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“Life Cycle Assessment of beverage packaging systems: A case study for Mexico.”

A dissertation presented by

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Abstract

As companies from the manufacturing sector define their sustainability strategy to meet global, national and internal goals, the need for reliable scientific data related to their environmental footprint, which supports decision making, has become more critical in the last years. The Mexican beverage industry has a significant weight in the national economy. By 2019 this industry was responsible for 1.9% of national GDP and was a source of employment for more than 1.5 million people. Although most of the largest companies track their environmental footprint and publish them in sustainability reports, there is no data related to far-reaching sustainability assessment such as Life Cycle Assessment (LCA). This work presents the implementation of an environmental LCA for four different packaging systems used by Mexican beverage companies (Non-returnable PET, refillable PET, refillable glass bottles and aluminium cans). This study includes a comprehensive literature review to know the tendencies, novelties and main results obtained with the execution of LCA for beverage packaging systems. The literature review allowed the identification of similar studies to this work which made it possible to compare and validate the results obtained. The LCA study considered the raw materials extraction, packaging manufacture, finished product manufacture, distribution, retail, washing and end-of-life stages. The goals of this LCA were: i) to determine and compare the environmental impacts generated by four beverage packaging systems offered in Mexico from a cradle-to-grave scope and ii) to identify the Hot Spots of each packaging system. Data inventory was built by using the ECOINVENT database, peer-reviewed publications and public data from industry. This study executed CML, AWARE and Cumulative Energy Demand impact assessments. The results of the study revealed that the NRPET bottle has the best environmental performance since it has a GWP of 174.45 kg CO_2eq while RGB has the worst performance with 1152.95 kg CO_2eq when considering a single life cycle. On the contrary, if evaluating multiple cycles, the REFPET system performed better since the average GWP per cycle is 50.26 45 kg CO_2eq if the packaging last at least 15 cycles. Moreover, the packaging manufacture stage is the most significant contributor for GWP and WF. The results intend: i) to provide scientific-based data for the beverage industry stakeholders, ii) to make possible a better understanding of their environmental footprint and iii) to lead decision-making based on Life Cycle Thinking. Finally, recommendations were set to enable beverage companies to reinforce or adapt their sustainability policy in other for them to achieve a sustainable supply chain.

Keywords: Sustainability strategy, life cycle assessment, beverage industry, sustainable supply chain, circular economy, Mexico, packaging materials.

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NOMENCLATURE / ABBREVIATIONS

Al-CAN	Aluminium can
ANPRAC	Asociación Nacional de Productores de Refrescos y Aguas Carbonatadas A.C.
CE	Circular economy
CED	Cumulative energy demand
CS	Corporate Sustainability
EoL	End of life
FU	Functional unit
GWP	Global warming potential
IA	Impact Assessment
IC	Impact category
ISO	International Organization for Standardization
LCA	Life cycle assessment
MSW	Municipal Solid Waste
NRPET	Non-refillable PET system
REFPET	Refillable PET system
RGB	Refillable glass bottle
SDG	Sustainable development goals
UN	United Nations
UNIDO	United Nations Industrial Development Organization
WF	Water Footprint

Section 1: Introduction

1.1 Manufacturing and Sustainability

1.1.1 Relevance of Manufacture

The manufacturing industry has become one of the essential pillars for economic development (Rocha, 2018) since it can lead to structural changes and transform low productive systems into highly productive ones.

In contrast with other industries, the manufacturing sector can generate value through the whole life cycle of the products as the ones offered by the service sectors. Furthermore, nations capabilities to adopt technological changes will determine their economic development (Haraguchi et al., 2017).

The specific benefits that manufacturing brings to society resume in four as described in the framework proposed by the United Nations Industrial Development Organization (UNIDO, 2017): i) increase in discretionary income, ii) decline in prices of massified goods, iii) diversification of manufacturing demand, and iv) massification of manufacturing demand.

At the same time, each benefit links with the others, creating a virtuous circle. The circle detonates by the massification of the goods demanded by the market. In the first instance, these goods are essential products but become more complex due to technological development.

Massification of products reduces production costs derived from the effect of the economies of scale. A decrease in prices leads to an increase in the purchasing power of final consumers. Moreover, an increase in sales leads to a rise in the company's revenue and salaries.

As mentioned previously, technological adoption and development are essential for economic thrive. As every nation has different capabilities, manufacturing industries based in each country varies significantly.

In the case of middle and upper-middle-income economies, since they have a greater capacity to invest in technology, manufacturing is more oriented towards producing technology-based goods. Despite this condition, these economies face a transition where they balance labour-based manufacturing and technology-based manufacturing.

In contrast, low-income nations have labour-based manufacturing, which requires large amounts of labour instead of capital, such as the food and beverage sector, textiles, essential chemical production, cement (Haraguchi et al., 2017).

For the particular case of the food and beverage sector, production strongly relates to local demand generated by the same population of the country. This condition occurs in every country besides its income level. Consequently, there is a significant parity of growth between the food and beverage industry and the national economy. Moreover, this sector has a very high potential in generating employment, as reported by (Haraguchi et al., 2017). Therefore, this sector is a key to the economic and inclusive growth of nations.

In the last 25 years, the manufacturing industry has contributed to economic growth worldwide and maintains its place as a lever for development, especially in low and middle-income countries such as some of the countries in the Latin America region (Haraguchi & Kitaoka, 2015). Although the value added to manufacturing and the number of jobs has decreased, this sector has maintained sustained growth and held its share as part of the global GDP (UNIDO, 2018).

1.1.2 The transition into sustainable businesses

Since 2015 all sectors from society have had the challenge to contribute to accomplishing the 17 Sustainable Development Goals (SDGs) defined in the 2030 Agenda. It was approved by the member states of the United Nations (UN) and a period of 15 years was set to achieve the targets of each SDG and to “Transform our world” (United Nations, 2015).

After six years from the launch of the Agenda, the speed and the impact of the results are far from the expected. Hence, in 2019 global leaders made a call for a “Decade of Action” where all stakeholders should work harder to achieve SDG within the ten years left (UN, 2019). In addition, as the world faces the COVID-19 pandemic, the efforts and advantages to transit to a sustainable way of life are even more critical and challenging than in past years (Filho et al., 2020; Mejia et al., 2020).

To transit to sustainability, it is indispensable to design alternative models to the traditional capitalist economic system. Many alternative models have been proposed and set the line to adapt the existent model through the last decade, as described next:

A) Doughnut Economics: This framework was presented by Kate Raworth in 2013. The framework is based on a simple but powerful statement “meeting the needs of all people within the means of the living planet” (Raworth, K. 2017). Essentially, the message is similar to the sustainable development definition given on the Brundtland Report in the 80’s, which describes it as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, H. 1987). The importance of a framework such as Doughnuts Economics is not just the statement but the innovative alternatives given by the author.

The framework is based on “Seven ways to think” how a sustainable economy should be. At a macroeconomic level, these “seven ways” call for three main changes:

I. Make economy useful for everyone - Instead of pursuing limited economic growth, what is needed is to meet people's needs within ecological limits.

II. Design to distribute - Let the market fix inequality and environmental problems shouldn’t be the standard. Instead, economies should be distributive since the beginning.

III. Create to generate - Change our production and consumption product to create a system where the waste of a process is the feedstock for others.

Doughnut economics give a macro level and global scale vision of what is needed to do. However, the author calls all social actors to develop the tools, system, and roadmap to make possible the idea. As was mentioned previously, Sustainable Development Goals are the global roadmap. While SDGs were not explicitly designed for industries, every company shall include innovation and strategy processes to contribute to all the goals.

In the same line, there is a wide range of opportunities for businesses to contribute and make a profit from it. Specifically for the manufacturing industry UN Global Compact in collaboration with KPGM, published the SDG Industry Matrix (UN Global Compact. et al., 2015). This document intends to guide any manufacturing company to know the opportunities and the main actions they can introduce in the business model for each of the 17 SGDs. Another critical document is the SDG Compass (GRI. et al., 2015), which encourages the business sector to change and adopt SDGs as a core business strategy.

B) Corporate sustainability (CS): This approach is the base for any company to succeed in the transition from business as usual to sustainable business. CS is about creating value, not just for the shareholders as in the business as usual, but to create economic, social and environmental value for all the company's stakeholders.

Companies introduce corporate sustainability through three main pillars: Environmental, Social, and Governance (ESG). In the recent years, strategy has become the fourth pillar of CS since it is crucial for companies to transit into sustainability while making profits and reducing the risk of a failed transition.

According to The Business Case for Sustainability proposed by Gilbert Hedstrom (Hedstrom. G, 2018), companies from any sector should concentrate on four main actions: growing revenue, enhancing the brand, reducing costs, and reducing risks. Some of these actions can be carried out in the short term and are mainly in the company's control. On the other hand, some steps should be considered long-term projects and have less direct control of the company to make it happen.

C) Life Cycle Assessment (LCA): The transition to sustainability needs a far-reach vision and a well-defined strategy as it was exposed. Companies need Tools, Initiatives and Approaches (TIA) to drive the change systematically. A broad range of TIAs have been put in practice in the last decade with different scopes, which allow organizations to quantify economic, environmental and social footprint and, in some cases delimiting by time as a determinant variable (Lozano, 2020). Recently, there has been a need to focus sustainability strategy on a systemic and broader vision at the business level rather than the business-as-usual internal level (Hedstrom, 2018; Silvestre & Fonseca, 2020).

For companies to adopt LCA, James Fava proposed the Sustainability Framework supported by Life Cycle Thinking and Approaches (Fava, 2011). Fava´s framework established levels of how companies adopt LCT by certain groups of maturity. As can be noticed notice in ***Figure 1***, depending on the level of maturity, the company carries on different programs and activities as the new business as usual as follows:

I. At the base of the pyramid or the equivalent of a company with an early level of maturity, companies only measure internal environmental data such as water consumption, energy demand.

II. In the next level, companies gather data from the whole supply chain and perform different LC assessments such as the environmental, social or cost life cycle.

III. In a different level of maturity, companies use the results of LCA to design internal sustainability policies or launch multi-stakeholder projects through the value chain.

