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Original Research

Life-Cycle Environmental Impact Assessment of Primary Beverage Containers: Glass versus Plastic Bottles

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Abstract: Pollution originating from the life cycle of packaging is increasing and can have potentially irreversible consequences for the environment. In the beverage industry, the most common materials used for the production of primary packaging are glass and plastic. The objective of this study was to compare the environmental impacts of polyethylene terephthalate and glass bottles. The Leopold Matrix was applied to evaluate the environmental impact of the life cycle of both bottles, using information from a wide range of scientific articles and peer-reviewed indexed journals. The evaluation took into account the abiotic, biotic, and anthropic components generating negative consequences for ecosystems, human health, and fauna and flora. The study found that both containers generate negative environmental impacts throughout their life cycle. This was evidenced in the results of the matrix, where the total values symbolize –712 and –690 for glass and plastic, respectively.

Keywords: *Life-Cycle Assessment, Environmental Impacts, Glass Bottle, Leopold Matrix, Solid Waste Management, Plastic Bottle*

Introduction

Packaging plays an important role throughout the food and beverage production and supply chain, but it is one of the main sources of increasing contamination. This is because its production and use has increased as it is present in most areas of human life, regardless of the material from which it is made (Ferrara et al. 2022; Varun, Sharma, and Nautiyal 2016; Żołek-Tryznowska and Holica 2020). Mass consumption industries tell us that the variability of environmental impacts and the reduction of their potential depend on the nature of the product consumed (Casson et al. 2022). These environmental impacts can be generated throughout the life cycle of products, from the consumption of resources in the extraction of raw materials, through manufacturing, transport, and waste management, highlighting that they may end up in incinerators, ecosystems, or landfills when they cannot be used (Šerešová and Kočí 2020).

COMMON GROUND

Packaging is the material used to cover a product, preserve its integrity, and protect it from external factors (Al-Kindi and Al-Baldawi 2021; Varun, Sharma, and Nautiyal 2016). Packaging is lightweight, inexpensive, and durable, but can be considered as waste and generate environmental impacts after use and at the end of its life-cycle (Al-Kindi and Al-Baldawi 2021; Varun, Sharma, and Nautiyal 2016). According to its level of functionality, packaging is classified into three categories: primary packaging, which is in direct contact with the product, wrapping and holding it; secondary packaging, which is used to group primary packaging and facilitate its distribution; and tertiary packaging, which is used for storage and shipping of secondary packaging, the most commonly used being wooden or plastic pallets (Mahmoudi and Parviziomran 2020; Šerešová and Kočí 2020).

An increasing number of industries are looking for hygienic, durable, and sustainable packaging (Varun, Sharma, and Nautiyal 2016). Many regions have begun implementing these options with the European Union (EU) serving as a prominent example. The EU is currently enacting a range of policies aimed at enhancing sustainability across all sectors, which includes the ambitious target of reducing greenhouse gas emissions by at least 55 percent by 2030 (Roosen et al. 2023). Industries from different regions aim to analyze the environmental impact by using methodologies and sustainable practices related to the production, packaging, and treatment of packaging. One of the methods used to assess the environmental impacts associated with a product is Life-Cycle Assessment (LCA), which is governed by the International Organization for Standardization (ISO) standards ISO 14044:2006 and ISO 14040:2006 and is used as a tool to compare different types of projects or products from an environmental impact perspective (Brock and Williams 2020; Pragati and Yasunobu 2022). It quantifies resource and energy consumption, greenhouse gas emissions, and waste levels (Banar and Cokaygil 2008; Bertolini et al. 2016).

The soft drinks and alcoholic beverages industry is no exception in this quest for sustainability. The most commonly used materials for primary packaging in this industry are cardboard, plastic, and glass (Šerešová and Kočí 2020). It is important for organizations to consider the environmental impact of primary packaging, in this case, bottles. For instance, the environmental impact of manufacturing beer is similar to that of its packaging when the entire life cycle is taken into account, with 50 percent of greenhouse gas emissions being caused by packaging (Meneses, Pasqualino, and Castells 2012; Shin and Searcy 2018). Similarly, the production of wine bottles generates approximately 55 percent of the total carbon footprint and is the third most significant water footprint (Bonamente et al. 2016). One of the ways to establish responsible consumption, given that the world's population will continue to grow by around 9.7 billion people by 2050, is to use the most environmentally friendly alternative of the existing primary packaging or to use packaging made of innovative materials (Versino et al. 2023).

