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A Holistic Cradle-To-Cradle Assessment Of Liquid Food Packaging

Evaluación Holística De La Cuna A La Cuna Del Envasado De Alimentos Líquidos

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ABSTRACT

This research investigates the ecological impact of the production processes of two packaging types in malt beverage marketing: plastic bottles and aluminum cans. The cradle-to-cradle life cycle assessment facilitates the analysis of carbon dioxide emissions and energy consumption associated with each packaging alternative, thereby allowing for comparisons rooted in sustainability principles. The findings suggest that polyethylene terephthalate (PET), commonly utilized in food packaging, possesses a detrimental environmental profile attributable to its substantial energy requirements and considerable carbon emissions associated with its production and processing phases. Conversely, while polypropylene, often utilized in plastic production bottle caps, exhibits a lower environmental impact than PET, it nevertheless fails to exceed the intrinsic sustainability benefits associated with aluminum. Aluminum displays considerable environmental advantages, characterized by reduced carbon emissions and energy requirements throughout the production process. Its elevated recyclability facilitates reintegration into the production cycle without compromising its physical and chemical properties, which is a crucial element in reducing environmental impact. The ongoing usability of materials diminishes the necessity for virgin raw materials, consequently conserving natural resources and reducing the generation of solid waste. The available evidence suggests that prioritizing aluminum cans represents a viable approach to improving sustainability in food packaging, especially within the malt beverage sector, to reduce negative environmental impacts. Similarly, the establishment of public policies that prioritize ecological education and sustainability is critical for promoting responsible consumption practices.

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Key words: Environmental conservation, Sustainable development, Environmental impact assessment, Environmental awareness.

RESUMEN

Este estudio analiza la huella ambiental en la cadena productiva de dos tipos de envase utilizada en la comercialización de bebidas maltadas: botellas de plástico y latas de aluminio. Utilizando el análisis del ciclo de vida desde la cuna a la cuna, las emisiones de dióxido de carbono y el consumo de energía están conectados a cada alternativa en el embalaje, lo que permite comparaciones basadas en la perspectiva de la sostenibilidad. Los resultados revelan que el PET, ampliamente utilizado en el empaque de alimentos, presenta un perfil ambiental desfavorable, teniendo en cuenta sus altas necesidades de energía y una contribución significativa a las emisiones de dióxido de carbono durante su producción y tratamiento. Por otro lado, el polipropileno (como el material principal de las tapas en las botellas de plástico), aunque menos impactante que el PET, no se equiparan a los beneficios característicos del aluminio en términos de sostenibilidad. Mientras tanto, el aluminio tiene una superioridad significativa desde un punto de vista ambiental, que muestra emisiones de dióxido de carbono más bajas y consumo reducido de energía en el proceso productivo. Su alto reciclaje, que permite que la cadena de producción se restablezca sin dañar sus propiedades químicas físicas, es un factor crucial para reducir el impacto ambiental. Debido a esta ventaja para el uso continuo, la necesidad de lograr materias primas crudas se reduce significativamente al promover la preservación de los recursos naturales y reducir la producción de residuos sólidos. Según esta evidencia, es aconsejable priorizar la estrategia de sostenibilidad para el uso de empaques de aluminio como un envasado de alimentos efectivo, como bebidas, para reducir el impacto negativo en el medio ambiente. Del mismo modo, para promover el consumo responsable, es importante implementar una política nacional orientada a la educación y sostenibilidad ambiental.

Palabras Clave: Conservación ambiental, Desarrollo sostenible, Evaluación del impacto ambiental, Sensibilización ambiental.

INTRODUCTION

The evaluation of the carbon footprint includes the analysis of various natural materials, including polymers, metals, and lignocellulosic compounds, confirming progress toward a more stable production model. In this context, Life Cycle Assessment (LCA) emerges as a promising tool for evaluating environmental sustainability throughout the life cycle of products and services, covering raw material extraction and handling to final disposal. This method enables the quantification of resources and emissions within the production chain, providing significant support for decision-making based on sustainable development and environmental efficiency criteria (Mahmud, et al., 2021).

A crucial phase is the collection of input and output data at each stage of the production chain. This process allows for a detailed assessment of the environmental impact of each material throughout the product's life cycle, contributing to result analysis based on research objectives (Ortega-Santiago, 2023; Sinha, et al., 2021).