IV. At the fourth level of maturity, organizations adopt Life Cycle Thinking (LCT) as the business as usual.

V. Finally, at the top, we have companies that reach sustainability according to the LCT approach.

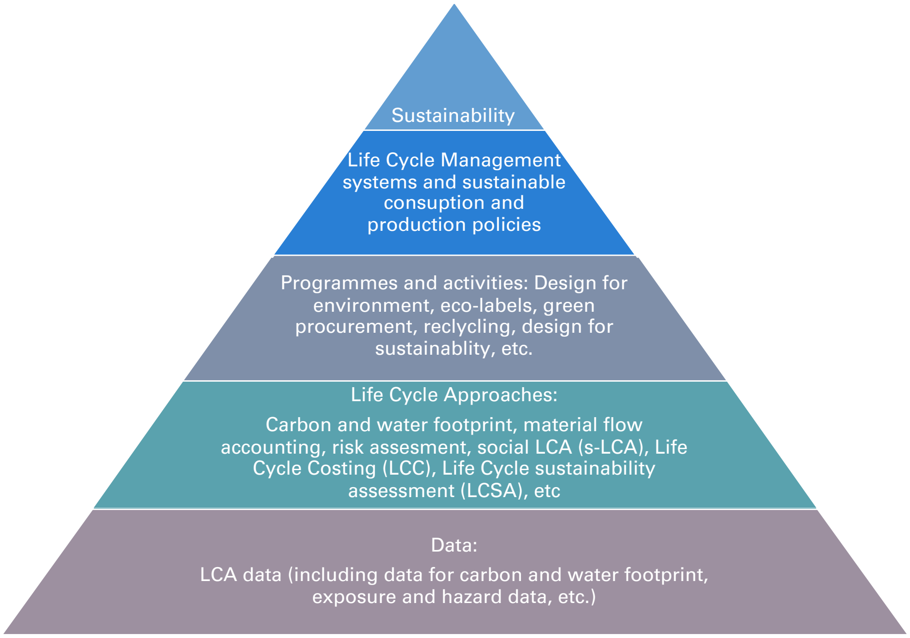


Figure 1: Sustainability Framework supported by Life Cycle Thinking and Approaches. Source from: (Fava, 2011)

Companies' transition to sustainability requires a genuine change in the mindset of how businesses are managed. Incorporation of Life Cycle Thinking (LCT) in the industry can help companies identify and improve their environmental impact through the whole supply chain. However, successful adoption of LCT requires the will and have people with technical knowledge and leadership within the business.

1.2 Problem rationale, objective and scope

As mentioned previously, many actions are needed to make possible the transition to sustainability. The lack of scientific-based data related to the environmental impacts generated by the manufacturing sector is the most urgent problem to be solved. This situation hinders companies' decision-making process to move towards a more sustainable supply chain model since they do not have the necessary data to compare and determine if the strategies will positively affect the business strategy.

Nowadays, the beverage industry faces different challenges in terms of its environmental performance. As is described in Section 2, the main issues faced by the beverage industry are water scarcity and waste management. Furthermore, since there is not an established national level strategy in Mexico that intends to overcome those problems, single private and local efforts should be made to overcome those problems.

Improving the environmental performance of the beverage industry is even more relevant due to its significant contribution to the national economy and because it is a source of employment for several people (ANPRAC, 2020).

This research aims to deeply analyze and evaluate the environmental impacts of the packaging systems used in different products offered by the Mexican beverage industry. Consequently, LCA methodology was used to determine and compare the environmental impacts generated by four beverage packaging systems offered in Mexico and answer the following research questions:

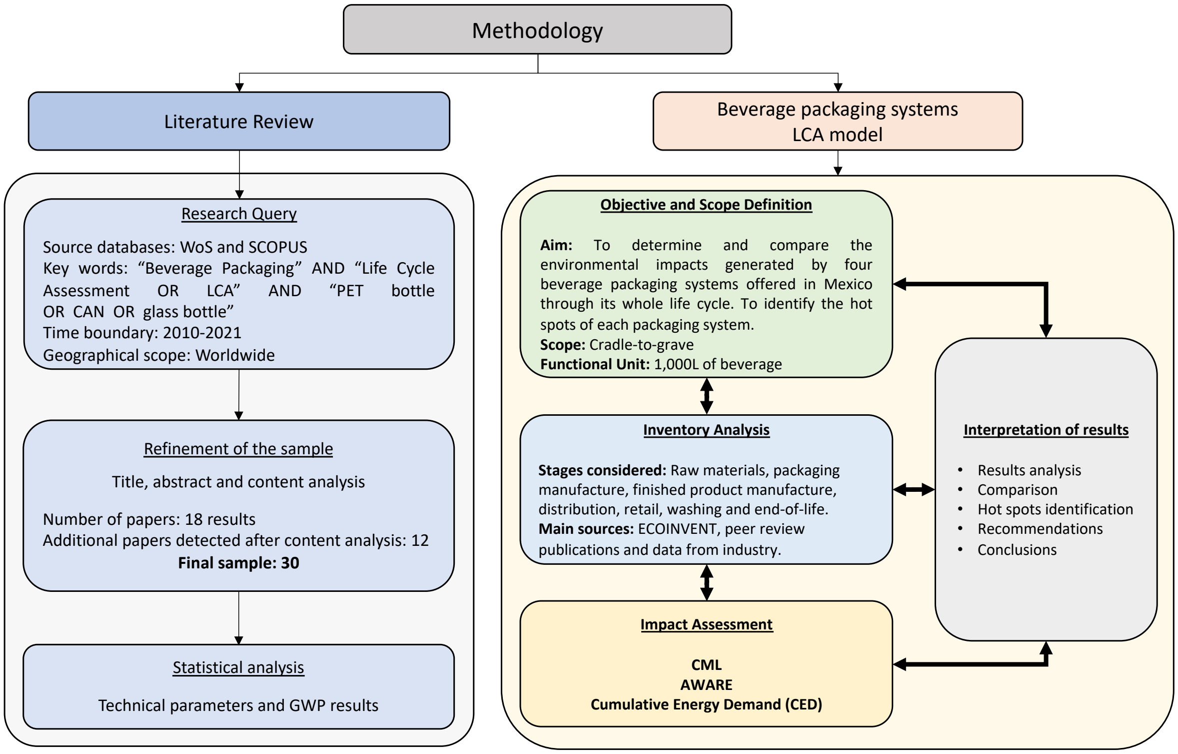
1. Which is the environmental impact of the selected packaging systems from a cradle-to-grave scope?
2. Which packaging system has the best environmental performance?
3. Which are the hot spots in the beverage industry supply chain?
4. Which are the recommendations to improve environmental performance?

The methodology followed to carry out his work is divided in two main sections:

i) Literature review
ii) LCA of beverage packaging systems, based on the ISO framework 14040-44 (ISO, 2006a; ISO, 2006b)

This methodology allows a broader vision of the impacts generated by the selected packaging systems since comparing the Mexican case and international results is possible. A graphical representation of the methodology can be seen in ***Figure 2***.

The relevance to carry out this study is to provide a recent and broader picture regarding the impacts of the beverage industry. Finally, the results of this study intend to lead to corporate and public scientific-based decision-making based on Life Cycle Thinking to enable beverage companies can better understand their environmental impact and reinforce or adapt their sustainability policy to achieve a sustainable supply chain.



Source databases: WoS and SCOPUS
Key words: “Beverage Packaging” AND “Life Cycle Assessment OR LCA” AND “PET bottle OR CAN OR glass bottle”
Time boundary: 2010-2021
Geographical scope: Worldwide

Title, abstract and content analysis

Number of papers: 18 results
Additional papers detected after content analysis: 12
Final sample: 30

Technical parameters and GWP results

Aim: To determine and compare the environmental impacts generated by four beverage packaging systems offered in Mexico through its whole life cycle. To identify the hot spots of each packaging system.
Scope: Cradle-to-grave
Functional Unit: 1,000L of beverage

Stages considered: Raw materials, packaging manufacture, finished product manufacture, distribution, retail, washing and end-of-life.
Main sources: ECOINVENT, peer review publications and data from industry.

CML
AWARE
Cumulative Energy Demand (CED)

- Results analysis
- Comparison
- Hot spots identification
- Recommendations
- Conclusions

Figure 2: Graphical representation for the methodology followed by this study. Own elaboration based on Santoyo-Castelazo et al. (2021).

Section 2: The Mexican beverage industry

Since the enactment of the North America Free Trade Agreement (NAFTA) in 1994, the Mexican beverage industry has been classified as part of the manufacturing sector. According to the North American Industrial Classification System (NAICS)**,** there are two sectors within this industry (INEGI, 2018a), which are: the production of Non-Alcoholic Beverages (NAB) and the production of Alcoholic Beverages (AB). ***Figure 3*** describes the composition of the beverage industry.

Companies involved in the NAB sector mainly produce carbonated beverages and water purification and bottling (either by filtration, pasteurization or reverse osmosis) and ice production. Other products within this same sector include hydrating, energy, flavoured drinks, non-alcoholic beverages, and water purification.

On the other hand, companies that belong to the AB sector comprise the production of beer, wineries and distilleries and in the obtention of ethyl alcohol for human and industrial consumption.

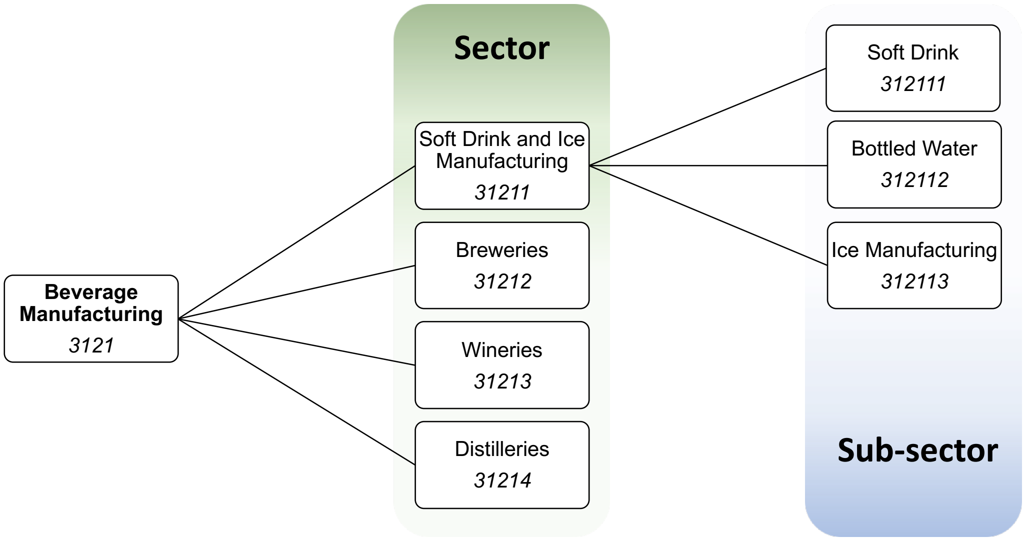


Figure 3: Beverage industry classification according to NAICS. Adapted from: INEGI (2018a)

2.1 Economic contribution

The beverage industry supply chain is divided into three stages, which is presented in ***Figure 4***:

i) Upstream: This stage covers the activities carried out by beverage companies' suppliers. As in almost every industry, the first activity is virgin raw materials extraction (oil, aluminium, silica sand, etc.). The second step in the supply chain is the transformation of raw materials into key materials for the industry, such as PET resin, glass, cardboard, etc. After obtaining key materials, the packaging manufacture is done to produce valuable products for the beverage companies such as bottles, caps, labels or plastic crates. Finally, the delivery of these products to the bottling company.

ii) On-site: The second stage happens within the bottling companies' boundaries. These activities generally encompass the manufacture of the finished product, its distribution, storage, and sale to retail customers.

iii) Downstream: The third stage covers the retail of the products, the consumption and the final disposal (landfill, incineration, etc.) or recovery of waste (reuse, recycling, etc.)

