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Sustainable Development of Packaging Material Manufacturing Processes Using Looping Method

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Abstract

This study examines the environmental benefits of implementing a closed-loop system utilising the looping method in the production of corrugated board packaging materials for blueberries in comparison to conventional open-loop production systems. Using Life Cycle Assessment (LCA) and the EF 3.1 impact assessment method in the Sphera LCA for Experts software, the study evaluates the environmental impacts of both systems, with a focus on the recycling rate (ranging from 30% to 84.5%) and material flow. Results demonstrate that the looped system, with an 84.5% recycled content, significantly reduces environmental impacts across all major categories, including climate change (– 22%), freshwater ecotoxicity (– 22%), terrestrial eutrophication (– 45%), and fossil resource use (– 17%). A Pareto analysis revealed that more than 80% of the total environmental impact originates from five impact categories. The findings support the integration of circular economy principles and eco-design in packaging development, highlighting the potential of the looping system for sustainable packaging strategies.

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Keywords: packaging material; closed-loop system; open-loop system; environmental impacts; life cycle assessment; recycling rate; circular economy; sustainable development; corrugated board; blueberry

1. Introduction

The growth of packaging waste in the EU has raised sustainability concerns. In 2022, total packaging waste reached 83.4 million tons, with paper/cardboard (40.8%) and plastics (19.3%) as dominant streams [1]. In Hungary, the average

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packaging waste per capita reached 166 kg, exceeding the EU average. [1]. Corrugated board packaging, often used in fruit supply chains such as blueberries, presents a more sustainable alternative to plastic. Its recyclability and biodegradability align with circular economy principles. [2].

According to the Green Deal [3] and the Circular Economy Action Plan [4], and the Packaging Directive [5], the target is for recycling of packaging waste, for 75 % by 2025 and 85% by 2030 and thus reducing the amount of waste.

The revised Packaging Directive [5] and its implementing Regulation [6] and the relevant standards pose a significant challenge for manufacturers and users [7–10]. These expectations require rethinking packaging design from selecting packaging materials, including packaging sizing, use and end-of-life.

Circular solutions are key in the design of sustainable packaging. Moreover, it is no longer enough to consider the 3 R models, but rather to integrate the 9 R model developed by Potting et al. [11]. Corrugated board packaging, especially in food supply chains such as blueberries, offers a viable pathway due to biodegradability and recyclability. However, conventional open-loop production fails to maximize recycling potential. Closed-loop approaches, which apply looping methods, enable packaging waste to re-enter the production cycle as a secondary raw material.

Blueberries are often packaged in small, multi-portion containers, contributing to waste and environmental issues. Sustainable packaging solutions, such as those made from recyclable and compostable materials, are gaining traction. Adopting circular economy principles can reduce waste and improve the sustainability of the blueberry supply chain [12, 13].

1.1. Literature review

Sasaki et al. [14, 15] evaluated strawberry packaging systems using LCA, linking food loss reduction with environmental impacts. The findings indicated that reducing food loss during transportation through overharvesting does not effectively lessen the life cycle impact. Therefore, creating optimal packaging that balances the trade-offs between reducing food loss and minimizing environmental impact is essential [15]. Jang et al. [16] studied online food delivery in Korea, where plastics dominated (73 kt in 2020). Almenar et al. [17] demonstrated that PLA containers extend blueberry shelf life, while Lagos-López et al. [18] tested starch-based biopolymer films, showing potential but vulnerability to deterioration.

In the case of packaging materials, Life Cycle Assessment (LCA) is increasingly playing a central role in the transition to circular solutions [19–21]. However, a synergistic effect can be achieved by integrating several methods when planning for sustainability. LCA, Circular Economy (CE) and Environmental, Social and Governance (ESG) principles together aim to promote sustainability [22, 23]. LCA assesses environmental impacts throughout the whole life cycle of a product, offering static (ALCA) and future-oriented (CLCA) approaches [24]. Patel et al. [25] developed an LCA-based consumer tool for packaging footprints. Choi et al. [26] showed significant GHG reductions from closed-loop plastic recycling.

