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Choosing the Right LCA Methodology for Sustainable Beverage Production

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Abstract

Life Cycle Assessment (LCA) is widely used to evaluate and reduce the environmental impact of products and industrial systems. In the beverage industry, which relies heavily on packaging materials, energy, and water resources, selecting an appropriate LCA methodology is essential for achieving sustainability goals in the industry. This review analyzes the major LCA approaches used in beverage production, including cradle-to-grave, cradle-to-gate, gate-to-gate, cradle-to-use, and end-of-life assessments. This paper compares the system boundaries, advantages, and limitations of these approaches and discusses their applications in beverage packaging systems, such as PET bottles, aluminum cans, and glass containers. A systematic review of 86 peer-reviewed studies published between 2000 and 2024 was conducted using major scientific databases. The results show that cradle-to-grave analysis remains the most commonly applied methodology, whereas newer studies increasingly focus on recycling, circular economy strategies, and marine plastic pollution. This study highlights how selecting an appropriate LCA method can support better environmental decision-making, sustainable product design, and improved resource efficiency in beverage production systems.

Keywords: Beverage Industry, Beverage Packaging, Circular Economy, Life Cycle Assessment (LCA), Plastic Pollution, Sustainable Production.

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1. Introduction

Life Cycle Assessment has become an important tool for evaluating the environmental performance of industrial systems. It provides a structured methodology for assessing the environmental impacts of a product throughout its entire life cycle, including raw material extraction, manufacturing, distribution, use, and final disposal [1],[2]. For many years, the food and beverage industry has been one of the sectors in which LCA has been widely applied owing to the significant consumption of packaging materials, water, and energy resources. Early environmental analyses of beverage packaging were conducted by large beverage companies to compare packaging alternatives and improve resource efficiency. Since then, LCA has evolved into a widely recognized decision-making tool for sustainable production and packaging design [3],[4],[5]. LCA has subsequently been applied to a wide range of beverage packaging formats, including polyethylene terephthalate (PET), polylactic acid (PLA), aluminum cans, and glass bottles, enabling comparative assessment of their environmental impacts across different life-cycle stages [6],[7],[8],[9]. Each material presents trade-offs: PET is lightweight and recyclable but derived from fossil fuels, PLA is bio-based but demands high agricultural input, and glass is reusable but energy-intensive to produce. Beverage companies must weigh these factors using LCA models that reflect their sustainability focus, such as emission reduction, circularity, and localized production. The environmental impacts associated with beverage packaging have attracted increasing attention in recent years. Packaging materials such as polyethylene terephthalate (PET), aluminum, and glass have different environmental trade-offs related to energy consumption, recyclability, and greenhouse gas emissions [10],[11]. For example, PET bottles are lightweight and widely recyclable, but they are produced from fossil-based materials. Aluminum cans offer high recycling rates but require high energy consumption during production, whereas glass bottles are reusable but relatively heavy and energy-intensive to manufacture. Plastic pollution has become a major environmental concern related to beverage packaging. A large proportion of global plastic production is used for packaging applications, and mismanaged waste contributes to marine pollution and ecosystem damage [12],[13]. Consequently, policymakers, researchers, and manufacturers increasingly rely on LCA to identify environmental hotspots and develop more sustainable packaging solutions. The results of LCA studies depend strongly on methodological choices, such as system boundaries, functional units, and impact assessment methods. Different LCA approaches may produce different environmental results for the same product systems. Therefore, selecting the most appropriate LCA methodology is a critical step in conducting reliable sustainability assessments of products. This review aims to analyze the main LCA methodologies used in beverage production and evaluate their advantages, limitations, and practical applications in sustainability decision-making [14],[15].

The LCA methodology consists of four stages: goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation. The framework is based on the ISO 14040 standards for LCA, which were released in 1997 and updated in 2006 [1]. The four main stages of life cycle assessment are illustrated in Figure 1.