This scientific study conducts a comparative analysis based on LCA principles, focusing on two malt beverage packaging formats: polymer containers and aluminum alloy cans.

The carbon footprint is analyzed by measuring CO_2 emissions and energy consumption expressed in Megajoules (MJ) to promote a quantitative and qualitative assessment of each alternative.

The study follows the "Cradle to Cradle" (C2C) approach, expanding traditional environmental assessment methods and promoting regenerative material management strategies. This perspective goes beyond evaluating the simple production and distribution of containers, considering their end-of-life management, assessing their behavior, and their capacity for reintegration into sustainable production cycles (Del Serrone, et al., 2025). Thus, the objective is not only to analyze environmental impact but also to establish a foundation for optimizing packaging systems, significantly reducing their ecological footprint.

This method facilitates the fair evaluation of both traditional and new alternatives by providing a comprehensive analysis of their comparative impact [Peralta, et al., 2021).

The C2C model addresses the urgent need for a holistic packaging assessment throughout its life cycle, covering raw material extraction to final product disposal. This approach promotes not only production reduction but also the efficient recovery of used resources. Inspired by the cyclical processes of natural ecosystems, the "Cradle to Cradle" (C2C) design philosophy ensures that materials retain their functionality without compromising quality.

This paradigm presents a compelling alternative to conventional linear manufacturing models, establishing a conceptual framework that continuously reinterprets production processes by integrating inputs that can be effectively reintegrated into biological or technological cycles. Instead of focusing solely on consumption reduction, this approach redefines fundamental industrial design principles, promoting the development of products that not only minimize waste but also facilitate their reintegration into circular systems, thus optimizing resource efficiency. Within this context, C2C challenges traditional waste perceptions, redefining materials as valuable resources within a circular economy and addressing inefficiencies to minimize environmental externalities (Atik, S., et al., 2021, Durão, et al., 2024).

The main objective of research is to evaluate the environmental impact of two types of beverage containers and identify potential ways to improve their sustainability metrics. By understanding CO_2 emissions and energy consumption associated with different packaging types, more effective strategies can be formulated to reduce the carbon footprint and promote sustainable packaging practices (Santos & Nogueira, 2021). Additionally, the "Cradle to Cradle" approach emphasizes the importance of material processing, contributing to a circular methodology in resource management. It is particularly significant in the current context, where the circular economy and waste reduction are key objectives for various industries (Adenle, et al., 2024).

Research on malt beverage containers within this extended framework will enhance the understanding of how materials and production methodologies can be optimized to reduce environmental impact, establishing a strong foundation for future advancements in sustainable packaging, development and management.

Theoretical basis

The life cycle analysis principle

The ISO 14040 and ISO 14044 (Weidema, P., 2022; Schaubroeck, T., et al., 2022) standards establish the fundamental methodological framework for the meticulous implementation of Life Cycle Assessment (LCA), providing standardized guidelines that ensure consistency, reproducibility, and scientific validity in evaluating the environmental impact of products and processes (Tam, et al., 2022; Niño-Apolinar, et al., 2022; Monroy-Ortiz y Correa.Soto, 2021).

). These regulations outline a structured procedure divided into four key phases:

• **Goal and Scope Definition:** This preliminary phase determines the study's purpose, the system under analysis, and the life cycle boundaries. Functional units and inclusion/exclusion criteria are established, ensuring the analysis accurately reflects specific conditions.

• **Life Cycle Inventory (LCI) Analysis:** This phase involves collecting and organizing quantitative data on input and output flows within the production system, including resource consumption, energy use, and emissions. A thorough characterization of unit processes is required to ensure data representativeness and precision.

• **Life Cycle Impact Assessment (LCIA):** Inventory data is converted into specific environmental impact categories such as climate change, eutrophication, and acidification. Standardized methodologies assess each identified flow, enabling an objective quantification of the environmental burden associated with the studied product.

• **Results Interpretation**: This phase involves synthesizing and critically analyzing findings from the previous stages. Critical system points are identified, uncertainty analyses are performed, and improvement strategies are developed based on sustainability and environmental efficiency criteria.

As defined by the UNE-EN ISO 14040 standard, LCA is an analytical methodology that comprehensively evaluates the environmental impacts associated with a product throughout its life cycle. It is an essential tool for informed decision-making in environmental management (Borri, et al., 2022). The application of this approach in the present research will not only facilitate the measurement of CO_2 emissions and energy consumption across different packaging systems but also contribute to strategies formulations aimed at process optimization and environmental footprint mitigation.