Recent developments integrate LCA with circular economy (CE) and ESG frameworks to enable holistic sustainability evaluations. Nevertheless, a gap remains in applying these models to fibre-based packaging systems using high recycling rates. This study addresses this gap by applying LCA to a real-world case study of corrugated board packaging for blueberries, comparing open-loop and looping-enhanced closed-loop systems.

2. Data and Methods

2.1. Life Cycle Impact Assessment Framework

The LCA was conducted using Sphera LCA for Experts software. The functional unit was defined as 1000 kg of packaging material. System boundaries encompassed raw material extraction, production, transport, usage, and end-of-life treatment, including recycling. We employed two LCIA methods: EF 3.1 for general analysis and CML 2016 for specific impact evaluation. Two systems were compared:

- Open-loop system: packaging waste incinerated/landfilled.
- Closed-loop system: 84.5% recycled content reintroduced into production.

Figure 1 presents the LCA framework for open-loop and closed-loop systems.

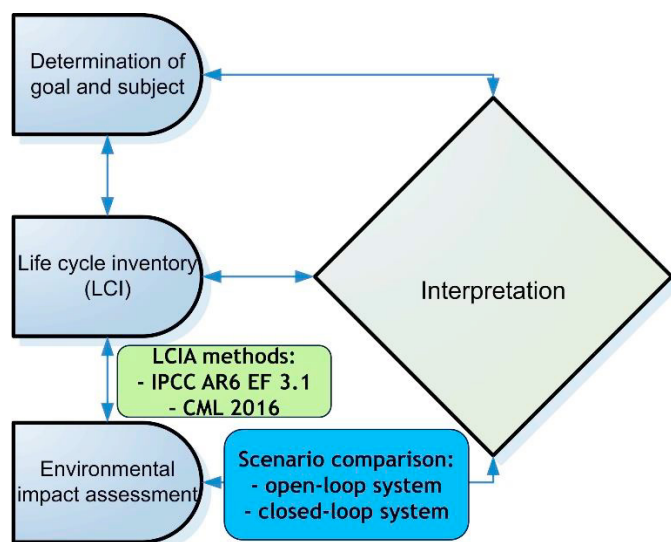


Fig. 1. Framework for open-loop and closed-loop systems.

2.2. Life Cycle Inventory (LCI)

Tables 1 and 2 contain the life cycle inventory (LCI) analysis data at all process and plan levels, which we used in the Sphera LCA for Experts software during the analyses.

Table 1. Life Cycle Inventory (LCI) regarding the open-loop manufacturing system for the corrugated board (CB) packaging material. (Functional unit: 1000 kg of packaging material).

Flow type	Process Flow Name	Plan Flow Name
Input	Corn starch [Materials from renewable raw materials]	RER: glued laminated timber, laminated wood boards spruce (12% moisture)
Input	Wood (abs. dry) [Materials from renewable raw materials]	RER: Lightweight wood fiber panel (EN15804 A1-A3)
Input	Kraft paper bleached (t92) [Materials from renewable raw materials]	RER: corrugated board, excl. paper production, input: paper Sphera/FEFCO
Input	Offset ink [Valuable substances]	RER: water-based paint white (EN15804 A1-A3)
Input	Water (surface run-off, from techno sphere surfaces) [Operating materials]	RER: Tap water from surface water
Input	Electricity [Electric power]	RER: Electricity grid mix (production mix)
Input	Packaging material	Packaging product
Output	Wastewater (untreated)	RER: Municipal wastewater treatment (mix)
Output	Wastepaper	RER: Paper and board in waste incineration plant

Table 2. Life Cycle Inventory (LCI) regarding the closed-loop manufacturing system for the corrugated board (CB) packaging material. (Functional unit: 1000 kg of packaging material).