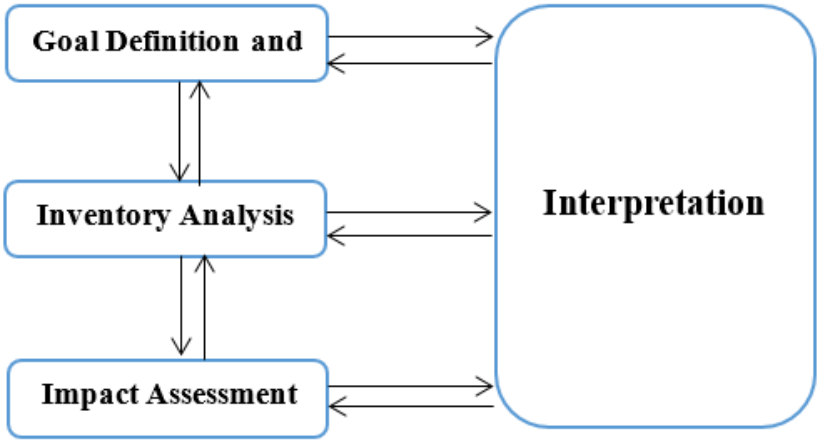


Fig. 1. Phases of Life Cycle Assessment based on ISO 14040 (Source: EPA).

In this review, only articles from peer-reviewed journals were considered, as the emphasis was on studies that had undergone independent peer evaluation. Books and book chapters were excluded because it was unclear whether they had been subjected to the same level of scrutiny. However, this exclusion poses a limitation, as it might have led to the omission of pertinent LCA studies. Reviews and methodology papers were also excluded because the focus was on LCA studies. Although review papers offer a critical analysis of LCAs, they do not present new LCA results and may lead to duplication if a paper is reviewed by its authors and then again in a review. Methodology papers were considered only if the proposed methods were applied to an LCA within the same paper. A literature search was performed using Web of Knowledge, ScienceDirect, and Google Scholar, employing keywords such as 'LCA,' 'life cycle analysis,' and 'carbon footprint' in conjunction with 'plastic and aluminium.' This search yielded 310 potential studies. After screening based on the subject matter, 244 studies were retained. Further refinement based on publication text reduced this number by 40. After removing duplicates, 86 studies were selected for the review. A summary of the main Life Cycle Assessment methodologies, including their functional units, scope, strengths, and typical applications, is presented in Table 1.

Table 1. Summary of Life Cycle Assessment (LCA) methodologies, including functional unit, system boundary, strengths, and typical applications. (Author)

Article Title	Authors	Materials Analyzed	LCA Scope	Software/Database	Key Findings
Life Cycle Assessment of Drinks Packaging: Are There Environmentally-Friendly Alternatives to Plastics?	A. Brock, I.D. Williams	PET, HDPE, glass, aluminium, Tetra Pak, milk cartons	Cradle-to-grave (excluding transport)	openLCA, ELCD	Recycled aluminium cans (pressurized), Tetra Pak (juice), and milk cartons were less impactful than plastics. The results found that in each category

					there was a less impactful beverage packaging than plastic bottles.
Life Cycle Assessment of Polylactic Acid and Polyethylene Terephthalate Bottles for Drinking Water	Fausto Gironi, Vincenzo Piemonte	PLA, PET	Cradle-to-grave	SimaPro7, Ecoinvent v2.0	PLA offers renewable advantages but causes higher impact on the ecosystem and human health. On the other hand, the LCAs cradle to grave showed that PLA is more convenient than PET when the final destination of PLA bottles is recycling.
Life Cycle Assessment of a Basic Lager Beer	Siret Talve	Glass bottles, packaging materials	Cradle-to-shop (excluding consumption)	KCL-ECO, KCL database	Major impacts from agriculture and transport; 98% bottle reuse reduces impact significantly.
Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles –What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis	Elena Tamburini, Stefania Costa, Daniela Summa, Letizia Battistella, Elisa Anna Fano	PLA, PET	Cradle-to-grave	Recipe and Ecoinvent v2.0	Reusable bottles are eco-friendlier long-term, but hygiene and washing impact their benefits; PET recycling supports circular economy, while PLA has high agricultural impact.
Production, use, and fate of all plastics ever made.	Geyer, R., Jam beck J.R., Law, K.L.	PLA, PET, packaging materials	Cradle-to-grave	review	Plastic Playing a key role in almost all sectors such as, for example, food storage, fashion and clothing industry, construction industry, pharmaceuticals and personal care products, and