Currently, Europe and China account for 27 percent and 33 percent, respectively, of the global leadership in the search for eco-friendly, biodegradable packaging materials. However, it is worth noting that Middle and South America's regional share is decreasing and currently stands at only 11 percent for bio-based global plastic production. Although, Middle and South America contribute only 4 percent to the annual world plastic production, there are still significant opportunities for innovative packaging solutions that can promote environmental sustainability (Plastics Europe AISBL 2023).

Plastic packaging has heat resistance, has low density, and is lightweight and, thus, is superior to other materials (Jahandari 2023). Additionally, it is an economical alternative that is resistant to degradation, has a good shelf life, and is versatile (Boutros, Saba, and Manneh 2021; Šerešová and Kočí 2020; Statista Research Department 2021b). Some researchers claim that we are the "planet of plastic" (Żołek-Tryznowska and Holica 2020)—there is evidence that its production has grown from 50 Mt to over 360 Mt in forty years, with packaging constituting 40 percent of the production (Debeaufort 2021; Żołek-Tryznowska and Holica 2020). In 2022, global plastic consumption amounted to 400.3 Mt, with almost half of it concentrated in North America and China (17% and 32%, respectively). This figures to an increase of almost 30 Mt from 2018 (Plastics Europe AISBL 2023). By 2050, global plastic production is projected to be close to 600 Mt per year (Figure 1), with quantified emissions of 2.8 Gt of CO_2e (Zhang et al. 2020; Statista Research Department 2024a). It is important to note that the largest market for plastics is packaging, which has been boosted by the growth of mass consumer industries (Geyer, Jambeck, and Law 2017).

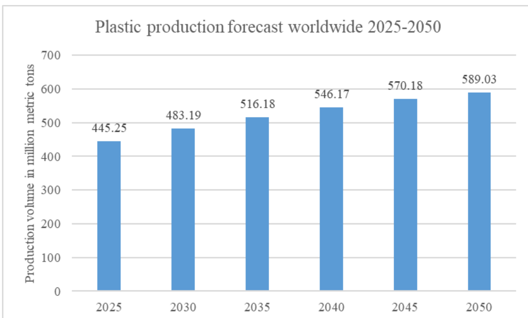

Figure 1: Plastic Production Forecast Worldwide 2025–2050
Source: Statista Research Department 2023a

Glass packaging is pressure resistant, impermeable, and easy to sterilize; in addition, it is of higher quality and weight than other materials (Balzarotti et al. 2015; Boutros, Saba, and Manneh 2021; Ferrara and De Feo 2020). In 2019, there was evidence of global life-cycle emissions of glass totaling to 860 Mt of CO_2e (Statista Research Department 2021a). In addition, global production of glass containers and bottles amounted to nearly 743 billion units in 2023, and it is forecast to rise to around 916 billion units by 2028 (Statista Research Department 2023c) (Figure 2). On the other hand, it is important to consider that it is an easily recyclable material, with a high recycling rate of around 70 percent in Europe (Vasilaki et al. 2016). Therefore, consumers reject plastic packaging because they perceive glass packaging to be more sustainable and have a minimal negative impact on the environment. However, they do not evaluate the impact over its entire life cycle (Ferrara, De Feo, and Picone 2021; Ferrara and De Feo 2020; Golub, Sanzharovskii, and Mikhailidi 2022).

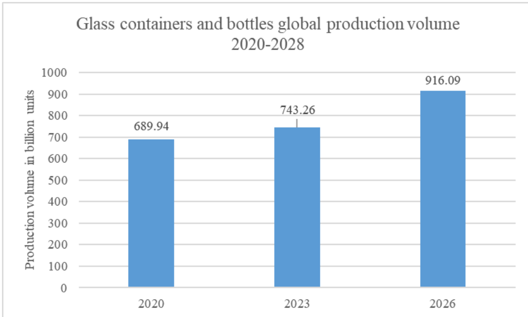

Figure 2: Glass Containers and Bottles Global Production Forecast Worldwide 2020–2028
Source: Statista Research Department 2023c

The objective of this study is to quantitatively analyze the environmental impact of primary packaging materials used in the beverage industry, comparing glass and polyethylene terephthalate (PET) plastic. The study will test the following hypothesis: PET plastic bottles have a greater environmental impact than glass bottles throughout their life cycle at the stages considered.