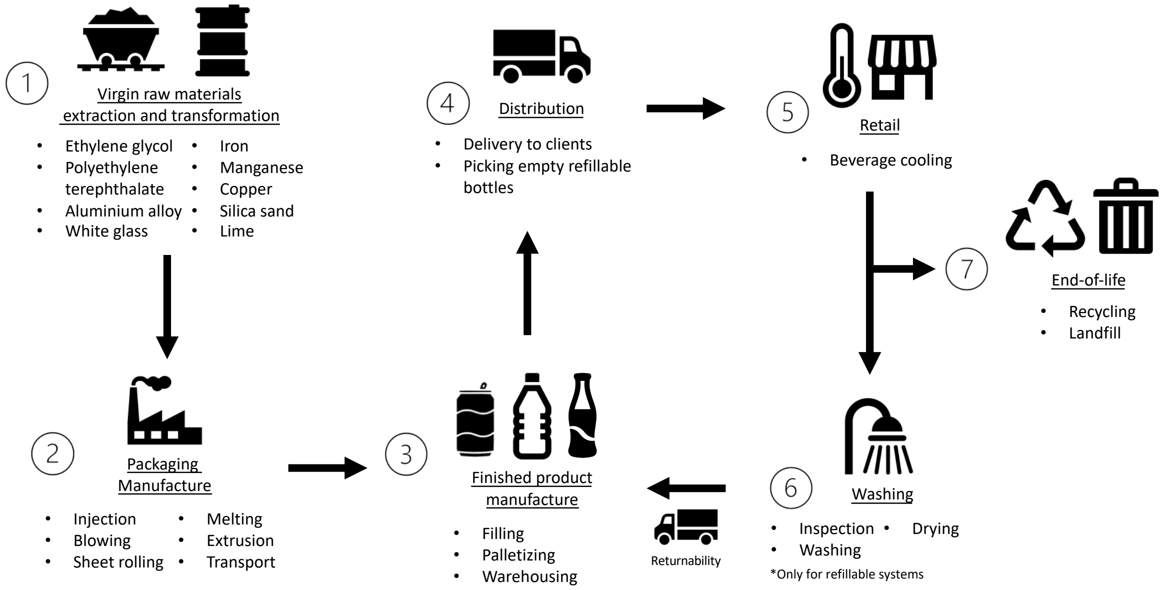


Figure 4: Beverage industry supply chain. Own elaborated with data from [KOF, 2021]

This industry has a crucial impact on the national economy. By 2019, according to data reported in the Monthly Survey of the Manufacturing Industry (MSMI), the value of the production of this industry represents a total of $485.01 billion Mexican pesos [MXN] (constant 2013 LUC). That amount represents approximately 1.9% of the national GDP, while that exact figure represents 6.01% of the entire manufacturing sector's value (INEGI, 2020).

With the same data from the MSMI, it can be determined that the two sub-sectors which generate the most outstanding economic value are the Manufacture of soft drinks and other non-alcoholic beverages with 45% of the total or a weight of $219.84 MXN billion (constant 2013 LUC) and brewing with 38% or a value of $185.17 MXN billions (constant 2013 LUC). ***Figure 5*** details the market share of each sector.

The beverage industry has seasonal sales behaviour, as is represented in ***Figure 6***. It has a high season between May and August and a low season from December to February. The figure shows a clear growth trend for soft drinks, distilled agave beverages and brewery sub-sectors, while the rest do not have significant increases.

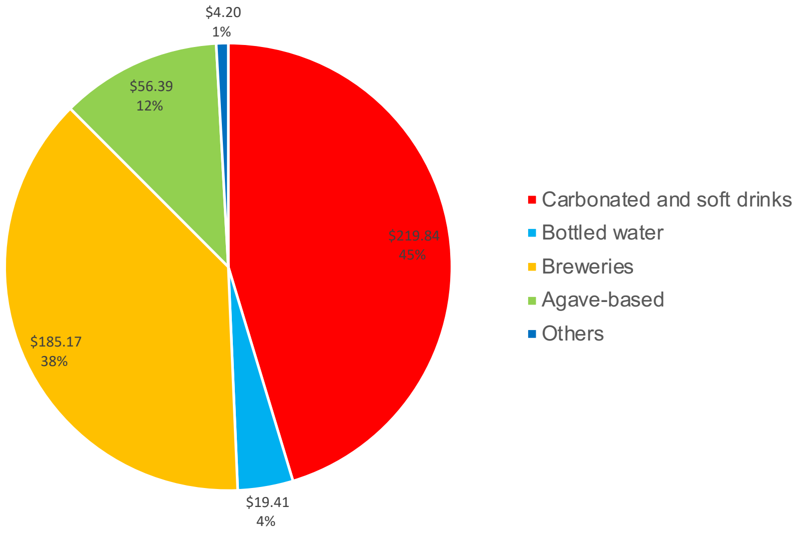


Figure 5: Mexican Beverage Market Share by category in 2019. Own elaborated with data from INEGI (2020). Figures in billions Mexican Pesos (constant 2013 LUC)

Within Mexican households, products from the beverage industry are among the primary sources of expenditures. The annual average household expenditure represented 2.8% by 2018, according to the National Survey of Household Income and Expenditure (INEGI, 2018b), which is equivalent to a total of $ 105.56 MXN billions (constant 2013 LUC) and accounts for approximately 24.54% of the sales of the entire industry.

As stated previously, the Mexican beverage industry represents an essential source of employment. According to data from the National Association of Producers of Soft Drinks and Carbonated Waters, in 2018, this industry was a source of employment for an annual average of 1,630,287 people, which considers either direct or indirect jobs (ANPRAC, 2020).

2.2 Packaging for the beverage industry

There is a very particular phenomenon in the beverage industry since the entire product portfolio depends entirely on its packaging. Without some sort of packaging, the product could not be distributed or even consumed. This relationship between packaging and product, called Product-Packaging Combination (Koeijer et al., 2017), generates the offer of different packaging systems. Each packaging system has the purpose of satisfying the needs of consumers and guaranteeing the quality of the product.

For the case of the beverage industry, the packaging is divided into three categories:

i) Primary packaging: Consists of the container where the product is located and other elements such as the cap, lid, and label. Some of the most common primary packaging systems available in the Mexican market are: Non-Returnable PET bottle (NRPET), Refillable PET bottle (REFPET), Aluminium CAN, Non-Refillable Glass bottle (NRGB), Refillable Glass bottle (RGB), Bag in Box (BIB), Carton based packaging, Pouch and High Density Polyethylene (HDPE) bottle.

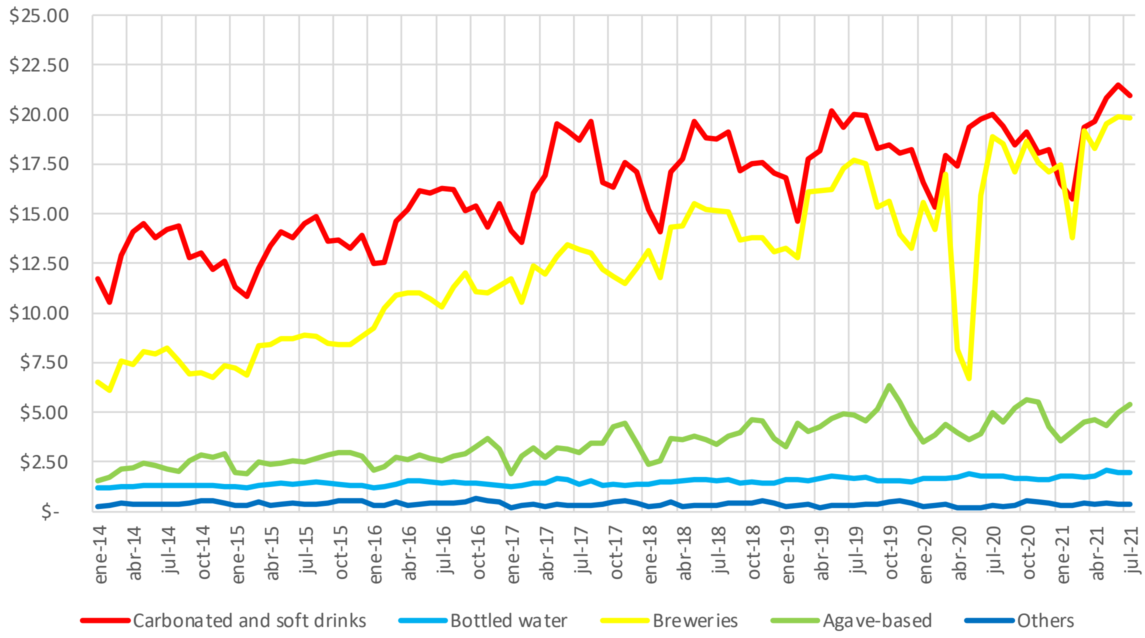


Figure 6: Monthly variation of sales value by sub-category from 2014 to 2021. Own elaborated with data from INEGI (2020). Figures in billion Mexican Pesos (constant 2013 LUC)

As mentioned above, the primary packaging system is made of different materials. Each material generates a specific environmental impact during its life cycle because of the production and transformation of the raw materials and because each system generally has particular markets, which results in different types of use.

ii) Secondary packaging: Its main purpose is to place together and maintain the integrity of a specific number of units of the finished product. Since there are multiple presentations, there are also different kinds of materials used by the industry. The most common are plastic crates, cardboard boxes, LDPE shrink film and polyolefin shrink film.

iii) Tertiary packaging: This category makes possible to distribute the finished product, although in this case, it is in large volumes. For instance, wood or plastic pallets and LDPE stretch film.

2.3 Environmental impact

Like any other economic activity, the beverage industry generates impacts on the environment that extend throughout the entire supply chain. In the beverage industry, water is regularly used for two main activities: i) as raw material for the product and ii) for the production process (washing, cooling, etc.).

Given the national regulations on water and the volumes that all the companies from this sector need, it is necessary to request a concession from the National Water Commission (CONAGUA) as stated in the Mexican National Water Law. These concessions can be granted, both for surface water bodies in 4% of the cases; as for underground water sources, in 96% of the circumstances. (Delgado, G. 2014).

By 2012, according to an analysis of the Public Registry of Water Rights (REPDA) information carried out by (Delgado, G. 2014), there were just under 500 concessions granted to the beverage industry. These concessions add up to 242.8 million m^3 per year. ***Table 1*** presents the proportions by the kind of products produced in each bottling facility depending on the sector they belong to. Additionally, the analysis concludes that the beverage industry has a presence throughout the national territory.

Table 1: Water concessions for the beverage industry. Source from (Delgado, 2014)

Sector	**Kind of beverage produced at the bottling facility**	**# of Water concessions**	**Total water volume (m^3/year)**
Non-alcoholic Beverages	Carbonated and Non-carbonated	227	61,564,681.39
	Carbonated (only)	13	2,565,564.50
	Non-carbonated (only)	117	13,735,789.19
Alcoholic Beverages	Brewing	51	162,566,699.00
	Others	81	2,449,270.95
	Total	489	242,882,005.03

As mentioned previously, there is a strong relation between packaging and products in the beverage industry. Environmental impact related to each packaging system through their Life Cycle is one of the main problems faced by the industry.