					many other applications; plastic has been rapidly become the third widespread material worldwide after cement and steel.
LIFE CYCLE ANALYSIS OF BEVERAGE PACKAGING	Shajahan Maidin* Shafinaz Ismail Azmiza Idayu Azman	Plastic bottles, glass bottles, and aluminium cans	Cradle-to-grave	openLCA open-source software	Aluminium cans and glass bottles are less environmentally impactful than plastic bottles, and shifting away from single-use plastics toward more recyclable alternatives is crucial; further research on paper bottles and stronger recycling initiatives in Malaysia are recommended.
LIFE CYCLE ASSESSMENT OF BEVERAGE PACKAGING	Alice Brock and Ian Williams	glass bottles, aluminium cans, milk cartons, Tetra Pak, polyethylene terephthalate (PET) bottles and high-density polythene (HDPE) bottles.	evaluate and review the costs, benefits, advantages and disadvantages of plastics as a beverage packaging material;	openLCA open-source software	There are more environmentally friendly single-use alternatives to plastic bottles—such as recycled aluminium cans, Tetra Pak, and milk cartons—but reusable packaging offers the best path toward sustainability, as all options still have environmental impacts
The Evolution of Life Cycle Assessment in the Food and Beverage Industry: A Review	Takunda Y. Chitaka1 and Taahira Goga2	Various Industry Reports	Gradle to grave	Environmental Impacts, Marine Pollution	LCA is increasingly used to assess environmental impacts in the food and beverage industry,

					especially for single-use plastics.
Environmental Overview: Complete Life Cycle Assessment of North American Container Glass	PE Americas - Alexandria, VA Glass Packaging Institute	Glass	Cradle-to-Grave, Gate-to-Gate, Cradle-to-Gate	openLCA	
Beverage Packaging in the United States: A Comparative Life Cycle Assessment	Flora D'Souza	Various (glass, PET and aluminium)	Cradle-to-Grave		Packaging materials with high recycling rates, high recycled content, and efficient circular systems—especially aluminum have the greatest potential to reduce environmental impacts. Aluminum cans perform best overall due to lightweight design, high recycled content, and strong recycling infrastructure. PET bottles perform well but have room for improvement in recycling rates and content.
Life Cycle Assessment of Ground Coffee and Comparison of Different Brewing Methods: A Case Study of Organic Arabica Coffee	Bhanupong Phrommarat *		Cradle-to-grave; brewing methods (electric drip, moka pot, pour-over)	ISO 14040/44, Recipe, Eco invent 3.1	Cultivation is a major hotspot; moka pot brewing high in resource impact; organic farming reduces impact.

in Northern Thailand					
Comparative Life Cycle Assessment of Packaging Systems for Extended Shelf-Life Milk	By Massimo Bertolini, Eleonora Bottani, Giuseppe Vignali* and Andrea Volpi	carton, PET, HDPE	Cradle-to-grave: material production, transport, use, disposal (Italian context)	ISO 14040, CED, CML2001, SimaPro	Multilayer cartons least impactful; PET bottles highest; recycling is critical
An evaluation of life cycle assessment of European milk production	Ming-Jia Yan a, *, James Humphreys b, Nicholas M. Holden	LCA	Cradle-to-grave	ISO 14040,	Highlighted technical inconsistencies, arbitrary assumptions, and recommended improvements for future agricultural LCAs, such as standardized functional units and better boundary definitions.
Fifteen Years of ISO 14040: A Review	Jonathan Pryshlakivsky a, *, Cory Searcy b	ISO	ISO	ISO	Improvements in clarity and structure of standards; persistent issues with uncertainty, allocation methods, and economic aspects. ISO 14040 evolved into a stable, widely-used LCA standard post-2006, but needs better performance evaluation and selective updates to stay relevant.
Life cycle assessment (LCA) applied to the process	Leslie Jacquemin, Pierre-Yves Pontalier,	None specifically; discusses process	Review of LCA in process industries; focus on	review paper	LCA is a useful tool in process systems engineering for integrating