Theoretical Framework

The life cycle of a product or service is defined as "consecutive and interlinked stages of a product (or service) system, from raw material acquisition or generation from natural resources to final disposal" (Bittrich, Ruiz, and Larios-Francia 2022; ISO 2016).

The LCA is an environmental management technique that assesses environmental impacts throughout a product's life cycle in four phases: objective and scope definition, inventory analysis, environmental impact, and interpretation of results (ISO 2006a, 2006b; Ghinea and Leahu 2017; Rodrigues, König, and Freire 2023).

This study was carried out using a "cradle to grave" approach, so that the boundaries of the study encompassed all stages of the life cycle of primary packaging, from the extraction of raw materials to the disposal of the final product (Coria 2008).

The decision for considering PET plastic and glass bottles was based on the fact that both materials had the highest share of the global packaging mix in 2022. In the global beverage packaging industry, there is evidence of a preference for the use of PET and glass bottles, which represent 30.7 percent and 23.4 percent, respectively, with cans, tetra pack cartons, and other containers also in the market (Statista Research Department 2023a) (Figure 3).

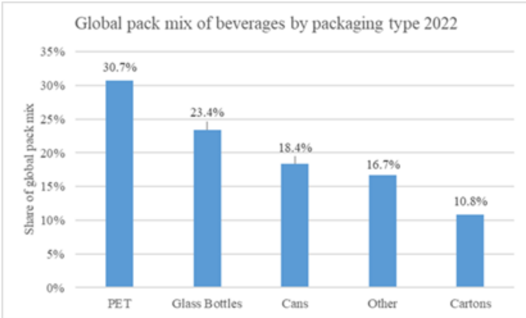

Figure 3: Global Beverage Pack Mix by Packaging Type in 2022
Source: Statista Research Department 2023a

Life Cycle of PET Plastic Bottles

Every stage of the life cycle of PET plastic bottles is a contributor to climate change and environmental degradation (Statista Research Department 2021b). It starts with the extraction of raw materials for production. At this stage, fossil fuels are used, mainly oil and gas, which can affect ecosystems and the life within them (Brock and Williams 2020; Statista Research Department 2021b). The main impacts are the emission of petroleum hydrocarbon gases into the atmosphere and the consumption of hydroelectric energy loads in the surrounding processes, which lead, respectively, to the depletion of the ozone layer and a high generation of solid waste (Brock and Williams 2020).

During the production phase, nitrogen oxides and sulfur dioxide are emitted, which affects the environment and the respiration of living organisms and causes aquatic and terrestrial acidification (Boutros, Saba, and Manneh 2021; Stefanini et al. 2021). The aforementioned effects result in an impact that is equivalent to 379 ng of abiotic depletion potential at the production stage (Mannheim 2021). A lot of energy is needed to get to the production stage, 50 percent of which is used in the extrusion process (Vargas et al. 2015). In addition, it reduces the quality of life and affects the health of people, who, over time, begin to become aware of the impact of the entire bottle life cycle (Badowska-Witos 2020).

Finally, in terms of waste management stage, the present techniques for disposing of PET bottles include landfill, incineration, and recycling via mechanical and chemical treatment (Thew et al. 2023).

The PET recycling process in the biotechnology industry typically consists of three primary stages: sterilization, fermentation, and product purification (Zhou et al. 2024). During the initial stages, sterilization and fermentation necessitate considerable energy and fresh water consumption (Yu, Wu, and Chen 2019). As a result of terephthalic acid purification, the resultant effluent contains at least 0.609 kg of NaCl per kg of PET degradation, leading to secondary pollution and resource wastage owing to acidification (Zhou et al. 2024). Furthermore, it has been noted that PET plastic bottles have very limited recyclability because they are made of polymer chains that shorten each time they are recycled (Brock and Williams 2020), which means that only 20 percent of the PET plastic produced in the world can be recycled (Boutros, Saba, and Manneh 2021).

On the other hand, bottle waste ends up polluting ecosystems because it takes thousands of years to decompose. Looking at plastic bottles alone, they decompose in about 450 years (Statista Research Department 2021b; Stefanini et al. 2021). Approximately 40 percent of the plastics produced ends up in landfills (Boutros, Saba, and Manneh 2021), where, it is estimated, between 7.2 and 14.1 Mt of plastic waste are disposed of (Badowska-Witos 2020).