Around the world, waste management of post-consumer packaging is one of the biggest concerns, especially the ones derived from single-use plastic packaging. Many different projects, associations, and regulations have been promoted to face this challenge locally, nationally, or globally.

One of the most significant global efforts is carried out by the Ellen MacArthur Foundation to promote the Circular Economy (CE) framework. Circular Economic is a regenerative production and consumption model where the waste from one process should become the feedstock for other processes. This framework aligns with Doughnut Economic described in Section 1.1.2 and intends to be a vital tool for a successful transition to sustainability.

CE framework defines two main branches of how materials can be reintegrated. On one branch, there is the technical materials flow where finite resources such as oil or different ores can be recycled, refurbished, reused, etc. On the other branch, the biological materials flow in which renewable resources can be incorporated into the biosphere as compost or used as biofuels or transformed into biomaterials.

It is crucial to mention that globally various countries have been launched national roadmaps to achieve a Circular Economy within the following 10, 15 or 30 years (Schandl. H, et al., 2020; Ministry of energy, science, technology, environment & climate change, 2018; Ministerio dell´ambiente e della tutella del territorio e del mare, 2017; Košir, L.G. et al., 2018; Ministry of Infrastructure and the Environment, 2016; Ministry for an Ecological and Solidary Transition, 2018; SITRA, 2016; Gobierno de Colombia, 2019; Gobierno de Chile, 2020). Although Mexico does not currently have a national roadmap or law regarding CE, it is possible to find private and local efforts (ECOCE, 2021; SEDEMA, 2019; Gobierno de Guadalajara, 2021).

For the beverage industry, CE has become one of the pillars of the sustainability strategy. Nowadays, Mexican companies focus their efforts on using recycled materials and increasing the presence of returnable presentations. Regardless of biobased or biodegradable materials that have been introduced to some packaging systems, this alternative is not considered by the industry to date as a priority (ARCA Continental [ARCA], 2021; Coca Cola FEMSA [KOF], 2021; Organización Cultiba, 2021).

Those efforts are actions that intend to mitigate the environmental impact of the end-of-life of their products. At a national scale, Mexico produced 44.6 million tons of Municipal Solid Waste (MSW) in 2017, according to data from the Environment Report in Mexico 2018 (SEMARNAT, 2019). Moreover, Mexico City metropolitan area is the region that produces the most considerable amount of MSW with 12 thousand tons/day (Galicia et al., 2019).

According to (Moreno et al., 2013), Mexico City´s MSW mass composition is integrated of 49.5% of organic matter, which can be treated with biological systems such as composting or producing biogas. An inorganic fraction represents 48.9%, including plastics, textiles, glass, cardboard, etc. A minor fraction (0.18%) of hazardous waste is mixed within the MSW, representing a considerable risk for the population's environment, safety, and health.

Furthermore, the work of (Moreno et al., 2013) displays detailed results highlighting the contribution of some materials strongly related to the packaging used by the beverage industry. PET bottles represented 1.21%, while aluminium can (0.2%), glass bottles (2.65%) and Tetrapack (1.1%). Jointly those fractions represent 5.6% (672 tons/day) of Mexico City total MSW.

Therefore, it is essential for beverage companies to transit to CE to preserve the economic impact and improve the environmental footprint. Although companies will not adopt sustainability practices because of goodwill, they should embrace them to reduce the effects of environmental, political, economic and social threats. Those threats could be regulations about the labelling, bans on single-use plastics or more worry water scarcity. Companies need to act before these threats put at risk the viability of the company.

Section 3: Literature Review: LCA for beverage packaging systems

3.1 Objective, scope and methodology

Since this study presents the execution of an LCA for different beverage systems, an international literature review was carried out. This literature review aims to know the tendencies, novelties, and main results obtained with LCA execution for diverse beverage packaging systems. Moreover, similar studies were found that allowed comparison and validation of the results obtained in this work. A graphical resume of the followed methodology for this literature review can be seen in ***Figure 2***.

Web of Science (WoS) and Scopus (SCO) databases were selected to perform the search. Additionally, the following keywords and boolean rules were used to delimit the query: "beverage packaging" AND "Life Cycle Assessment OR LCA" AND "PET bottle OR CAN OR Glass bottle". Finally, only publications from 2010-2021 were considered in the search.

The first sample was integrated by 31 results (16 WoS - 15 SCO). From this sample, just peer review articles have been considered. To refine the sample, title, abstract, and content analysis was done following the steps defined by (Santoyo-Castelazo et al., 2021).

This refinement was proper to identify the studies in which only glass, REFPET, NRPET bottles or aluminium CAN packaging systems were compared or modelled. Studies related to other packaging systems or food products were not considered. As a result of this refinement, the sample was reduced to 18 papers.

Additional publications were found while reading the selected articles and consequently added to the sample. Therefore, the final sample comprised of 29 papers plus the findings of this study, as seen in ***Table 2***.

3.2 Findings

3.2.1 Geographical Scope

Most LCA studies about the selected beverage packaging systems have been carried out within Italy and the UK territory in the last decade, with four publications each. The USA and Spain register three publications while other countries like Japan, Thailand, China, Poland, Palestine, Lebanon, Mauritius, Finland, France, Brazil and Hungary just report one study, as seen in ***Figure 7-A***.

For the specific case of Mexico, only one entry was found. This study was published in 2008 (Romero-Hernández et al., 2008) and had a particular focus on the NRPET system. The study does not present quantitative results about any impact category; however, qualitative conclusions are presented. Moreover, the study determined the environmental impact of different recycling scenarios.

In resume, Europe is the region in which more studies about beverage packaging with 18 publications. Followed by the Americas with six publications, considering this study. The Middle East and Far East Asia report two publications each one. Finally, Africa and the Southeast Asia region report only one study. It was not possible to find any study from Oceania.

3.2.2 System boundaries and functional unit

The literature review revealed that LCA about beverage packaging systems has a clear tendency to determine impact through a cradle-to-grave scope, as seen in ***Figure 7-B***. The most common stages included in the cradle-to-grave scope are: i) raw material extraction, ii) packaging manufacture, iii) filling, iv) distribution and v) end-of-life.

It is important to note that the stages which have the most significant environmental impact, considering the cradle to grave scope, are raw material extraction and packaging manufacture. Therefore, packaging systems with low content of recycled materials showed worse performance since most of the virgin raw materials come from the mining or oil and gas sectors. For the packaging manufacturing stage, energetic demand to produce glass, aluminium sheets or the injection or blowing of plastic bottles contributes the most to environmental impact.

The most common studied End of Life (EoL) scenarios were recycling, incineration and landfill (Pasqualino et al., 2011; Nessi et al., 2012; Kuczenski & Geyer, 2012; Foolmaun & Ramjeeawon, 2013; Chilton et al., 2010; Nakatani et al., 2010). Depending on the studied impact category, the results showed that landfill is generally the worst option. In contrast, the results are inconclusive for different recycling methods as chemical and mechanical recycling have different results depending on the waste collection system, available technology, and the selected impact category.

In addition, the most used Functional Unit (FU) presented in the studies is the packaging needed to deliver 1 L of beverage while 1,000 L was the second, as seen in ***Figure 6-C***. FU related to the volume was found in 19 studies. In contrast, FU associated with mass was found in 6 studies and FU described, which involves delivered units of the finished product in 3. A novel FU proposal was found in (Niero & Olsen, 2016), which refers to the environmental impact produced by one hl of delivered beverage and the usage of its packaging for 30 cycles.

Table 2: Literature review - LCA of beverage packaging

Author	Geographical Scope	Goals	Studied Packaging Systems	Functional Unit	Studied product	Scope/ Boundaries	LCIA Method	Analyzed Impact Categories	End of life scenario	Data Sources	Software	Packaging systems weight and capacity	GWP / FU
Romero-Hernández et al., (2008)	Mexico	To provide insight on waste management scenarios and waste products comparisons	NRPET bottles, Aluminium CAN, and RGB	Not detailed	Not detailed	Cradle to grave	Not detailed	GWP	Recycling and landfill	Information from industry, national reports and peer-reviewed literature	Not detailed	Not detailed	Not detailed
Chilton et al. (2010)	United Kingdom	To quantify the environmental burdens associated with the collection, processing, recycling and incineration of post-consumer PET	PET bottle	1 tonne of post-consumer PET	Non-alcoholic beverage	End of life	Eco-indicator 99 (H)	All categories	Incineration and recycling	Primary research, information from industry, reports and peer-reviewed literature	SimaPro	N/A[a]	Recycling – 1,700 kg Incineration 1 – 1,400 kg Incineration 2 - 1,600 kg
Shen et al. (2010)	Western Europe and Taiwan	To assess the environmental impacts of recycled PET fibre compared with virgin PET fibre.	PET bottle	1 tonne of recycled PET fibre	Not detailed	Cradle to grave	CML	NREU, GWP,AD, AC, Eut, H.Tox, FW.Tox, T.Tox and PCO.	Recycling (mechanical recycling, semi-mechanical recycling, back-to-oligomer recycling and back-to-monomer)	ECONINVENT V2, Plastics Europe, information from industry (Wellman International Ltd., Long John Group, Far Eastern New Century Co.) reports and peer-reviewed literature	Not detailed	N/A[a]	Mech.-1.33 t Semi.Mech-2.21 t Chem-2.82 t
Nakatani et al. (2010)	Japan and China	To compare domestic and transboundary recycling scenarios between Japan and China and disposal scenarios from the viewpoints of greenhouse gases (GHG) emission and fossil resource consumption.	PET bottle	1 kg of post-consumer PET bottle	Not detailed	End of life	IPCC 2001	GWP and NREU	Recycling (mechanical and chemical) landfill and incineration	Japan PET Bottle Association and Industrial Information Research Center, reports and peer-reviewed literature	Not detailed	N/A[a]	0.731 kg
(Gironi & Piemonte, 2011)	Europe	To examine the environmental benefits of bottles made from PLA in comparison with bottles made from PET	PET bottle	1,000 units of 500 ml bottles	Drinking water	Cradle to grave	Ecoindicator 99	Endpoint: Human Health Ecosystem Quality and Resources	Composting, landfill, recycling and incineration	ECOINVENT V2 and peer-reviewed literature	SimaPro	PET bottle - 12.2 g approx.	17.202 kg
Almeida et al., 2010)	Brazil	To check the feasibility of the EMERGY tool using the LCI of different packaging systems to help designers regarding materials selection.	Aluminium CAN, NRPET bottle	1,000 L	Not detailed	Cradle to grave	Emergy	Emergy	Recycling and landfill	Peer-reviewed literature	Not detailed	Aluminium CAN—0.35 L PET bottle – 2 L	N/A[a]
Xie et al., 2011)	China	To evaluate the environmental burdens associated with milk packaging products	Tetra pack and pouch	1,000 L	Milk	Cradle to grave	Eco-Indicator 99	Endpoint: Human Health Ecosystem Quality and Resources	Recycling and landfill	ECOINVENT, information from industry and peer-reviewed literature	SimaPro	Aseptic packaging 1 L / 28.56g Pouch - 0.2 L / 3.55g	N/A[a]