industry: a review	Caroline Sablayrolles	industries in general	integration with process systems engineering		environmental considerations. It is used for multi-objective optimization but is limited by black-box process assumptions and static operating conditions.
Recent developments in Life Cycle Assessment	Finnveden et al.	None specifically; discusses examples in energy, agriculture, transport, waste	Review of recent methodological advances in LCA and its broader integration	review paper	Distinction between attributional and consequential LCA is critical. Recent advancements include scenario modelling, hybrid LCA, improved LCIA modelling, and uncertainty analysis.
Life Cycle Assessment Software Selection Can Impact Results	Speck, Selke, Auras, Fitzsimmons	Aluminum, Corrugated board, Glass, Polyethylene terephthalate (PET)	Comparative analysis of LCA software (SimaPro vs. GaBi) using consistent material scenarios	(SimaPro vs. GaBi)	LCA results can vary significantly depending on the software used due to differences in characterization factors and impact methodology implementation.
Life cycle inventory of recycling portable nickel–cadmium batteries	Carl Johan Rydh a,*, Magnus Karlström b	Lithium, cadmium, nickel, cobalt, zinc, lead (battery materials)	Cradle-to-gate	Not specified; likely manual or database-based (e.g., BUWAL)	E-waste recycling can be an important secondary source for rare metals. - Environmental performance depends heavily on recovery efficiency
Impacts of aluminum production: A cradle-to-gate investigation using life-cycle assessment	Shahjadi Hisan Farjana, Nazmul Huda *, M.A. Parvez Mahmud	Plastics, aluminum, copper, gold, silver, rare earth elements, packaging	Cradle-to-grave	SimaPro 7.1	PET bottles have significantly higher environmental impacts than glass in several impact categories. - Transportation and end-of-life

					stages matter greatly
Addressing sustainability in the aluminum industry: a critical review of life cycle assessments	Gang Liu*, Daniel B. Müller	PET, HDPE, LDPE, PP, PS, multilayer plastic packaging	Cradle-to-grave	SimaPro 8	Aluminum cans have a high environmental burden due to raw material extraction and electricity use. - Recycling can reduce the impacts significantly.
Life cycle assessment of non-alcoholic single-serve polyethylene terephthalate beverage bottles in the state of California	DongHo Kanga,b, Rafael Auras a, ⁎, Jay Singhc	Polyethylene terephthalate (PET) bottles (including PET body, polypropylene cap and label)	Cradle-to-grave	review paper	Environmental impact of machine tool use in manufacturing Mass production is most energy-efficient
Environmental implications and market analysis of soft drink packaging systems in Mexico. A waste management approach	Omar Romero-Hernández & Sergio Romero Hernández & David Muñoz & Emiliano Detta-Silveira & Arturo Palacios-Brun & Adriana Laguna	PET bottles, aluminum cans, and glass bottles (for comparative analysis)	Cradle-to-grave	review paper	Review and comparison of LCA approaches for engineered productsEncouraged: process + input-output hybrid LCA

2. Results and Discussion

Figure 2 shows the distribution of studies according to the type of Life Cycle Assessment methodology employed. The findings indicate that, within the review period, nine studies focused on carbon footprint analyses, 53 studies applied traditional LCA methods, and eight studies integrated conventional LCA with an additional environmental metric to assess plastic pollution impacts. The remaining studies, categorized as “other” in the chart, involved assessments that extended beyond the conventional boundaries of LCA. For instance, some studies examined different end-of-life scenarios and waste management strategies. One study incorporated life cycle costing into its analysis, while another employed a hybrid methodology to assess the environmental benefits of redesigning plastic milk bottles. Another example is Cottafava et al., who used LCA

within a two-step approach to identify an environmental break-even point by comparing various end-of-life and use-phase options for single-use and reusable cups. In addition, only one study incorporated a material circularity indicator to address circularity. Furthermore, two studies combined material flow analysis (MFA) with LCA to relate mass-based metrics to indicators of environmental harm MFA and LCA serve as complementary methodologies, allowing for more detailed analyses of complex systems [15],[16].