The final alternative is incineration, which accounts for the disposal of 2 percent to 25 percent of all municipal solid waste and will continue to grow due to the high demand for this type of product from beverage producers (Olatunbosun, Emeka, and James 2016). It generates an eco-toxicity impact on the planet's flora and fauna of 102 ng on a scale of 400, as calculated by the GaBi 9.5 software (Mannheim 2021).

Life Cycle of Glass Bottles

The distribution of raw materials used in the production of glass bottles is 63 percent silica sand, 14 percent sodium carbonate, 7 percent limestone, and 1 percent aluminum oxide, among others (Boutros, Saba, and Manneh 2021; Statista Research Department 2021a). During the silica sand melting process, furnaces require high temperatures to reach the melting point of 1,700°C, resulting in high energy consumption and greenhouse gas emissions (Stefanini et al. 2021). The manufacturing process requires the use of fossil fuels and nonrenewable energy due to the large amounts of energy required in the process (Boutros, Saba, and Manneh 2021; Ferrara and De Feo 2020). The greenhouse gas emissions resulting from the production of glass bottles are relatively high, measuring 0.38 CO_2eq (Vasilaki et al. 2016). This causes deterioration of the respiratory system, which is affected by silica sand and other heavy metals (Saleh 2016).

The manufacturing stage has a high potential for ozone depletion through the emission of methane and carbon dioxide, which contributes to climate change (Boutros, Saba, and Manneh 2021; Stefanini et al. 2021). Water and soil are affected by aquatic and terrestrial acidification caused by emissions of acidifying gases (sulfur dioxide and nitrogen oxides) (Boutros, Saba, and Manneh 2021; Stefanini et al. 2021). The health of the population is also altered in this phase, since it has high percentages of carcinogenic categories, caused by the increase in radiation in the soil and the release of arsenic accompanied by aromatic hydrocarbons (Boutros, Saba, and Manneh 2021; Stefanini et al. 2021).

In waste management, glass bottles display greater efficiency and recycling rates than other materials (Ferrara and De Feo 2023). In Italy, the approximate percentages for each scenario are as follows: incineration of glass amounts to 0 percent, while landfill disposal stands at 23 percent and recycling accounts for 77 percent (Ferrara and De Feo 2020; Stefanini et al. 2021). Bottle recycling symbolizes an energy saving of around 83 percent, as the production of 1 t of glass bottles from recycled glass waste requires 1.27 GJ of energy compared with 7.33 GJ when using virgin sources (Saleh 2016). Nonetheless, recycling incurs substantial energy usage for melting and shaping glass (Landi, Germani, and Marconi 2019).

Glass bottles can be reused, resulting in a 40 percent reduction in environmental impact per single reuse, with an average of six reuses per bottle (Amienyo, Camilleri, and Azapagic 2014; Ferrara, De Feo, and Picone 2021). However, sterilization and washing during the reuse have a significant environmental impact due to the use of hot water, caustic soda, fuel, electricity, and chemicals (Cleary 2013; Ferrara, De Feo, and Picone 2021; Landi, Germani, and Marconi 2019).

Impacts of the Life Cycle of PET Plastic Bottles

The following is a summary of the environmental impacts identified in the life cycle of PET plastic bottles, taking into account the literature review of life-cycle studies (Table 1).

Table 1: Summary of the Impacts of the Life Cycle of PET Plastic Bottles

Phases	*Components*	*Impacts*	*Sources*
Extraction	Abiotic	Depletion of the ozone layer due to high consumption of hydroelectric power Contribution to global warming Atmospheric pollution caused by the emission of petroleum hydrocarbon gases Deterioration of the landscape	Brock and Williams (2020), Statista Research Department (2021b)
	Biotic	Deterioration of natural habitats	
	Anthropic	Risk of respiratory disease	
Production	Abiotic	Depletion of the ozone layer through the emission of greenhouse gases such as methane and carbon dioxide Consumption of energy resources Emission of greenhouse gases	Badowska-Witos (2020), Mannheim (2021), Boutros, Saba, and Manneh (2021), Stefanini et al. (2021).
	Biotic	Aquatic and terrestrial acidification caused by emissions of acidifying gases	
	Anthropic	Reduction in the quality of life Risk of respiratory diseases due to nitrogen and sulfur dioxide emissions	