Phases of life cycle assessment

Life Cycle Assessment (LCA) entails a comprehensive and systematic analysis of the environmental effects associated with a product, process, or activity throughout its entire lifespan. This methodological framework encompasses the complete life cycle of a product, beginning with raw material extraction and concluding with final disposal. It includes production, distribution, utilization, and waste management stages (Salazar-Sánchez y Solanilla-Duque, 2023; Terlouw, et al., 2021; Torrenegra-Alarcon, et al., 2019).

Each phase is fundamentally associated with specific inputs, including raw materials and energy consumption, as well as quantifiable outputs, such as waste generation and pollutant emissions. The subsequent figure elucidates the relationships among these components.

Scope of life cycle assessment

Considering the sequential stages that constitute the life cycle, several methodological approaches are identified in LCA studies, the most addressed being:

- **Gate to Gate:** This approach is confined to an exclusive examination of a company's internal operations, focusing specifically on the manufacturing processes directly implemented by the entity.

- **Cradle to Gate:** This assessment framework includes process evaluation from raw material extraction and preparation to the industrial transformation phase. It does not consider subsequent stages such as distribution, utilization, or end-of-life management.

- **Gate to Grave:** This expands the system boundary to encompass not only the manufacturing phase but also the waste management processes required for the product's disposal at the end of its life cycle.

- **Cradle to Grave:** This approach offers a holistic perspective, delineating the environmental impact throughout the entire life cycle of a product, from raw material extraction to final disposal methods, which may include landfilling, incineration, or alternative end-of-life treatments.

• **Cradle to Cradle (C2C):** This paradigm exemplifies a transformative approach to sustainability, advocating for a regenerative framework in which materials are perpetually reintegrated into the production process. This methodology effectively eliminates waste generation while maintaining material integrity. In stark contrast to the traditional Cradle to Grave model, which assumes a linear trajectory culminating in landfill disposal, Cradle to Cradle promotes the continuous circulation of materials within technical or biological cycles. This approach seeks to preserve material utility indefinitely and eliminates the notion of disposal as an outcome (Foroughi, et al., 2021).

MATERIALS AND METHODS

This study, employing a descriptive and comparative approach, presents a comprehensive life cycle assessment (LCA) of materials used in malt beverage packaging. The primary objective is to evaluate and compare the environmental impact of different packaging types, specifically thermoplastic polymer bottles—polyethylene terephthalate (PET) and polypropylene (PP)—and aluminum (AL) cans. The study began with the measurement of carbon dioxide emissions (expressed in kg CO_2) and energy consumption (in MJ) across the entire life cycle of these materials. polypropylene cap was excluded due to its negligible mass (~2 × 10^{-3} kg), as determined using a high-precision analytical balance. Additionally, packaging was omitted from logistical calculations since both systems share equivalent packing proportions, rendering their impact statistically insignificant.

To ensure methodological rigor and comparability, the 330 ml packaging format was selected as the reference unit. In analyzing raw material transportation, the product use was also excluded from the environmental assessment, as its contribution was minimal. This decision is based on the premise that refrigeration is not universally required, nor is storage exclusively dedicated to this product category. For thermoplastic polymers, recyclability and reuse cycles were examined, while for aluminum, the study assessed the energy requirements of manufacturing and its potential for reintegration into future production cycles.

From a logistical standpoint, the study mapped transportation routes and distances for raw materials from suppliers to processing plants and distribution centers. A comprehensive environmental impact assessment was focused on CO_2 emissions and energy consumption at each stage of the packaging life cycle, including raw material extraction, processing, transportation, distribution, use, and final disposal. The Ashby tables were employed as a heuristic reference to quantify CO_2 emissions associated with each material.

Following data collection, a detailed analysis was performed to identify the life cycle stages with the most significant environmental impact for each packaging type. Subsequently, a comparative assessment between PET and aluminum packaging was undertaken to elucidate key differences in their environmental performance, particularly concerning their contribution to climate change. This analysis aimed to enhance methodological accuracy and reinforce the scientific validity of the study's conclusions.

RESULTS AND DISCUSSION

Container inventory analysis

The data presented in Tables 1 and 2 indicate that PET packaging exhibits a significantly higher environmental impact in CO_2 emissions, reaching a total of 0.1708 kg. This highlights PET's greater carbon footprint compared to aluminum cans.