Author	Geographical Scope	Goals	Studied Packaging Systems	Functional Unit	Studied product	Scope/ Boundaries	LCIA Method	Analyzed Impact Categories	End of life scenario	Data Sources	Software	Packaging systems weight and capacity	GWP / FU
Pasqualino et al., (2011)	Spain	To evaluate the environmental impact of producing and disposing of several types of beverage packaging. To identify hot spots in both processes.	Aseptic carton (Tetrapack), Aluminium CAN, glass, HDPE and PET bottles	1 L	Juice, beer and water	End of Life	Not detailed	GWP and CED	Recycling, incineration and landfill	ECOINVENT V2.1	Not detailed	Aseptic packaging 0.2-1.5 L / 15-53g HDPE bottle – 0.2-1.5L / 238.5- 50g Aluminium CAN 0.33-0.5L / 17.35-22.4g PET bottle – 0.33-8L / 14-140g Glass bottle – 0.33-1L / 238.5-492.7g	Aseptic 1 L -> 113 g CAN 0.33 L -> 826 g PET 1.5 L -> 78 g
Kuczenski & Geyer, (2012)	California, USA	To determine the impacts of PET bottle recycling in the CRV program to evaluate its effectiveness at reducing environmental burdens.	PET bottle	1 L	Non-alcoholic beverage	End of Life	CML and TRACI-2.0	All categories	Recycling	ECOINVENT V2.01, US LCI database and EMFAC	Non detailed	Bottle+Cap – 1L / 40.8 g	Pre-consumer 178.8 g Post-consumer 33.9-49.3 g
Foolmaun & Ramjeeawon, (2013)	Mauritius	To investigate and compare the environmental and social impacts of four selected disposal alternatives of used PET bottles.	PET bottle	1 tonne of used PET bottles	Not detailed	End of Life	Eco-indicator 99	All categories	Landfilling, incineration with energy recovery flake production (partial recycling)	Ministry of Local Government, Ministry of Environment and Sustainable Development, ECOINVENT	SimaPro	N/A[a]	Not detailed
Komly et al. (2012)	France	To assess the environmental efficiency of the end-of-life management of polyethylene terephthalate (PET) bottles. To define optimal targets for efficient waste management.	PET bottle	1 kg	Not detailed	Cradle to grave	CML	AD, Ac, Eut, GWP, H.Tox, FW.Tox, T.Tox and PCO.	Incineration, landfill, recycling by mechanical, chemical or thermal processes	ECOINVENT V2, Plastics Europe, RDC-Environnement, SINOE, scientific reports and peer-reviewed literature	SimaPro	Not detailed	S1 - 3.12kg S2 - 2.78kg
Nessi et al. (2012)	Italy	To evaluate the energetic and environmental performance of different drinking water consumption alternatives	NRPET (virgin and PLA) and REFPET bottle	152.1 L	Drinking water	End of life	CML 2001	AD, GWP, Eut and CED	Recycling and incineration	ECOINVENT V2.2, information from industry, national reports and peer-reviewed literature	SimaPro	NRPET (virgin) – 2L / 35.66 g REFPET bottle – 1.5 L / 35.18 g NRPET (PLA) – 0.5L 20.91 g	NRPET(V) 23.8-24.8 kg NRPET(PLA) 25-27.4 kg REFPET 16.5 kg
Meneses et al. (2012)	Spain	To evaluate the environmental impact of the most common packaging options for milk products and their disposal options.	Aseptic packaging (Tetrapack), HDPE and PET bottles	1 L of milk	Milk	Cradle to grave	Not detailed	GWP and Ac	Recycling, incineration and landfill	ECOINVENT V2.1, LCA food database and peer-reviewed literature	Not detailed	Aseptic packaging 0.2L / 15g 1 L / 36.43g 1.5L / 53.06g 2L / 69.34g HDPE bottle - 1 L / 33.03 g 1.5 L / 53.62g PET bottle – 1.5 L / 47.95g	Aseptic 1 L -> 1.2kg HDPE bottle - 1.5 L -> 1.35kg

Author	Geographical Scope	Goals	Studied Packaging Systems	Functional Unit	Studied product	Scope/ Boundaries	LCIA Method	Analyzed Impact Categories	End of life scenario	Data Sources	Software	Packaging systems weight and capacity	GWP / FU
Amienyo et al. (2012)	United Kingdom	To estimate the environmental impacts and identify the 'hot spots in the life cycle of carbonated drinks products and sector in the United Kingdom	RGB, Aluminium CAN and NPET bottle	1 L	Soft drinks	Cradle to grave	CML 2001	GWP, PED, AD, Ac, H.Tox, FW. Tox, MA. Tox, PCO, Eut, T.Tox and OD	Recycling and landfill	CCaLC, ECOINVENT V2.2, information from industry and Gabi databases	CCALC and Gabi	RGB+ cap+paper label 0.75 L / 600.1 g Aluminium cans - 0.33 L / 13.035 g NRPET+cap+label 0.5-2L / 27.45 - 47 g	PET (0.5L) – 293 g PET (2L) – 151 g CAN – 312 g RGB – 555 g
Papong et al. (2014)	Thailand	To analyze the life cycle environmental performance of PLA drinking water bottles	PET bottle (biobased -PLA)	1,000 units of 250 ml bottles	Drinking water	Cradle to grave	CML 2 baseline 2000	GWP, Ac, Eut, H. Tox, CED and FED	Composting, landfill, recycling, and incineration	ECOINVENT, IPCC method, national LCI database of Thailand and information from industry	SimaPro	PLA bottle – 0.25 L	1.04-83.15 kg
Manfredi & Vignali, (2015)	Europe	To assess the sustainability and the environmental performance of hot filling systems and aseptic packaging systems used for beverages. To identify hot spots in both processes.	PET bottle (Hot fill) and aseptic packaging	0.5 L of juice	Juice	Cradle to grave	ReCiPe	GWP, OD, T.Ac, FW. Eut, M.Eut, H.Tox, PCO, PM, T. Tox, FW. Tox, M. Tox, Rad, WD, Met. D, and FRD	Recycling, incineration and landfill	ECOINVENT V2.2, information from industry and peer-reviewed literature	Sima Pro	PET bottle+CAP 0.5L / 27.1g Aseptic+CAP 0.5L / 19.1g	PET - 31.6 g Aseptic - 25.4 g
Simon et al. (2016)	No particular one (some data from Hungary)	To evaluate the environmental impact of the most common packaging options and their disposal options	Aluminium CAN, NRPET (multilayer), REFPET, PLA and Glass bottles	1,000 L	Soft drinks and beer	Cradle to grave	CML and Eco-Indicator 99	GWP, H.Tox and Smog	Recycling, incineration and landfill	GaBi software, international/national reports and peer-reviewed literature	GaBi	Aluminium CAN 0.33-0.5L / 14.5-18.5gr NRPET bottle 0.5-2L / 28-61gr REFPET bottle 2 L / 132 gr Glass bottle 0.33-0.5L/300-360gr PLA bottle 1.5 L /35 gr Beverage cartons 1 L / 30 gr	CAN 0.33-0.5L/134-1,170g NRPET 0.5-2L/85-1,070g Glass 0.33-0.5L/45-12,900g PLA 66-500g Cartons 88-511g
Chen et al. (2016)	USA	To quantify and compare environmental impacts of PET bottles produced through traditional petroleum refineries and biorefineries To explore the system-wide advantages or limitations of fully bio-based PET bottle production scenarios	PET bottle (from bio-based PET and fossil PET)	1 kg of PET bottles	Not detailed	Cradle to gate (feedstock extraction, component production and product manufacturing)	TRACI v2.1 and ReCiPe v1.08	FRD, GWP, Ac, HHP, Tox, T. Eut, Smog and OD	Not included in the scope	ECOINVENT V3, PlasticsEurope, U.S. Life Cycle Inventory database, industry collaborators and peer-reviewed literature	GaBi	Bottle – 0.5 L / 10g approx..	Forest residue - 4.14-4.92 kg Corn stover - 5.49-6.48 kg Fossil PTA - 4.74-6.36 kg
Saleh, (2016)	Palestine	To evaluate and compare the potential environmental impacts of glass, aluminium and PET packaging materials	RGB, Aluminium CAN and PET bottle	1,000 L of beverage	Not detailed	Cradle to grave	Impact 2002+	W, NREU, SW, H. Tox, T. Ac, GWP and Ref	Recycling	Information from industry, national/international reports and peer-reviewed literature	Excel	RGB - 0.300 L / 220 g Aluminium CAN - 0.330 L / 14 g PET bottles - 2 L / 54 g	RGB - 2,573.8 kg CAN - 460.22 kg PET - 44.46 kg