Waste Management	Abiotic	Contribution to global warming Release of gases from waste incineration Consumption of energy resources	Olatunbosun, Emeka, and James (2016), Brock and Williams (2020), Boutros, Saba, and Manneh (2021), Stefanini et al. (2021), Badowska-Witos (2020), Mannheim (2021), Statista Research Department (2021b).
	Biotic	Deterioration of ecosystems due to excess solid waste generated Eco-toxicity for flora and fauna	
	Anthropic	Deterioration of human health Recycling disabled by materials that cannot be reused	

Impacts of the Life Cycle of Glass Bottles

The following is a summary of the environmental impacts identified in the life cycle of glass bottles, taking into account the literature review of life-cycle studies (Table 2).

Table 2: Summary of the Impacts of the Life Cycle of Glass Bottles

Phases	*Components*	*Impacts*	*Sources*
Extraction	Abiotic	Atmospheric pollution produced by the requirement of large amounts of energy Deterioration of landscapes Eco-toxicity of soils due to the release of ions	Saleh (2016), Vasilaki et al. (2016), Ferrara and De Feo (2020), Boutros, Saba, and Manneh (2021), Statista Research Department (2021a), Stefanini et al. (2021).
	Biotic	Alteration of flora and fauna habitats Alteration of ecosystems	
	Anthropic	Deterioration of health Respiratory system affected by silica sand and other heavy metals	
Production	Abiotic	Depletion of the ozone layer due to emissions of greenhouse gases such as methane and carbon dioxide Aquatic and terrestrial acidification due to emissions of acidifying gases Consumption of water resources	Boutros, Saba, and Manneh (2021), Stefanini et al. (2021).
	Biotic	Alteration of flora and fauna habitat	
	Anthropic	Deterioration of human health due to increased radiation from the earth and release of arsenic	

Waste Management	Abiotic	Use of resources in the sterilization and washing processes Contribution to global warming	Cleary (2013), Saleh (2016), Amienyo, Camilleri, and Azapagic (2014), Landi, Germani, and Marconi (2019), Ferrara, De Feo, and Picone (2021), Stefanini et al. (2021), Ferrara and De Feo (2023).
	Biotic	Alteration of ecosystems Accumulation of glass bottles in ecosystems	
	Anthropic	Deterioration of human and animal health	

Materials and Methods

The environmental LCA of primary beverage packaging was developed using the cause–effect matrix methodology "Leopold Matrix." In order to identify the environmental impacts and the importance of various actions in the life cycle of PET and glass bottles, a systematic literature review method was used.

Articles from indexed academic journals published in the following databases were identified as sources of information: Scopus, ProQuest, and Web of Science. In addition, several inclusion and exclusion criteria were defined for the studies: they should be less than 6 years old, written in English or Spanish, and open access (Figure 4).

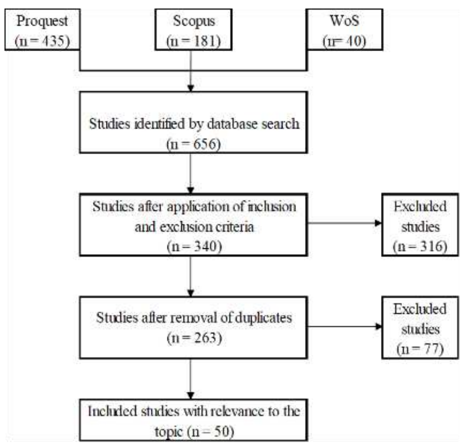

Figure 4: Prisma Flowchart

The search strategy for each material was as follows: for PET plastic bottles, the operator (("plastic bottle" OR "botella de plástico" OR "PET bottle") AND ("LCA" OR "life cycle assessment" OR "análisis del ciclo de vida") AND ("environmental impacts" OR "impactos ambientales")), and for glass bottles, the operator (("glass bottle" OR "botella de vidrio")

AND ("LCA" OR "life cycle assessment" OR "análisis del ciclo de vida") AND ("environmental impacts" OR "impactos ambientales")).

Once the review was complete, fifty articles were included and analyzed to develop the Leopold Matrix. This methodology uses two types of matrices in successive stages of analysis: (1) the matrix for the identification of environmental impacts based on the relationship between the LCA phases and the factors to be evaluated and (2) the importance matrix as a first qualitative assessment of the identified environmental impacts on the different environmental factors. The Leopold Matrix allows an assessment of both the aggressiveness of the activity and the environmental factors that are affected by the activity (Coria 2008). It is used to quantitatively measure the environmental impact of each material, taking into account environmental factors at specific stages of the bottles' life cycle (Bittrich, Ruiz, and Larios-Francia 2022).