Flow type	Process Flow Name	Plan Flow Name
Input	Corn starch [Materials from renewable raw materials]	RER: glued laminated timber, laminated wood boards spruce (12% moisture)
Input	Wood (abs. dry) [Materials from renewable raw materials]	RER: Lightweight wood fiber panel (EN15804 A1-A3)
Input	Kraft paper bleached (t92) [Materials from renewable raw materials]	RER: corrugated board, excl. paper production, input: paper Sphera/FEFCO
Input	Offset ink [Valuable substances]	RER: water-based paint white (EN15804 A1-A3)
Input	Water (surface run-off, from techno sphere surfaces) [Operating materials]	RER: Tap water from surface water
Input	Electricity [Electric power]	RER: Electricity grid mix (production mix)
Input	Recycled paper (with deinking t94) [Materials from renewable raw materials]	Recovered paper from this quantity goes 845 kg for looping; recycling extent: 84.5%.
Output	Wastewater (untreated)	RER: Municipal wastewater treatment (mix)
Output	Wastepaper	RER: Paper and board in waste incineration plant
Looped input	Recovered paper (mixed) [Materials from renewable raw materials]	Recycled paper (with deinking t94)

3. Results

3.1. Environmental Impact Comparison

Figures 2 and 3 illustrate the distribution of the most and least significant environmental impact categories associated with corrugated board packaging production under open-loop (without looping) and closed-loop (with looping) systems. While Figure 2 presents the dominant impact categories, Figure 3 highlights those with lower relevance.

Based on Figures 2-3, the looped solution shows a lower environmental impact than the open-loop solution in all impact categories examined. That is, a consistent trend emerges: the closed-loop approach achieves marked reductions in every impact category compared to the open-loop system. It indicates that the closed-loop system, with its looping and recycling, effectively reduces the carbon footprint. The most considerable absolute difference occurs in the following categories:

- Total climate change: 195 kg CO₂ eq. reduction
- Total freshwater ecotoxicity: 1287 CTUe reduction
- Land use: 2255 Pt reduction
- Resource use, fossils: 2879 MJ reduction
- Climate change, land use and LUC: 3.84 kg CO₂ eq. reduction
- Terrestrial eutrophication: 4.48 Mole of N eq. reduction

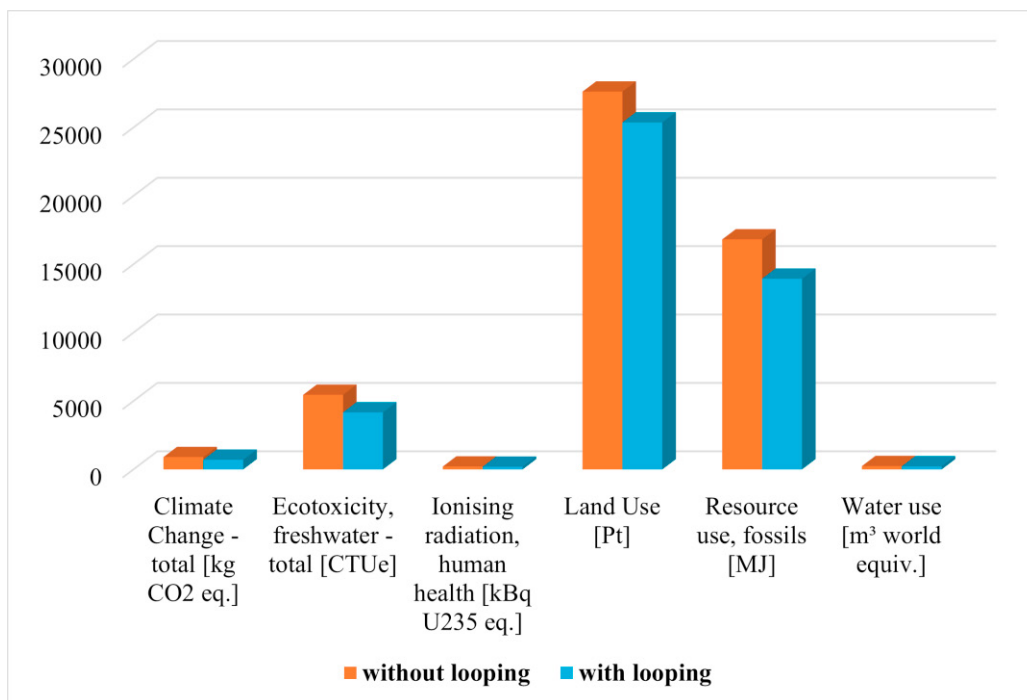


Fig. 2. Most significant environmental impact categories associated with the production of 1000 kg corrugated board packaging, using the EF 3.1 method.