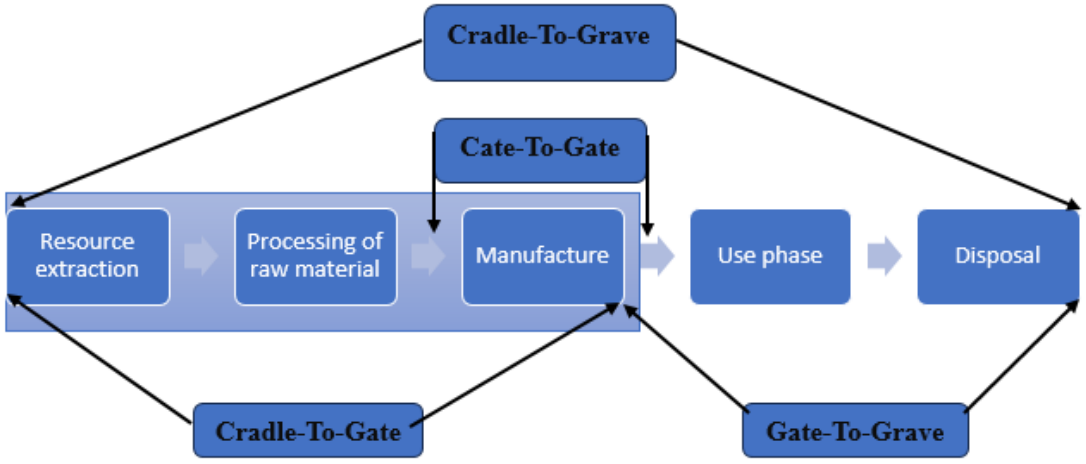


Fig. 2. Common system boundary definitions used in Life Cycle Assessment (adapted from PE, 2009).

- **Cradle-to-Grave Analysis**
  A total of 53 papers; approximately 62% of the reviewed studies applied a cradle-to-grave system boundary. This approach examines environmental impacts from raw material extraction through manufacturing, distribution, product use, and final disposal. Because it provides a comprehensive overview of environmental impacts, cradle-to-grave analysis is particularly useful for policy development and long-term sustainability planning. However, the method requires extensive data collection and complex modeling, which can increase uncertainty in some cases [6],[17].
- **Cradle-to-Gate Analysis:**
  Cradle-to-gate studies evaluate environmental impacts from raw material extraction up to the factory gate, before the product reaches the consumer. This approach is commonly used for comparing production technologies and evaluating supply chain impacts. Several studies comparing PET and bio-based materials have used cradle-to-gate analysis to evaluate environmental trade-offs in beverage packaging systems. Nonetheless, practical application can be hindered by real-world constraints in recycling infrastructure [18],[19].
- **Gate-to-Gate Analysis**:
  Eight reviewed papers had a gate-to-gate scope. Gate-to-gate models focus on a specific part of the lifecycle, typically the manufacturing process inside a factory. Although they are not all-encompassing, they facilitate targeted enhancements

and quicker decision-making [10]. These models are particularly beneficial for manufacturers aiming to reduce emissions and energy consumption in controlled settings.

- **End-of-life**
  The end-of-life stage includes waste management processes such as recycling, incineration, and landfill disposal. Environmental impacts at this stage depend strongly on local waste management infrastructure and consumer behavior. Effective recycling systems can significantly reduce the environmental burden associated with beverage packaging materials [20],[21]. Table 2 provides an overview of the different LCA methodologies, including their scope, strengths, limitations, and best applications.

Table 2. Overview of Life Cycle Assessment Methodologies, Their Scope, Strengths, Limitations, and Applications (Author)

Methodology	Scope	Strengths	Limitations	Best Used For
Cradle-to-Grave	Full lifecycle	Comprehensive and holistic	High data and time demand	Strategic planning, full impact assessments
Cradle-to-Cradle	Lifecycle + reuse	Emphasizes circular economy principles	Requires robust recycling systems	Sustainable product and packaging design
Gate-to-Gate	Specific stage	Simple, fast, operationally focused	Ignores upstream and downstream impacts	Process improvement and operational audits
Cradle-to-use	Raw materials to use	Focuses on production and distribution impacts	Excludes use-phase and end-of-life consequences	Product development, supply chain evaluation
End-of-life	Disposal and recycling	Highlights final environmental burden or recovery	Misses' earlier lifecycle impacts	Waste management strategy, material recovery assessment