This double-entry matrix has the components with their environmental impacts in the rows and the stages in the columns (Coria 2008). If there is an interaction between row and column, the box is divided into two by a diagonal line. For the upper part, which represents the magnitude of the impact, a number between 1 and 10 is placed, and the sign depends on whether it generates a beneficial (+) or detrimental (–) effect on the environment. For the lower part, a positive value between 1 and 10 is assigned, symbolizing importance. The sum of the interactions makes it possible to obtain the final value for each type of material, which is calculated using an arithmetic formula (Garmendia et al. 2005). The components considered in the matrix are as follows:

1. Abiotic Scope: Emphasis on external conditions; subcomponents to consider are water, atmosphere, landscape, and soil
2. Biotic Scope: Emphasis on environmental impact on flora and fauna
3. Anthropic Scope: Emphasis on health subcomponent

The stages in the life cycle of both materials that have to be taken into account are as follows:

1. Extraction: Emphasis on raw material extraction activities
2. Production: Focus on specific activities in the manufacturing process
3. Waste Management: Focus on the final treatment of products at the end of their life cycle, such as incineration, landfill, reuse, and recycling

Based on the aforementioned components and stages, we can define that the evaluation of each of the interactions was based on the information provided. However, intervals were needed to help us measure both the magnitude of each of the impacts and their relevance for the analysis. Tables 3 and 4 were used for this purpose.

Table 3: Magnitude Rating

Magnitude Rating	*Definition*	*People Exposed*	*Extension*
1	Unlikely	< 5	Specific
3	Possible	5–29	Local
5	Likely	30–59	District
7	Highly likely	60–100	Regional
10	Extremely likely	>100	National

Source: OEFA 2023

Table 4: Importance Rating

Magnitude Rating	*Definition*	*Sensitivity*
1	Nonhazardous	Null
3	Slightly hazardous	Low
5	Moderately hazardous	Medium
7	Hazardous	High
10	Very hazardous	Extreme

Source: OEFA 2023

Results

Taking into account the aforementioned stages and environmental components, the Leopold impact assessment matrices were developed for the life cycles of PET plastic bottles and glass bottles.

Stages of the life cycle			Extraction		Production		Waste management							
Environmental factors / Environmental actions			Blasting and Drilling	Offshore constructions	Resin production	Bottle production	Recycling	Landfill	Incineration	Negative average	Positive average	Arithmetic average	Impact of components	Impact of the product
Environmental components/sub-components		Environmental impacts	Results											
Abiotic	Atmosphere	Quality (gases, particulate matter)	-3/2	-3/2	-3/4	-3/4			-6/6	5	0	-72	-481	-690
		Contribution to climate change					4/8	-6/6	-6/8	2	1	-52		
	Water	Aquatic acidification	-5/4	-5/6	-3/2	-6/6				4	0	-92		
		Water resource consumption								0	0	0		
	Soil	Land acidification	-4/5	-5/5				-7/8	-7/10	4	0	-171		
		Soil quality	-4/4	-4/5			2/3	-6/8		3	1	-78		
	Landscape	Deterioration of landscapes						-4/4		1	0	-16		
Biotic	Flora	Ecosystem alteration					4/6			0	1	24	-139	
		Habitat alteration	-3/3	-3/3			5/6	-5/5	-6/8	4	1	-61		
	Fauna	Ecosystem disturbance		-4/4			5/6			1	1	14		
		Habitat disturbance	-3/3	-3/5			6/6	-8/8	-8/8	4	1	-116		
Antropic	Health	Disease generation	-3/2	-3/2		-3/4		-4/4	-5/6	5	0	-70	-70	
Negative average			7	8	2	3	0	7	6	-690				
Positive average			0	0	0	0	6	0	0					
Arithmetic average			-86	-127	-18	-60	158	-261	-296					

Figure 5: Leopold Matrix for the Life Cycle of PET Plastic Bottle

After the life-cycle impact assessment of the PET plastic bottle, the matrix resulted in an overall score of –690 due to the intersection and analysis of thirty-nine interactions between the environmental factors and the proposed actions. The most prominent component was the abiotic component with a score of –481, resulting from large negative scores attributed to environmental impacts such as water acidification, soil quality variation, and gas emissions—scores of –92, –78, and –72, respectively (Figure 5).