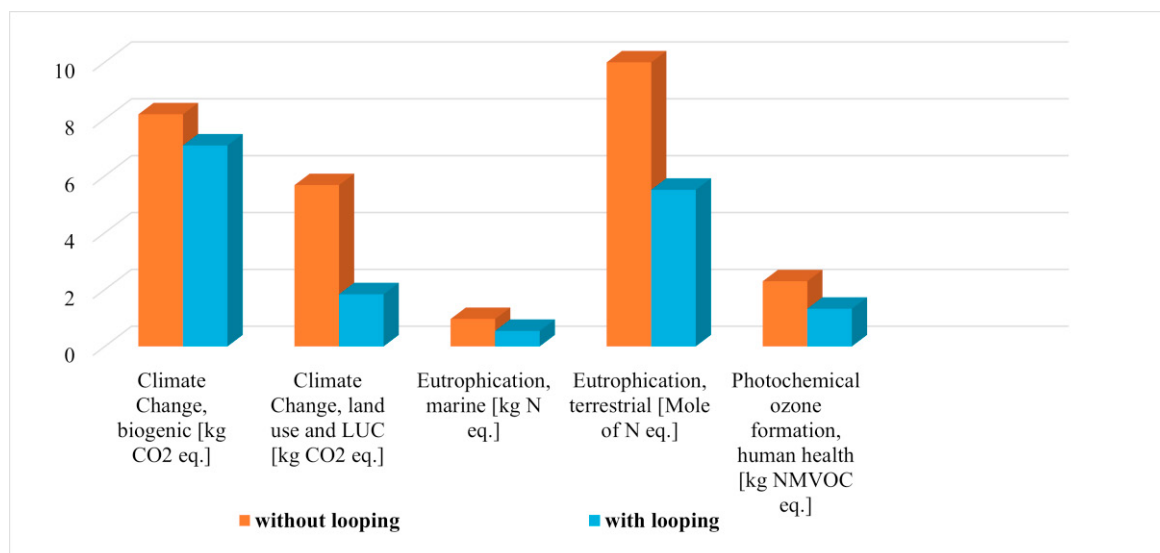


Fig. 3. Least significant environmental impact categories associated with the production of 1000 kg corrugated board packaging, using the EF 3.1 method.

Figure 4 applies normalization and weighting to the impact categories for both the open-loop and closed-loop systems in personal equivalent units based on the EF 3.1 normalization and weighting methods.