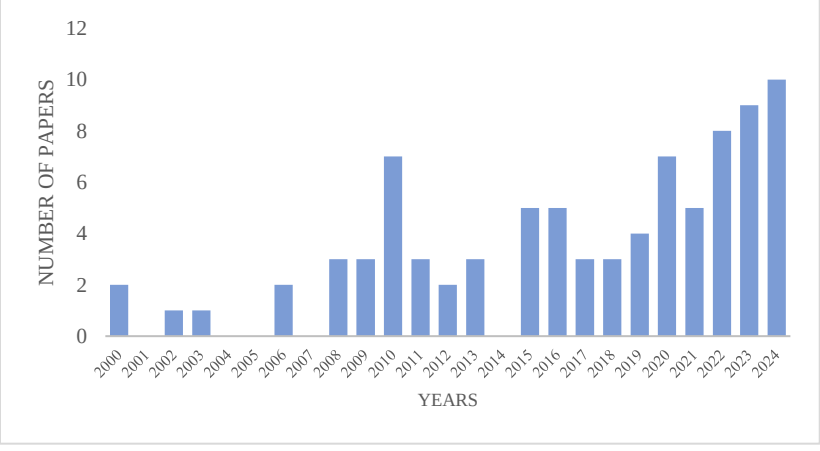


Fig. 3. Number of product-specific, food and beverage LCAs conducted from 2000 to 2024. (author)

Carbon and water footprint assessments are recognized as specific forms of Life Cycle Assessments. The analysis showed that studies estimating greenhouse gas (GHG) emissions—essentially carbon footprints—often calculate energy use or cumulative

energy demand as part of their evaluation. Fetner and Miller [10] incorporated water consumption as an additional indicator to assess environmental payback periods. The total number of studies reviewed suggests that, despite the growing focus on global warming and climate change, most investigations consider multiple environmental impact indicators rather than a single metric [17]. Among the earliest LCA studies identified within the review timeframe were those of Sevitz et al. and Zabaniotou and Kassidi [22]. Over the years, the publication trend of LCA studies has been irregular, with fluctuations in output rather than a clear and linear increase. However, a more consistent rise in interest has been observed since 2017, with the number of studies showing steady growth—a trajectory that is expected to continue into 2024 [23].

In recent years, marine plastic pollution has been increasingly addressed in LCA studies. The Medellin Declaration highlighted that current LCA methods do not adequately capture marine plastic impacts, and major LCA databases lack data on plastic leakage emissions and related characterization factors. Projects such as MarILCA aim to fill this gap by integrating marine litter impacts into LCA. Although research on plastic pollution impact models is growing, their practical application remains limited. Early efforts include the study of factors affecting entanglement and models accounting for microplastic fragmentation and degradation [24]. However, the development of robust models is challenged by a limited understanding of the impact of plastic on species and ecosystems. Meanwhile, simple marine litter indicators based on weight, leakage rates, and degradation have been used. Among the six relevant studies, half were from Europe, and the others were from South Africa, Brazil, and the USA.

3. Scope of studies

The scope of a Life Cycle Assessment is largely determined by the system boundaries defined by the researcher or practitioner. While a full cradle-to-grave analysis is considered the standard approach, some assessments may concentrate on specific segments of the life cycle, such as gate-to-gate evaluations (see Figure 3). The majority of studies adopted the cradle-to-grave approach (62%), followed by cradle-to-gate (10%) and gate-to-gate (4%). Less frequently used scopes included gate-to-grave, cradle-to-use, use-to-grave, and end-of-life assessments.

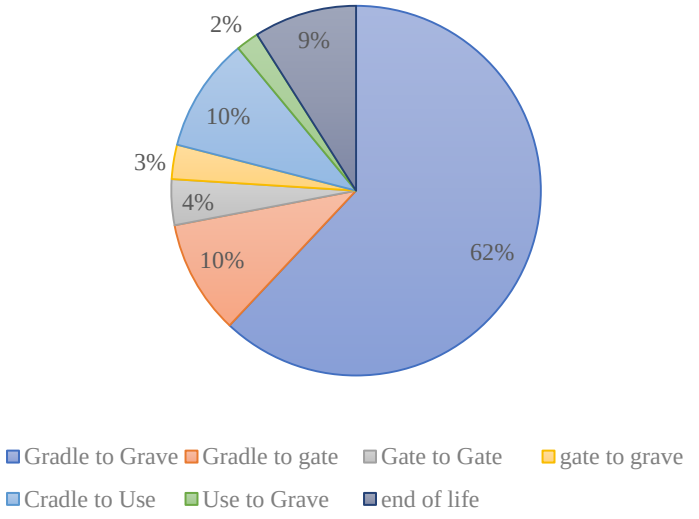


Fig. 4. Scopes of reviewed LCA studies.