Author	Geographical Scope	Goals	Studied Packaging Systems	Functional Unit	Studied product	Scope/ Boundaries	LCIA Method	Analyzed Impact Categories	End of life scenario	Data Sources	Software	Packaging systems weight and capacity	GWP / FU
Kang et al. (2017)	California, USA	To evaluate the environmental burden of non-alcoholic single-serving PET beverage bottle systems	PET bottle	1,000 L	Non-alcoholic beverage (Carbonated soda drink, water and tea)	Cradle to grave	TRACI v2.1	All categories	Open and closed-loop recycling / energy recovery with incineration and landfill	ECOINVENT V2.2, American Chemistry Council, CalRecycle, EarthShift, Franklin Associates, NAPCOR, NewPoint Group, US Census Bureau, US ITC and US-EI 2.2 database.	SimaPro	Bottle+Cap+Label CSD – 0.591 L / 28.101 g Water – 0.591 L / 23.905 g Juice – 0.591 L / 27.005 g	S1 - 187 kg S2 - 181 kg S3 - 168 kg S4 - 180 kg S5 – 178 kg
Bonamente et al. (2016)	Italy	To assess the CF and the WF of a typical Italian wine	Glass bottle	0.75 L of wine	Wine	Cradle to grave	Carbon and Water footprint	GWP and W	Recycling, incineration and landfill	ECOINVENT V3.1, CropWat and peer-reviewed literature	SimaPro	Glass bottle – 0.75 L / 450g	1.07 kg
Meneses et al. (2016)	Spain	To determine the environmental load of an aged red wine over its entire life cycle	Glass bottle	0.75 L	Wine	Cradle to grave	ReCiPe	GWP, Ac, FW.Eut, H.Tox, Agri and WD	Recycling	ECOINVENT V3.1, information from industry and peer-reviewed literature	Not detailed	Glass bottle – 0.75	Glass bottle 951 g
Bertolini et al. (2016)	Italy	To compare the environmental impact of adopting three different packaging systems	Multilayer carton, PET and HDPE bottles	1 L	Milk	Cradle to grave	CML2001 and cumulative energy demand	GWP, POC, OD, H.Tox, Ac and Eut	Recycling, energy recovery and landfill	ECOINVENT V2.2, Plastics Europe US LCI, ELCD database and peer-reviewed literature	Sima Pro	PET bottle - 25.2g HDPE - 31.6g Multilayer carton 32.38g	PET bottle - 165g HDPE - 165g Multilayer carton 104g
Niero & Olsen, (2016)	United Kingdom	To investigate the effects of including the recycled material from aluminium cans, to understand whether can-to-can recycling should be promoted or not.	Aluminium CAN	1 hl and its usage for 30 loops	Not detailed	Cradle to grave	Cumulative Exergy Demand and ReCiPe 2008+	RD, H.Tox and GWP	Landfill, recycling and material reintegration	ECOINVENT V3.1 and peer-reviewed literature	Sima Pro	Aluminium CAN - 0.33 L	CAN (UBC) 48-79 kg approx. CAN (MAP) 55-103 kg approx.
Ponstein et al., (2019)	Finland	To estimate the environmental impacts and identify the 'hot spots in the life cycle of the wine market in Finland To evaluate the environmental performance of different packaging systems used for wine.	NRGB, Bag in Box (BIB), Beverage carton, PET bottle and Pouch	0.75 L of wine	Wine	Cradle to grave	Carbon Footprint	GWP	Not detailed	ECOINVENT V3.4, DEFRA, IPCC and peer-reviewed literature	Not detailed	NRGB - 0.75 L / 480g BIB - 3 L / 0.179g	NRGB - 1.681 kg BIB -1.2 kg PET - 1.33 kg Pouch - 1.218 kg Carton - 1.21 kg
Brock & Williams, (2020)	United Kingdom	To know advantages and disadvantage of different packaging systems. To determine if there is less environmentally impactful beverage packaging than plastic bottles	RGB, aluminium can, Tetra Pack, PET bottles and HDPE bottles	1 L	Milk, fruit juice and pressurized 'fizzy' drinks	Packaging manufacture and end-of-life	CML	All categories	Recycling / Final disposal	European reference Life Cycle Database of the Joint Research Center, existing LCA, scientific reports and peer-reviewed literature	OpenLCA	1 L containers/ not weight provided	Not detailed
Bałdowska-Witos et al., (2020)	Poland	To demonstrate the impact of bottle production on the natural environment of two types of PET and PLA polymer materials.	PET and PLA bottle	1,000 units of 500 ml bottles	Not detailed	Gate to gate (bottle production)	IMPACT 2002+, Ecoindicator 99/E, CML and IPCC	GWP, Human Health Ecosystem Quality and Resources	N/A[a]	ECOINVENT V3.3	Sima Pro	PET and PLA bottle 0.5 L	PET - 0.438* kg PLA – 38.14*kg *estimated
Ferrara et al. (2021)	Italy	To identify the packaging system for mineral water with the best environmental performance	RGB and PET bottle	1 L	Natural (N) and sparkling (S) water	Cradle to grave	ReCiPe 2016 (H)	All categories	Recycling, incineration and landfill	ECOINVENT V3, CorePla, Comieco, CiAl and information from industry	SimaPro	RGB+ cap+paper label- 1 L / 452.87 g PET+cap+ label - 1 L / 22.8(N)-25.7(S) g	RGB(S) - 166.1g RGB(N) - 190.7g PET(S) - 191.9g PET(N) - 188.5g

Author	Geographical Scope	Goals	Studied Packaging Systems	Functional Unit	Studied product	Scope/ Boundaries	LCIA Method	Analyzed Impact Categories	End of life scenario	Data Sources	Software	Packaging systems weight and capacity	GWP / FU
Boutros et al. (2021)	Lebanon	To compare the life cycle environmental impacts of PET and returnable glass bottles used for carbonated beverages	PET bottle and RGB	500 ml	Carbonated beverages	Cradle to grave	IMPACT 2002+ and WULCA	All categories	Landfill, open dumping and Recycling	ECOINVENT and information from industry	Sima Pro	PET bottle – 0.5 L RGB – 0.25 L	PET bottle - 173g RGB - 177g
This work Luna-Garcini, H. et al. (2021)	Mexico	To determine and compare environmental impacts of 4 different packaging systems	NRPET, REFPET, RGB and Aluminum Can	1,000 L	Carbonated beverages	Cradle to grave	CML and TRACI-2.0	All categories	Recycling and landfill	ECOINVENT, information from industry and peer-reviewed literature	Sima Pro	NRPET - 0.6 L/17.75g REFPET - 2.5L /110g RGB - 0.355 L/415g CAN - 0.355 L/12.5g	NRPET - 174.45 kg REFPET - 296.58 kg RGB - 1,152.95 kg CAN - 497.39 kg

Impact categories acronyms: Abiotic Depletion (AD), Human Health Particulate (HHP), Cumulative Energy Demand (CED), Photochemical Ozone Creation Potential (POC), Acidification (Ac), Fossil Resourse Depletion (FRD), Primary Energy Demand (PED), Eutrophication (Eut), Terrestrial Eutrophication (T. Eut), Fresh Water Eutrophication (FW. Eut), Global Warming potential (GWP), Ozone Depletion (OD), Marine Eutrophication (M. Eut), Human Toxicity (H.Tox), Water consumption (W), Particulate matter formation (PM), Fresh water aquatic ecotoxicity (FW.Tox), Solid Waste (SW), Marine Toxicity (M. Tox), Terrestrial ecotoxicity (T.Tox), Terrestrial acidification (T. Ac), Water Depletion (WD), Photochemical oxidation (PCO), Respiratory effects (Ref), Ionising radiation (RAD), Non-renewable energy use (NREU), Fossil Energy Demand (FED), Metal depletion (Met. D), Resource depletion (RD), Agricultural land occupation (Agri) and Water Scarcity (WS). Recycling process acronyms: Mechanic Recycling (Mech), Semi-mechanic Recycling (Sem.Mech) and Chemical Recycling (Chem).

[a] Not included in the scope of the study

3.2.3 Studied impact categories

Depending on the aim of the study, a considerable range of Impact Assessments (IA) was found, such as CML, IMPACT 2002+, TRACI, ReCiPe, Ecoindicator, Cumulative Energy Demand, IPCC and Water Footprint. Furthermore, it was identified that the most evaluated impact category was Global Warming Potential (GWP) since 19 studies quantified it, as seen in ***Figure 7-D***. Moreover, Human Toxicity (10 papers) and Acidification Potential (8 articles) were the second and third most studied impact categories. In contrast, impact categories related to water footprint were evaluated only in 4 publications. Additionally, a novel impact category was found in (Almeida et al., 2010), where Emergy was calculated to help designers select the material with the best environmental performance.

3.2.4 Packing systems analysis

The most studied packaging system is the NRPET bottle, as 25 papers quantified or compared the impact of this system, as seen in ***Figure 7-E***. NRPET end-of-life stage outstands from the rest since six articles focused on determining which alternative has the best environmental performance.

Furthermore, the results showed that NRPET has the best environmental performance on the GWP impact category compared with glass bottles or aluminium CAN if a single life is considered (Simon et al., 2016; Boutros et al., 2021; Pasqualino et al., 2011; Saleh, 2016; Amienyo et al., 2012). However, as discussed in Section 2.3, this result may be overestimated since the refillable alternatives can have a better performance if the packaging is used for more than one cycle. Nevertheless, NRPET bottles have a worse GWP than some carton based packaging systems (Bertolini et al., 2016; Manfredi & Vignali, 2015) or BIB alternatives (Ponstein et al., 2019).

Among NRPET system LCA, the comparison between biobased and fossil PET resins is represented in four studies (Simon et al., 2016; Papong et al., 2014; Chen, L. et al., 2016; Nessi et al., 2012). The results determined that biobased resins have lower GWP than fossil ones. However, bio-based resins have worse environmental performance in other impact categories such as Acidification Potential (Papong et al., 2014). Nevertheless, (Chen et al., 2016) concludes that further research is needed to have more results to determine the best source feedstock to produce PET resin. The authors propose additional research to develop more detailed avoided impact scenarios attributed to each bio-based feedstock.

It is essential to mention that NRPET bottles also have different impacts depending on the product contained in the bottle (Kang et al., 2017). Containers used for beverages that require hot-fill systems (juice, tea or isotonic) are heavier than the containers made for carbonated drinks or water. Therefore, as (Coelho et al., 2011) determined, the mass of PET used in the container directly affects the environmental performance of the whole life cycle.

RGB and Aluminium CAN are the second (10 papers) and the third (9 papers) most studied systems, respectively. Both also represent the worst environmental impact among the rest of the studied packaging systems.

An interesting case was presented by (Niero & Olsen, 2016) for Aluminium CAN circularity. This case study concluded that can-to-can recovery was the best alternative to manufacture the required aluminium alloy in CANs. Furthermore, they conclude that adopting a circular approach in the CAN life cycle is, at least for the GWP impact category, a better alternative than still using virgin raw materials. However, they found that it is still necessary to improve waste collection systems.

Although some studies evaluated other kinds of packaging systems such as Carton based containers, HDPE bottles, Pouchs or BIB system, it can be concluded that LCA for beverage packaging systems is driven by the comparison and quantification of environmental impacts for PET bottles.

3.2.5 Software and data sources

Furthermore, the authors reported the software used to carry out LCA calculations. Software varies between commercial and free licenses. Commercial software is the most used and one of the advantages of using them is access to ECOINVENT, USLCI and other databases. SimaPro was reported by 16 studies as the most used software, followed by GaBi reported by two authors, as seen in ***Figure 7-F***. However, free software such as CcALC (Amienyo et al., 2012), Open LCA (Brock & Williams, 2020) and Excel spreadsheet (Saleh, 2016) was used to calculate Impact Assessment.

The study used ECOINVENT, USLCI, DEFRA databases to build Life Cycle Inventory (LCI). For the case of plastic bottles, the papers mentioned Plastics Europe as the main source. Data from industry was also one of the main data sources as it describes the actual industrial process; meanwhile, primary information was more common to find for the packaging manufacture, filling and End of Life stages. Finally, the authors used data from academic peer-reviewed publications to complement the inventory.