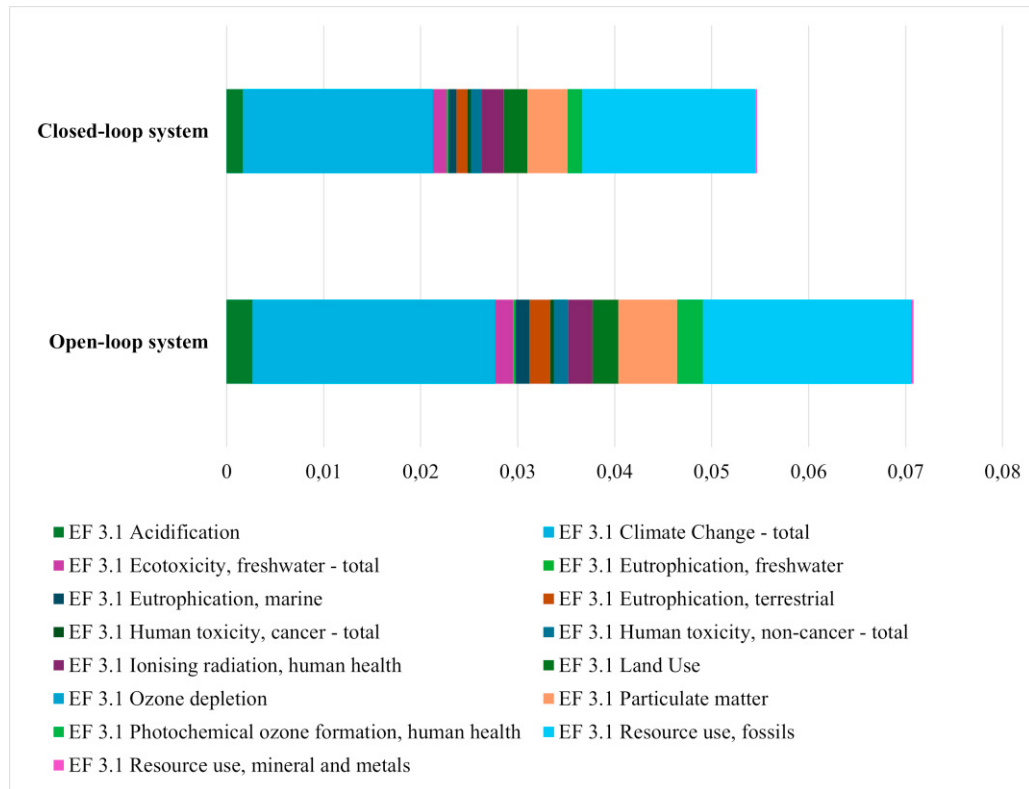


Fig. 4. Normalized and weighted environmental impacts for open-loop and closed-loop systems in personal equivalent. Functional unit: 1000 kg of packaging material. Normalization and weighting method: EF 3.1.

Closed-loop systems reduced climate change impacts by 22%, freshwater ecotoxicity by 22%, and fossil resource depletion by 17%. Normalized charts (Figures 2–6) show significant ecological advantages across all key categories.

3.2. PARETO analysis

Pareto analysis reveals which impact categories account for the majority of the total environmental burden, indicating where targeted interventions could be most effective. To identify priority areas for environmental improvement, Figure 5 displays a Pareto diagram for the closed-loop system.