Table 1. Inventory analysis results for plastic bottle (CO2 – Kg).

Material	Transport (Raw Material)	Raw Materials	Processing	Transport (Product)	End Of Life
PET	1.784E-05	8.58E-02	9.52E-02	8.46E-04	-1.55E-02
PP		7.60E-03	2.61E-03		-5.70E-03
TOTAL	1.784E-05	9.34E-02	9.78E-02	8.46E-04	-2.12E-02

Table 2. Results of the inventory analysis for aluminum (CO2 – Kg)

Material	*Transport (Raw Material)*	*Raw Materials*	*Processing*	*Transport (Product)*	*End of Life*

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Aluminium	2.720E-07	5.44E-02	1.90E-03	1.60E-04	1.90E-02
Total	2.720E-07	5.44E-02	1.90E-03	1.60E-04	1.90E-02

Regarding energy consumption, PET requires 0.797 MJe (as shown in Tables 3 and 4), underscoring its substantial energy demand throughout its life cycle. Consequently, PET emerges as a less environmentally sustainable option relative to aluminum packaging (Tamoor, et al., 2022; Ingrao, et al., 2023; Astarita, et al., 2023).

Table 3. Results of the inventory analysis for the plastic bottle (Mje-)

Material	*Transport (Raw Material)*	*Raw Materials*	*Processing*	*Transport (Product)*	*End of Life*
PET	1.53E-02	5.05E-01	1.17E-01	3.12E-03	6.95E-02
PP		5.24E-02	0.009396		2.57E-02
Total	1.53E-02	5.57E-01	1.26E-01	3.12E-03	9.51E-02

Table 4. Results of the inventory analysis for Aluminum can (Mje-)

Material	*Transport (Raw Material*	*Raw Materials*	*Processing*	*Transport (Product)*	*End of Life*
Aluminium	1.004E-06	2.57E-01	6.18E-03	5.90E-04	3.18E-02
Total	1.004E-06	2.57E-01	6.18E-03	5.90E-04	3.18E-02

A comprehensive life cycle analysis underscores the considerable environmental burden of the manufacturing phase for both materials. During raw material extraction, PET generates 0.0934 kg of CO_2, whereas aluminum accounts for 0.0544 kg. The disparity becomes more pronounced in the processing phase, with PET emitting 0.0978 kg of CO_2, while aluminum contributes only 0.0019 kg. PET's raw material acquisition phase demands 0.557 MJe—substantially exceeding other life cycle stages. Although aluminum exhibits a lower energy impact at 0.257 MJe, this value remains noteworthy.

The current research findings indicate that PET containers are associated with higher levels of CO_2 emissions in comparison to aluminum containers, underscoring their distinct environmental repercussions. From a methodological standpoint, the life cycle assessment (LCA) omitted marginal variables, including material weight and packaging, because both containers utilize the same logistical pathways. This analytical approach facilitated a more thorough assessment of the intrinsic environmental impacts related to the materials and their associated industrial processes.

Furthermore, it was determined that during the concluding stage of the life cycle, the management of post-consumer containers

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falls under the purview of the consumer, thereby rationalizing the exclusion of packaging from this phase of the analysis.

Concerning the utilization of the product, it was concluded that refrigeration does not serve as a universal or exclusive prerequisite, thereby precluding the possibility of assigning all emissions associated with storage to a specific category of container (Table 5).

Table 5. Consolidated inventory analysis

Packaging	CO_2 (kg)	Mje-
Plastics	1.708E-01	7.97E-01
Aluminium	3.55E-02	2.96E-01

Nonetheless, it is important to emphasize that polyethylene terephthalate (PET) containers demonstrate a substantial recyclability rate, suggesting considerable potential for mitigating carbon dioxide emissions, as evidenced by the data presented in Table 5, Figure 1 and Figure 2.

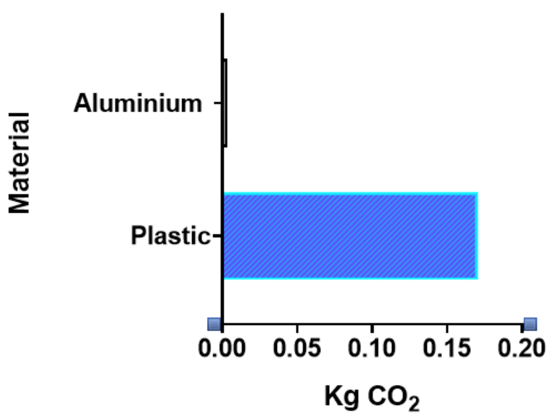

Figure 1. Total CO_2 emissions for packaging systems.