It is worth highlighting the presence of positive results within the matrix related to the biotic factors of PET plastic, where we can see that both fauna and flora ecosystem alterations have benefited from environmental actions such as recycling, as part of the waste management plan.

Stages of the life cycle			Extraction		Production		Waste management							
Environmental factors / Environmental actions			Dredging	Underground and surface excavations	Silica sand fusion	Bottle production	Recycling	Landfill	Incineration	Negative average	Positive average	Arithmetic average	Impact of components	Impact of the product
Environmental components/sub-components		Environmental impacts	Results											
Abiotic	Atmosphere	Quality (gases, particulate matter)			-6/8	-8/8				2	0	-112	-401	-712
		Contribution to climate change				-3/5	6/6	-4/6	6/6	2	2	33		
	Water	Aquatic acidification				-6/7			-2/3	2	0	-48		
		Water resource consumption				-4/6			-2/4	2	0	-32		
	Soil	Land acidification				-6/7		-2/2		2	0	-46		
		Soil quality	-6/6	-6/6				-2/2		3	0	-76		
	Landscape	Deterioration of landscapes	-8/6	-8/6				-6/4		3	0	-120		
Biotic	Flora	Ecosystem alteration	-6/8							1	0	-48	-269	
		Habitat alteration	-5/6	-5/6				-5/5		3	0	-85		
	Fauna	Ecosystem disturbance	-4/6							1	0	-24		
		Habitat disturbance	-4/6	-4/6				-8/8		3	0	-112		
Anthropic	Health	Disease generation			-3/2	-6/6				2	0	-42	-42	
Negative average			6	4	2	6	0	6	2	-712				
Positive average			0	0	0	0	1	0	1					
Arithmetic average			-210	-138	-54	-223	36	-145	22					

Figure 6: Leopold Matrix for the Life Cycle of Glass Bottle

As can be seen, the Leopold Matrix for the life cycle of the glass bottle has a total value of –712, with the highest impacts grouped in the abiotic components, with a value of –401. The main impacts are in two subcomponents: atmospheric quality and landscape degradation, with scores of –112 and –120, respectively. In addition, the biotic component has a value of –269, highlighting the alteration of habitats for both flora (–85) and fauna (–112). Similarly, the production stage has a negative value of 277, with –54 related to the melting of the quartz sand and –223 to the production of the bottle. On the other hand, it is important to note that the recycling and reuse stages have the highest positive scores in the weighted impact calculation, with thirty-six and twenty-two, respectively (Figure 6).

After presenting the results of the LCA through both matrices, the following comparative table was constructed, taking into account the environmental components and interactions exposed in the life cycle of both bottle materials (Table 5).

Table 5: Comparative Table of the Life Cycles of PET Plastic and Glass Bottles

Components	*Definition*	*PET Plastic Bottle LCA*	*Glass Bottle LCA*
Abiotic	Atmosphere	Impact of –124 points was generated by waste management actions.	Glass production was the stage with the largest negative impact, with a value of –79.
	Water	Water used in the production and extraction process generated an impact of –92.	It had an effect of –80 points generated by glass production.
	Soil	Plastics had a significant impact on soil, mainly in the extraction stages, with a score of –249.	It had an impact of –122 points, mainly due to soil contamination.
	Landscape	The value of –16 was the lowest of all the abiotic components and of the table in general.	The value of –120 was the highest of all the abiotic components.
Biotic	Flora	Flora was one of the factors with the lowest impact of all the elements presented, as its negative impact was offset by the recycling measures that could be considered. The values were –37 for plastic and –133 for glass.	
	Fauna	The results were –102 for plastic and –136 for glass.	
Anthropic	Health	For plastic and glass production, the incidence of disease at the extraction (plastic) and production (glass) stages was –70 and –42, respectively.	

Discussion

The results of the environmental impact assessment of the life cycle of primary beverage containers made with PET plastic and glass show that both generate negative environmental impacts throughout their life cycle, taking into account the analysis of abiotic, biotic, and anthropic components. This is demonstrated by the results of the matrices, where the totals symbolize –712 and –690 for glass and PET, respectively. Glass bottles systems had the lowest global performance ratings because of their heavy weight and significant energy consumption during bottle manufacturing (Ferrara et al. 2022). However, studies have shown that the current production of both materials results in an impact on ecosystems and vital resources such as soil and water as a consequence of their acidification (Boutros, Saba, and Manneh 2021; Ferrara and De Feo 2023; Stefanini et al. 2021).