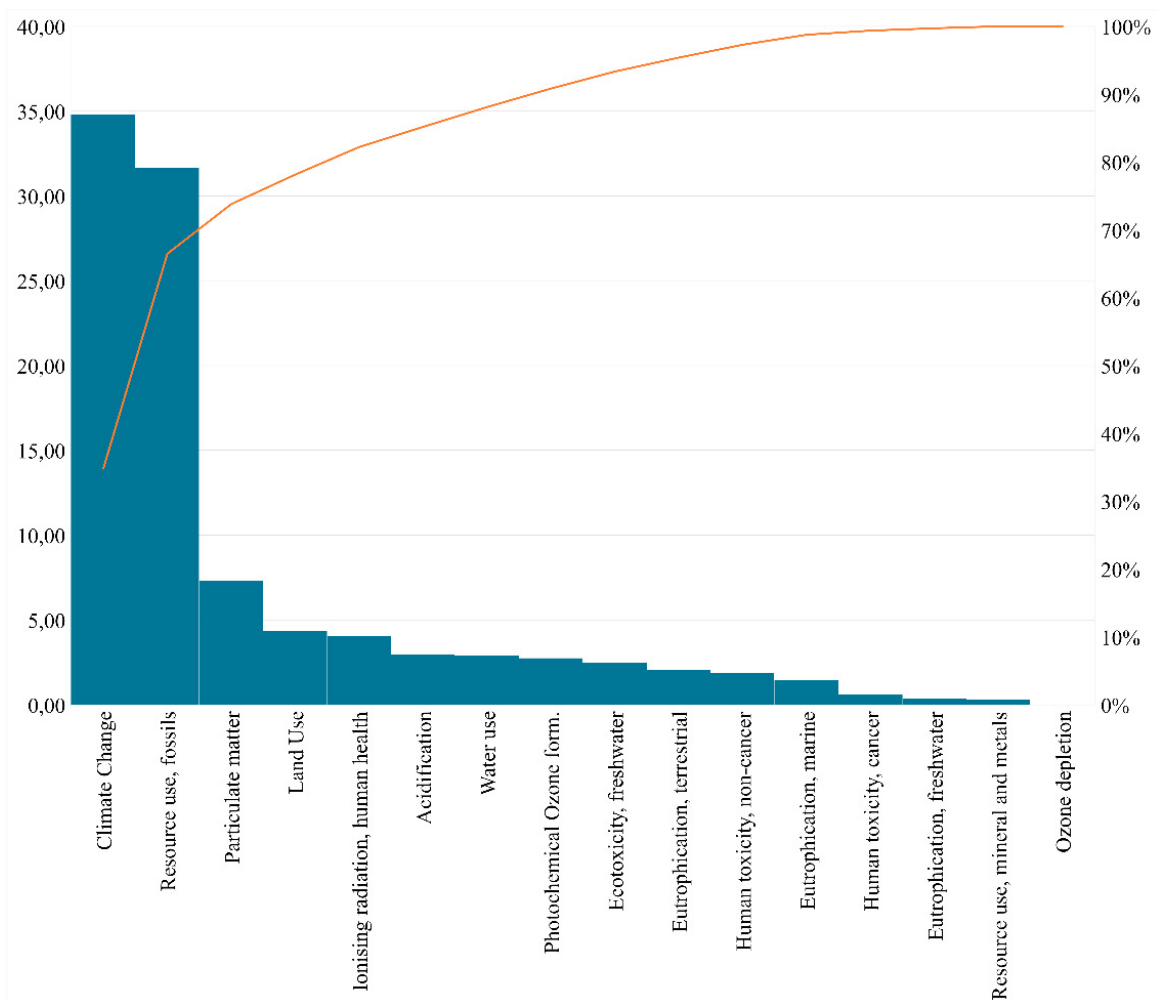


Fig. 5. PARETO analysis of percentage normalized and weighted impacts for the closed-loop system. Recycled content: 84.5%.

Pareto diagram reveals that over 74% of the environmental impact in both systems is concentrated in three categories: climate change, fossil resource use, and particulate matter.

3.2. Effect of the recycling rate

To further explore the role of recycling content in environmental performance, Figure 6 illustrates the relationship between varying recycling rates and their effects on global warming potential (GWP) and abiotic depletion of fossil resources (ADPF) using the CML 2016 impact assessment method in kg CO₂ equivalent and in megajoules. In this case, 1 kg of packaging material was considered the functional unit of calculations.