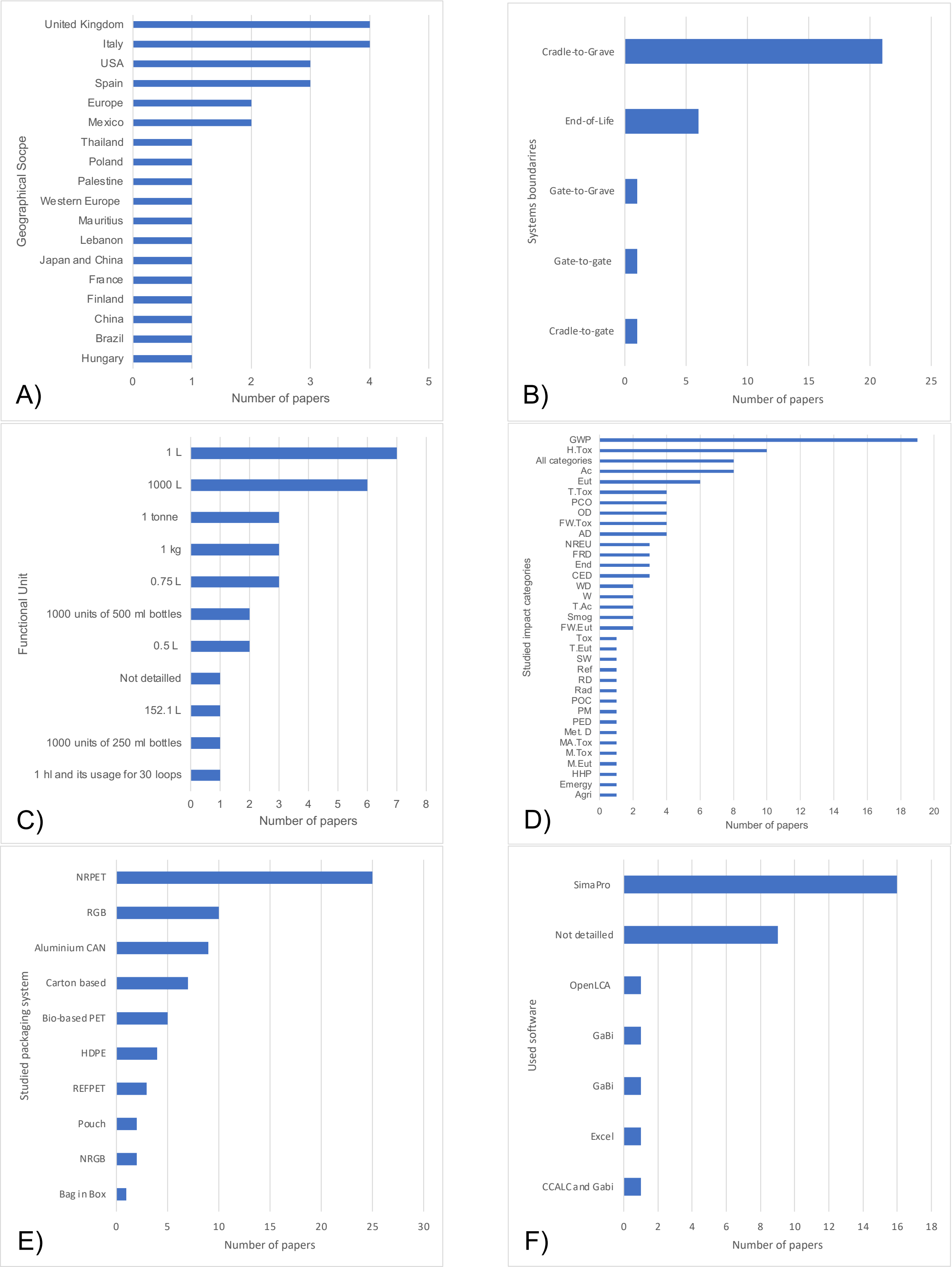


Figure 7: Graphical representation of previous LCA studies applied for beverage packaging systems (2010-2021). Own elaborated. A) Geographical Scope of LCA studies, B) Scope of LCA studies, C) Selected Functional Unit, D) Calculated Impact Categories, E) Studied Packaging System and F) Selected software

Section 4: LCA of different packaging systems used in the Mexican beverage industry

4.1 Experimental Methods

Life Cycle Assessment (LCA) methodology is an international standard defined by ISO 14040-44. The methodology is divided into four steps: i) goal and scope definition, ii) inventory analysis phase, iii) impact assessment execution, and iv) interpretation of results (ISO, 2006a; ISO, 2006b). In this section, all steps are described. Furthermore, a schematic resume of the methodological steps of this study is schematized in ***Figure 8***.

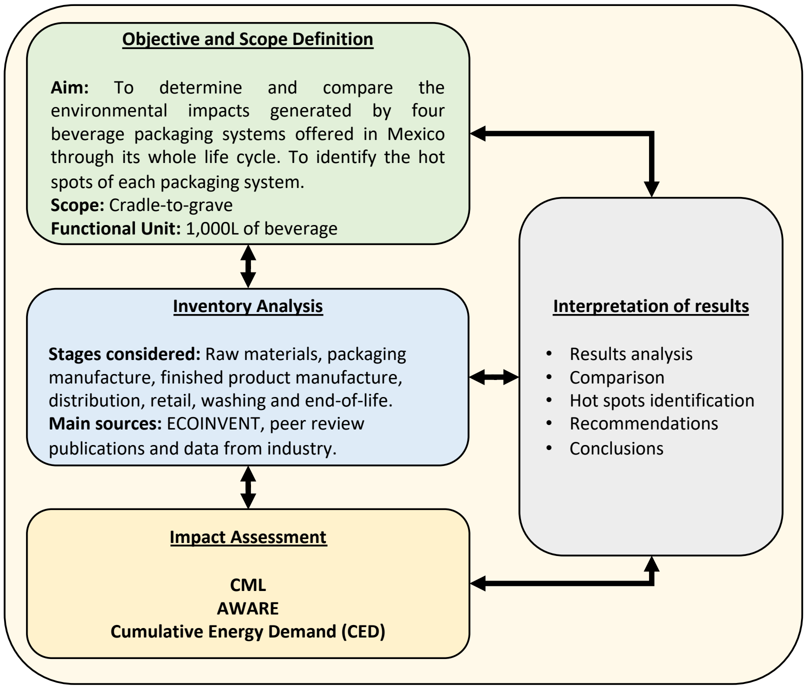


Figure 8: Schematic resume of the methodological steps followed by this study. Own elaboration based on ISO framework 14040-44 (ISO, 2006a; ISO, 2006b).

LCA is a powerful tool used to design strategies to improve environmental performance, support product development and marketing. Therefore, the goal and scope definition stage is crucial since the technical parameters, the system boundaries, and FU are set up. Additionally, the impact categories (ICs) and the impact assessment (IA) that help answer the research questions must be established.

As mentioned in section 1.2, this study aims to determine and compare the environmental impacts generated by NRPET, REFPET, RGB and Aluminium CAN beverage packaging systems offered in Mexico. To answer the following research question, “Which of the selected packaging systems has the best environmental performance from a cradle to grave scope?”.

Based on the literature review, the selected FU was 1,000 L of beverage. Therefore, all mass and energy flows were normalized to the required production of 1,000 L of beverage.

System boundaries were defined according to the supply chain model described in (KOF, 2021) and what was found in the studies by (Saleh, 2016; Amienyo et al., 2012) since these studies are similar to the assessment performed in this work. Therefore, the following stages were considered:

I. Raw materials extraction and transformation
II. Packaging manufacture
III. Finished product manufacture
IV. Distribution
V. Retail
VI. End-of-life
VII. Washing (considered only for refillable systems)

Graphical representations of the LC of non-refillable packaging systems are presented in ***Figure 9*** (NRPET and Aluminium CAN), while the graphic representation of refillable packaging systems can be seen in ***Figure 10*** (REFPET and RGB).

For this study, GWP and WF are the main Impact Categories (IC) for quantification and comparison; therefore, CML and AWARE impact assessments were chosen. However, other ICs are discussed in section 2.3 as they are relevant for the study to define recommendations and further work. SimaPro software was selected to carry out impact assessment (IA) calculations.

4.2 Life Cycle Inventory

One of the main challenges to executing a successful LCA was to find reliable data to build data inventory. Since there is not enough data that describes the Mexican scenario, several alternative sources have been consulted. Hence the Life Cycle Inventory was built mainly from three sources:

Public information from industry: The use of public data from annual reports can be described as a significant novelty for this job. Data about some materials and processes were found and used for the inventory. These data helped model key aspects from the beverage packaging and the finished product manufacturing stages with even more detail.

It is essential to mention that key aspects of the Mexican case's current situation, such as the recycled content on the packaging systems, the energetic and water consumption at the beverage companies' facilities, were found through these documents. Additionally, a more precise description of the supply chain, the raw materials needed, and the suppliers involved.

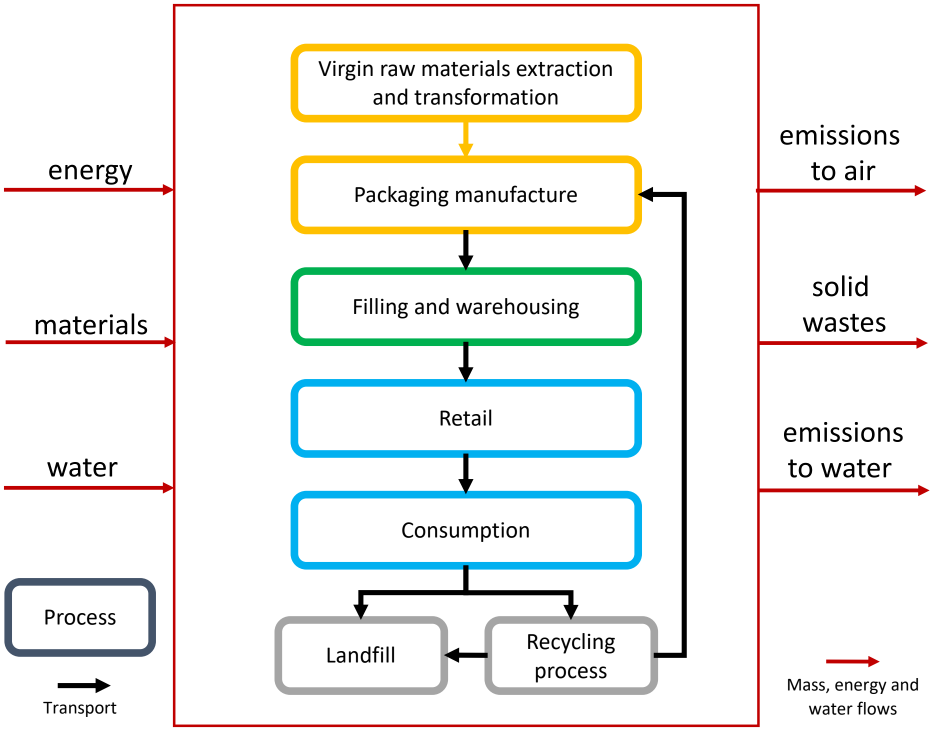


Figure 9: Life cycle and system boundaries graphical representation for non-refillable packaging systems (NRPET and CAN). Own elaborated figure.