The increase in bottle production has a negative impact on ecosystems, as it is almost impossible for bottles to degrade under natural conditions (Saibuatrong, Cheroennet, and Suwanmanee 2017). Previous studies evidence that, through the circular economy, the environmental impacts of both types of material can be mitigated (Gracida-Alvarez et al. 2023). However, glass bottles, due to their properties, can be reused on average up to six times and fully recovered, mitigating their environmental impacts (Amienyo, Camilleri, and Azapagic 2014; Amienyo and Azapagic 2016; Ferrara, De Feo, and Picone 2021). The global demand for post-consumer recycled resins in packaging for different industries stood at 4.8 Mt in 2021, with a projected increase of up to 6.37 Mt by 2026 (Statista Research Department 2024b).

From the analysis of the production processes of both types of packaging, it was identified that, in the case of PET plastic primary packaging, the negative impact was mainly in processes such as oil extraction, due to the significant emission of greenhouse gases in its production and the presence of macro, micro, and Nano plastics in oceans, forests, and urban regions. It has been reported that more than 8 Mt of plastic enter the oceans each year (Statista Research Department 2021b, 2023b). In the primary packaging of beverages from glass, the negative impact was evident in processes such as the extraction of silica sand and its melting, due to high energy consumption and greenhouse gas emissions, since the furnaces require high temperatures to reach the melting point, around 1,700°C (Stefanini et al. 2021). Additionally, they generate the emission of greenhouse gases such as sulfur dioxide or carbon dioxide, which contributes to the increase in global warming.

The environmental impacts on the planet's flora and fauna are evident. Both processes affect ecosystems and end up generating an eco-toxicity impact for all living beings, who are, thus, destined to a possible development of diseases in the process (Mannheim 2021). The results show that many animals in different ecosystems die of starvation or intoxication when mistaking pieces of plastic for food, highlighting that nine out of ten seabirds contain plastic in their stomachs (Statista Research Department 2021b, 2023b).

Public health is also affected by the life cycle of both types of primary packaging. PET plastic products have been linked to increased risk of illness and decreased quality of life, such as respiratory issues in production workers (Badowska-Witos 2020; Jahandari 2023).

Furthermore, micro plastic, which can range in size from 1 µm to 5 mm, is capable of passing through human cell walls, and inhalation is the main pathway for airborne plastic particles (Statista Research Department 2021b; Kutralam-Muniasamy et al. 2023; Jahandari 2023). In the glass packaging manufacture phase, the respiratory system is affected by silica sand and other heavy metals (Saleh 2016). In addition, it has carcinogenic categories with high percentages originating from radiation in the soil and the release of arsenic accompanied by aromatic hydrocarbons (Boutros, Saba, and Manneh 2021; Stefanini et al. 2021).

Therefore, it is recommended to promote an exhaustive analysis of the materials currently used for the production of primary packaging, such as for bottles used in different industries, in order to find a solution that can provide economic, social, and environmental benefits in the short term. These materials should be adjusted to meet sustainability requirements and the needs of the market and companies. In the industry there is evidence of packaging developments from fibrillated Nano cellulose, a very promising material for the environment and with a wide range of applications due to its strong mechanical properties and high specific surface area (Bittrich, Ruiz, and Larios-Francia 2022; Jin et al. 2020; Kim, Youn, and Lee 2015). Likewise, packaging from starch films, a material that has the ability to form naturally and is highly renewable (Żołek-Tryznowska and Holica 2020).

Improving the current production and recycling methods for both materials is imperative to optimize resources and minimize ecological impact. Therefore, it is crucial to advance research and technological development in this field. For instance, in 2020, South Korea produced roughly 560,000 t of waste glass bottles, with a reported recycling rate of 76.8 percent. Nevertheless, compared with countries such as Germany and Japan, with their advanced recycling infrastructure and policies, the rate falls approximately 10 percent short (Lee, Kim, and Lee 2023).

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Informed Consent

The authors obtained informed consent from all participants.

Conflict of Interest

The authors declare that there is no conflict of interest.

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