friendly material application and recycling technologies. Based on theoretical sorting and case analysis of Apple Inc., the core conclusions are summarized as follows:

Intrinsic logical coupling. The adoption of eco-friendly materials lowers recycling difficulties at the product design source, while advanced recycling technologies provide end-of-life support for large-scale popularization of eco-friendly materials. The two elements form mutually reinforcing positive cycles within closed-loop supply chains.

Remarkable dual benefits. Case analysis indicates the integrated model generates economic benefits through raw material cost savings and operational efficiency improvement, and delivers significant positive environmental externalities via carbon emission reduction and mineral resource conservation.

DOI: 10.54254/2754-1169/2026.36096

Systematic engineering characteristics. The construction of closed-loop supply chains constitutes a complex systematic project covering technology, economy, management and policy dimensions. Given the large number of stakeholders involved, enterprises' voluntary initiatives alone cannot resolve the challenges of high initial investment and cross-party coordination difficulties. Joint efforts from governments, enterprises and the whole society are indispensable.

4.2. Research limitations and future research prospects

This paper relies on qualitative analysis of a single enterprise case without cross-industry comparative research, limiting the generalizability of its conclusions. Restricted by data availability, this study fails to conduct accurate monetary valuation of economic and environmental benefits. Future research can be expanded in the following directions: First, expand single-case research to explore differentiated closed-loop supply chain models across industries including automobile manufacturing, home appliances and fast-moving consumer goods, and carry out inter-industry comparative analysis. Second, with the continuous improvement of ESG information disclosure systems, future research can adopt big data technology and panel data of listed companies to re-examine whether eco-friendly materials and recycling technologies generate long-term corporate performance growth. Third, explore the application of emerging technologies such as artificial intelligence and digital twins in refined management of closed-loop supply chains.

References

[1] Guide, V. D. R., & Van Wassenhove, L. N. (2001). Managing product returns for remanufacturing. *Production and Operations Management, 10*(2), 142-155.

[2] Fleischmann, M., Krikke, H. R., Dekker, R., et al. (2000). Quantitative models for reverse logistics: A review. *European Journal of Operational Research, 125*(1), 1-28.

[3] Savaskan, R. C., Bhattacharya, S., & Van Wassenhove, L. N. (2004). Closed-loop supply chain models with product remanufacturing. *Management Science, 50*(2), 239-252.

[4] Hao, H., Qiao, Q., Liu, Z., et al. (2017). Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case. *Resources, Conservation & Recycling, 122*, 114-125.

[5] Wang, Y., Li, B., & Shen, L. (2006). Pricing strategy model of supply chain and reverse supply chain system. *Chinese Journal of Management Science, 14*(4), 40-45.

[6] Wang, W., & Da, Q. (2011). Decision-making and coordination of closed-loop supply chain under reward and punishment mechanism. *Chinese Journal of Management Science, 19*(1), 43-49.

[7] Sun, H., & Da, Q. (2013). Research on differential pricing mechanism of closed-loop supply chain considering channel power structure and risk aversion. *Industrial Technology & Economy, 32*(3), 26-33.

[8] Yao, F., Liu, S., Chen, D., et al. (2019). Recycling and pricing decision of closed-loop supply chain with corporate social responsibility. *Control and Decision, 34*(9), 1981-1990.

[9] Yao, F., Xie, T., Yan, Y., et al. (2024). Closed-loop supply chain recycling decision considering green design and CSR under EPR system. *Computer Integrated Manufacturing Systems, 30*(6), 2213-2227.

[10] Wu, W., & Zhang, M. (2025). Decision analysis of power battery closed-loop supply chain under carbon cap trading and subsidy policies. *Chinese Journal of Management Science, 33*(8), 340-354.

[11] Li, X., Wang, Y., & Jiang, W. (2025). Recycling pricing decision of power battery closed-loop supply chain considering consumer heterogeneity. *Chinese Journal of Management Science, 33*(2), 279-291.

[12] Fu, Y., Deng, J., et al. (2023). Upcycling of waste PET plastics via acetic acid chemical depolymerization. *Nature Communications*.

[13] Huang, Y., Li, L., & Liu, X. (2025). Resource recycling technologies for waste lithium-ion batteries. *Modern Chemical Industry, 45*(9), 44-48.

[14] Apple Inc. (2023). *Environmental progress report 2023*. Cupertino: Apple.