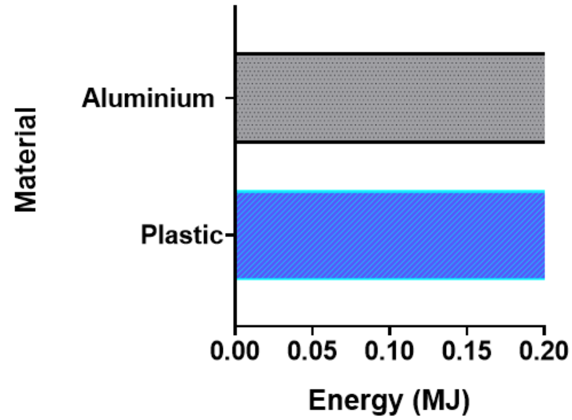

Figure 2. Total energy for packaging systems

Environmental Impact Assessment

The environmental impact assessment reveals that polyethylene terephthalate (PET) is the highest CO_2-emitting material among the evaluated options—polypropylene and aluminum. This finding underscore PET's unfavorable environmental profile due to its substantial greenhouse gas emissions throughout its life cycle, a conclusion that aligns with previous research. Furthermore, PET requires significantly more energy for its production and processing, exacerbating its ecological footprint. The combination of high CO_2 emissions and energy consumption positions PET as the least sustainable option compared to aluminum and polypropylene (Maidin, et al., 2024).

Polypropylene, while also a plastic, has a lower environmental impact than PET. However, its sustainability remains inferior to that of aluminum. Aluminum, in contrast, not only emits less CO_2 and requires less energy during production but is also highly recyclable. This material can be continuously repurposed without losing its properties, significantly reducing its long-term environmental burden. Its high recyclability minimizes the demand for virgin material extraction, decreases landfill waste, and preserves natural resources (Rivera, et al., 2022; Sanyé-Mengual, & Sala, S., 2022). These factors establish aluminum as the most sustainable choice among the materials analyzed.

Recommendations to consumers. Consumers are advised to opt for beverages packaged in aluminum containers, as this material has a significantly lower environmental footprint in CO_2 emissions and energy consumption throughout its life cycle. In contrast, plastic containers made of polypropylene and polyethylene terephthalate (PET) exhibit a considerably higher environmental impact, not only due to their elevated greenhouse gas emissions but also because of the substantial energy required for their production.

The selection of aluminum as a packaging material mitigates environmental impact and fosters more sustainable consumption habits. Its exceptional recyclability allows for multiple reuses without compromising its properties, significantly reducing the extraction of natural resources and minimizing landfill waste. Consequently, advocating for aluminum as a sustainable alternative constitutes a fundamental strategy for resource conservation.

Strengthening environmental education and raising public awareness about recycling and choosing sustainable packaging is imperative. Targeted educational initiatives and incentive programs can drive positive behavioral changes, encouraging more responsible consumption patterns and establishing a production and consumption model aligned with environmental sustainability principle.

CONCLUSIONS

Aluminum cans are distinguished as the preferred option owing to their reduced carbon dioxide emissions and enhanced energy efficiency. Their elevated recyclability, achieved without detracting from their physicochemical characteristics, diminishes the utilization of virgin resources and mitigates the accumulation of waste in landfills. In contrast, the utilization of PET constitutes a significant contributor to emissions and energy consumption, highlighting the imperative to improve its recyclability or investigate more sustainable alternatives. The implementation of the cradle-to-cradle framework in this research facilitates a comprehensive assessment of packaging life cycles, allowing for the identification of key opportunities for enhancement and the transition towards circular production paradigms. Implementing circular economy strategies not only reduces the environmental footprint associated with consumer goods but also promotes the creation of resilient and sustainable production systems.

One of the most significant global issues is the insufficient awareness among consumers regarding the environmental ramifications of packaging. Consequently, life cycle assessments function as a critical instrument for elucidating the ecological implications associated with packaging materials. The advancement of recycling initiatives and the implementation of environmental education are essential in mitigating the ecological impact linked to the production and disposal of packaging materials. Collective consciousness and sustainable practices are crucial in alleviating the global environmental impact.

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