However, there is a noticeable shift toward examining end-of-life impacts, even within broader cradle-to-grave analyses. In the context of beverage bottles, researchers have shown particular interest in exploring the environmental advantages of recycling post-consumer waste. Notably, two studies adopted a dual-scope approach, integrating both cradle-to-gate and cradle-to-grave analyses [6].

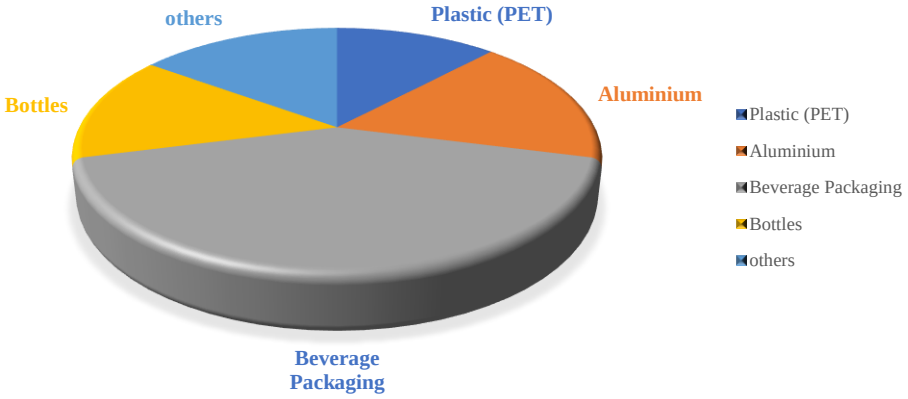


Fig. 5. Product composition of reviewed LCAs

The largest group of products evaluated in the reviewed Life Cycle Assessment studies corresponded closely to those identified as major contributors to plastic pollution. Beverage packaging emerged as the dominant category, representing the majority of the reviewed studies (Figure 4). Interest in this area has grown steadily since 2011, with notable increases in publication frequency: five studies in 2015, five in 2016, and a peak of ten in 2024. Among the beverage categories, milk and mineral water were the most frequently assessed, although not all studies specified the type of beverage analyzed.

Approximately 70% of beverage packaging LCAs have focused on polyethylene terephthalate (PET) bottles, which have been examined individually or compared with glass bottles and aluminum cans. Research interest in PET bottles began to rise in 2011, with a consistent output of 1–4 studies annually (excluding 2019) and reaching 5 studies in 2021. PET bottles can show lower environmental impacts than glass and aluminum under certain scenarios, particularly when differences in packaging weight, transport, recycled content, reuse rates, and end-of-life assumptions are considered [19]. Plastic bags and disposable cups each accounted for 15% of the reviewed studies. Interest in plastic bags peaked between 2009 and 2012 and returned after 2017, likely due to pollution concerns. The "other" category included items such as jars, cutlery, and trays. Public discourse has also shaped the LCA focus, as seen in the rise of straw studies after 2020, reflecting growing public awareness of plastic pollution and climate change impacts. However, a more consistent rise in interest has been observed since 2017, with increasing publication trends reported in the literature up to 2020 [23]. More recent studies (2021–2024) further confirm the continued growth of research in this field. More recent studies have incorporated additional indicators, such as carbon footprint, water footprint, and marine litter impact. Recent studies have increasingly focused on alternative materials and the environmental impacts of plastic products, including straws and microplastics [24],[25].

4. Conclusion

This review examined the major Life Cycle Assessment methodologies used to evaluate the environmental impacts of beverage production systems. These findings indicate that cradle-to-grave analysis remains the most comprehensive approach for assessing the overall environmental footprint of beverage packaging systems. However, other methodologies, such as cradle-to-gate and gate-to-gate analyses, can provide valuable insights for improving specific production processes. The growing focus on plastic pollution and circular economy strategies has increased the importance of evaluating recycling systems and end-of-life management options. Future LCA studies in the beverage sector should integrate improved data on plastic leakage, recycling performance, and the environmental impacts associated with marine litter.

Selecting an appropriate LCA methodology allows companies to make more informed decisions regarding packaging design, resource efficiency, and sustainable production strategies. As environmental regulations become stricter and consumer awareness continues to increase, LCA will remain a critical tool for guiding sustainable innovation in the beverage industry in the future.

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