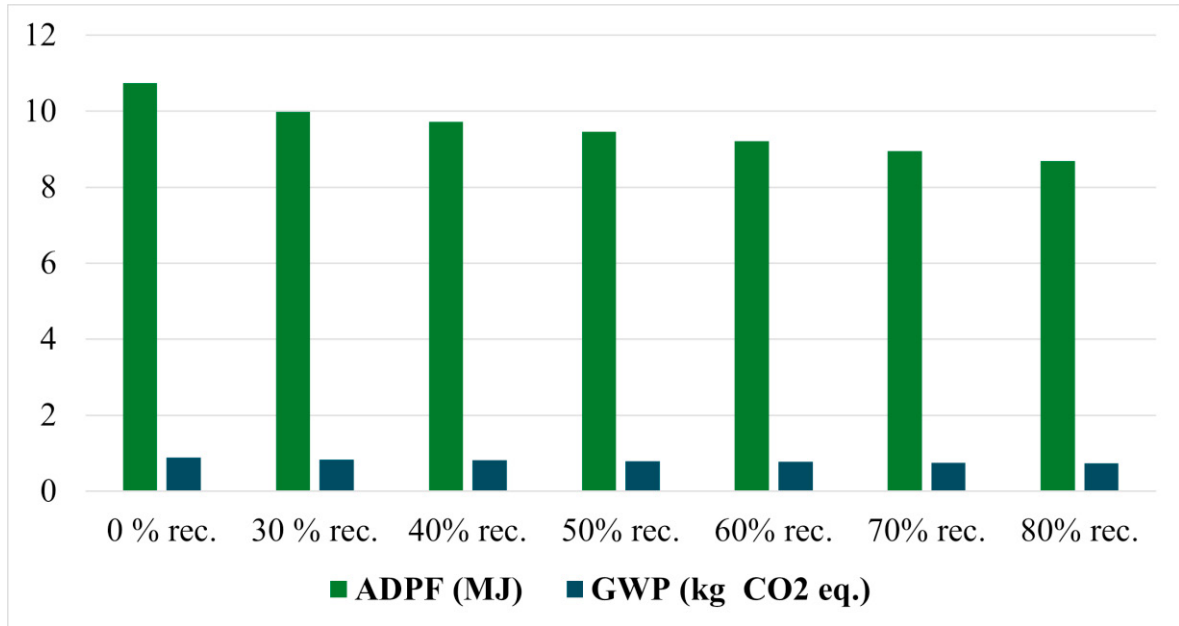


Fig. 6. Impact of variable recycling rate on the global warming potential (GWP) and fossil abiotic depletion (ADPF). Functional unit: 1 kg of packaging material.

Regarding Figure 6, we can see that increasing the recycling rate linearly reduces fossil abiotic depletion and global warming, further demonstrating the environmental benefits of circular closed-loop solutions. Higher recycling rates correlate linearly with improved environmental performance. Moving from 30% to 84.5% recycled content reduced GWP by 16% and ADPF by 18%.

3.3. Managerial and economic implications

- Producers: adopting closed-loop systems requires investment in recycling technologies and supply chain adjustments. Benefits include reduced raw material costs and compliance with EU directives.
- Retailers: marketing advantage through eco-friendly packaging, strengthening consumer perception.
- Barriers: higher initial costs for recycling infrastructure, logistical challenges in collection, and dependence on waste quality.
- Policy incentives: subsidies for recycling, carbon taxes, and stricter eco-design regulations could accelerate transition.

3.4. Limitations

- Results are specific to corrugated board; extrapolation to plastics or composites requires caution.
- Data limitations from databases (Ecoinvent, Eurostat) may affect accuracy.
- Economic estimates are indicative, not based on primary cost modelling.

4. Conclusion and Implications

Closed-loop packaging production with looping achieves significant environmental gains and supports EU sustainability targets. Key takeaways:

- Closed-loop reduces CO₂ emissions, eutrophication, and fossil use substantially.
- Pareto analysis highlights priority areas for intervention: climate change, fossil resource use, and particulate matter.
- Managerial implications show that eco-design and investment in recycling infrastructure can yield long-term sustainability and economic benefits.
- Policy support is crucial to overcome financial and logistical barriers.

A more detailed evaluation of the environmental impacts is summarised in Table 3, where the “reduction” percentages are convincing.

Table 3. Summarized conclusions.

Impact	Significant change	Looping benefit
Climate change (combined)	~22% reduction	Significant CO ₂ saving over the life cycle.
Biogenic and fossil carbon	Both are decreasing	The biogenic fraction is also decreasing, but less significant.
Freshwater ecotoxicity (inorganic)	~22% decrease	Strong improvement through reduction of heavy metal and chemical emissions.
Eutrophication (freshwater, marine, terrestrial)	17–43% decrease	Significant reduction in water body loads, especially in marine and terrestrial cases.
Human toxicity (carcinogenic and non-carcinogenic)	14–28% decrease	Human loads of inorganic origin are decreasing.
Ionizing radiation	~8.6% decrease	Moderate but relevant.
Ozone depletion	~6% decrease	Relatively small value, but direction is the same.
Particulate matter	~32% decrease	Significant reduction in health risks.
Photochemical ozone creation	~42% decrease	Outstanding improvement in air quality.
Resource use (fossil, mineral)	~17% (fossil), ~16% (mineral) decrease	Critical category for sustainability.
Water use	~8.7% decrease	Moderate improvement.

The looping method in closed-loop systems offers a scalable pathway to sustainable packaging. By integrating high recycling rates, manufacturers can achieve significant reductions in key environmental impacts. The study confirms the value of LCA-driven design in promoting circular economy strategies and provides a framework for operational and regulatory advancements. However, future research should expand to hybrid packaging materials and include detailed cost–benefit analyses.

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