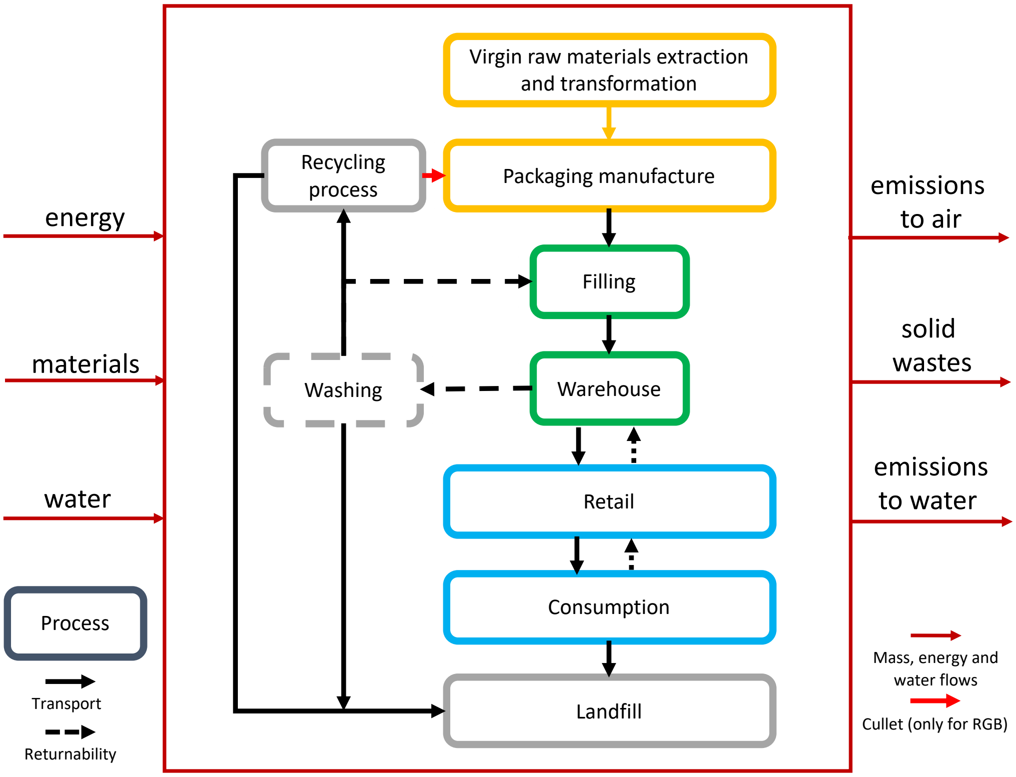


Figure 10: Life cycle and system boundaries graphical representation for refillable packaging systems (REFPET and RGB). Own elaborated figure.

Private companies' annual reports were consulted to determine the consumption of raw materials, energy, water and to know more about the industrial process (KOF, 2021; ARCA, 2021; VITRO, 2020; NOVELIS, 2020; Organización Cultiba, 2021; ALPLA, 2018). On the other hand, waste management data from governmental reports were used (SEDEMA, 2020).

Although relevant data has been found in this primary source, there is a lack of data for the raw materials extraction and end-of-life stages. To overcome this issue, secondary sources such as peer-reviewed publications and the ECOINVENT database was used.

ECOINVENT v3.4 database: This was the most used source since it contains data about the environmental impact of industrial processes, raw materials and energy production. It is crucial to notice that all materials and processes from the ECOINVENT database were adapted, if applicable, to the energetic Mexican mix. That was done to model the Mexican case study more precisely instead of calculating with global generic data.

Peer-reviewed publications: Was used to complement specific data about material and industrial processes.

Table 3 resumes the sources used by each stage of the life cycle of the studied packaging systems:

Table 3: Data sources by life cycle stage

Life Cycle stage	Concept	NRPET / REFPET	CAN	RGB
Stage 1: Raw materials extraction and Package Manufacture	Container (bottle or can)	KOF and ARCA annual reports ALPLA annual report	Niero, M. et.al. (2016) NOVELIS annual report	VITRO annual report
	Cap	ECOINVENT	Niero, M. et.al. (2016)	Boutros et.al., 2021
	Label	ECOINVENT	-	-
	Transport		CULTIBA annual report	
Stage 2: Finished product manufacture	Energy Water Direct emissions	KOF and ARCA annual reports		
Stage 3: Distribution	Transport	Calculated with Maps based on data from CULTIBA annual report		
Stage 4: Retail	Cooling Systems	KOF and ARCA annual reports		-
Stage 5: End of Life	Transport Process	ANPRAC ECOCE	Inventario de RS CDMX Niero, M. et.al. (2016) NOVELIS annual report	Informe de la situación actual del medio ambiente en México 2015
Stage 6: Washing	Process	Ferrara et.al., (2021) Boutros et.al., (2021)	-	Ferrara et.al., (2021) Boutros et.al., (2021)

A more detailed description of the inventory can be found in ***Annexes 1 to 4***, from supplementary material, display the complete inventory for all the studied packaging systems.

To delimit the system's boundaries, only the primary packaging involved for each method was considered for the study. ***Table 4*** resumes the characteristics of each system. As mentioned previously, calculations and the rest of the inventory were related to the selected presentation for each packaging system.

Table 4: Packaging system specifications and assumptions

	NRPET	REFPET	RGB	CAN
Container capacity (l)	0.6	2.5	0.355	0.355
Container weight (g)	17.75	127	280	10
Additional elements	HDPE cap BOPP label	HDPE cap	Aluminium crown	Aluminium lid
Recycled content on the main container	28%	0%	20%	59%
Necessary units to cover FU (1,000 l)	1,666.67	400	2,816.9	2,816.9

4.2.1 Raw materials extraction and packaging manufacture

As described in ***Table 4***, packaging systems have diverse characteristics, from the capacity of the container to its recycled content. The recycled content rate for each system was obtained through packaging manufacturing and beverage companies annual reports (KOF, 2021; ARCA, 2021; NOVELIS, 2020; ALPLA, 2018; VITRO, 2020).

The following assumptions were considered for this study:

For the case of Aluminium CAN, it was found that the body and the lid have different alloy compositions, according to (Niero & Olsen, 2016). Consequently, the average of their results was considered as the composition of the CAN for this study. Additionally, epoxy resin, polyester resin and acrylic varnish are required to produce the lacquer covering the can. Finally, the sheet rolling process was considered according to (Niero & Olsen, 2016).

For the NRPET system, the assembly considers virgin and recycled PET production and the blowing and injection of PET resin process to create empty bottles. The same steps as NRPET have been followed for cap and label. REFPET system shares the same processes for cap manufacture, virgin PET resin, blowing and injection of the container.

For the RGB system, virgin glass, cullet and bottle manufacture were considered. Moreover, it was considered the aluminium crown modelling, which includes a PVC liner.

To calculate transportation of materials it was assumed that the beverage company manufacture facility was based in the Mexico Valley Metropolitan Zone (ZMVM). Therefore, the study considered that all suppliers delivered to that facility.

Besides, to determine the distance between bottling facilities and suppliers, the actual location of genuine suppliers was referenced. Those suppliers were selected based on the official list published in CULTIBA´s 2020 annual report (Organización

Cultiba, 2021). Finally, actual distances between suppliers' facilities and the beverage company were measured using Google Earth Pro.

4.2.2 Finished product manufacture

This study considered data from beverage companies annual reports (KOF, 2021; ARCA, 2021) since these reports present data related to the environmental performance of their internal operations. These internal operations include filling and warehousing. All the studied packaging systems share the same internal processes. However, it is important to indicate that washing of refillable products is not considered in this stage.

The companies' annual reports register indicators about water and energy consumption for a litre of finished product. According to that information, specific consumption for each packaging system was calculated. Other indicators such as waste generation and waste management were found in those reports. The energetic matrix presented in (KOF 2021) was used to simplify the Mexican study case with more precision.

4.2.3 Distribution

As the actual location of the beverage company's facility was determined, the location of the warehouses in the ZMVM was also established. Therefore, the distance between the manufacturing facility and warehouses (T1) was calculated with Google Earth Pro. Transportation between warehouses and retailers (T2) is not considered. Fleet models were selected according to information from (Coca Cola FEMSA, 2020)

4.2.4 Retail

At the retail stage, energy consumed by cooling systems was calculated from the market's most common cooling systems models. A relationship between available space and the number of finished products for each packaging system was calculated following the methodology presented in the study by (Amienyo et al., 2012). Calculations can be found in Annexe 5. It is essential to notice that this stage was not included for the RGB system since the use of cooling systems is standard.

4.2.5 End of life and Washing

For the Mexican case study, two end-of-life scenarios were determined according to **(**Moreno et al., 2013**;** SEDEMA, 2020) due to available technology in Mexico Valley Zone: i) recycling and ii) landfill. According to (ANPRAC, 2021; Monteverde, M., 2020**)** national recycling rates for PET, HDPE, glass and BOPP are 56%, 37%, 23.5% and 3.5% respectively. For Aluminium CAN recycling rate (73%) was determined according to the findings of (Niero & Olsen, 2016; NOVELIS, 2020). It was assumed that, for the rest of the materials, the non-recycled fraction was sent to landfill. Distance to landfill and recycling facilities was calculated with Google Earth Pro. Moreover, all distances were considered the same for all packaging systems (SEDEMA, 2020).

Finally, the energy matrix was assumed to be the same for the washing process since this stage is carried out in the same facilities where the filling process takes place. Water, energy and materials consumption were defined from the studies by (Ferrara et al., 2021; Boutros et al., 2021). Transport between warehouse to beverage manufacture facility is also considered since it is crucial for refillable systems.

4.3 Results and interpretation

As mentioned previously, SimaPro software was used to carry out IA calculations. CML, AWARE (Boulay et al. 2016) and CED IA were executed to estimate the environmental impacts of each packaging system. Long term emissions and infrastructure were excluded from the analysis. From CML-IA (Guinée, J.B. et al., 2002), GPW is the first category discussed in this section, providing a deeper analysis. Moreover, there is a particular focus on the effects caused by virgin raw materials extraction, raw materials transformation and packaging manufacture stages.

Furthermore, this section analyses the results from other impact categories, including Water Footprint and Cumulative Energy Demand. Finally, a discussion about the effect of returnability on GWP and WF is performed to determine the benefits of using these systems.

4.3.1 Global Warming Potential

Raw materials and packaging manufacture stages discussion

- **NRPET system**

Environmental impact derived from producing and carrying 1,000 L of beverage on NRPET bottles result in the emission of 174.45 kg CO_2eq. The results obtained for NRPET are comparable against the ones obtained by (Kuczenski & Geyer, 2012) 178.8 kg CO_2eq (Ferrara et al., 2021) 191.9 kg CO_2eq and (Bertolini et al., 2016) 165.1 kg CO_2eq. Despite those studies presenting the results for other products than carbonated soft drinks, the weight of the bottles is comparable.

Moreover, for a single life cycle, NRPET bottles have the best environmental performance, aligned to the results found in the studies by (Saleh, 2016; Amienyo et al., 2012; Boutros et al., 2021).

As shown in ***Figure 11-A***, packaging manufacturing is the stage that contributes the most since it is responsible for the emissions of 121.14 kg CO_2 eq. Specifically, virgin PET resin production, injection and blowing processes are the main responsible due to the energetic requirements.

For the case of the NRPET system, a sensitivity analysis was carried out to determine the effect on GWP of increasing recycling rate on PET bottles. As seen in ***Figure 12***, increasing the recycling rate by an additional 1% represents a decrease in GW emissions of 857.56 g CO_2 eq. If beverage companies reach their goal of including at least 50% recycling rate content by 2030 (KOF 2021; ARCA 2021), they might save 18.87 kg CO_2eq. per FU with respect 2020.

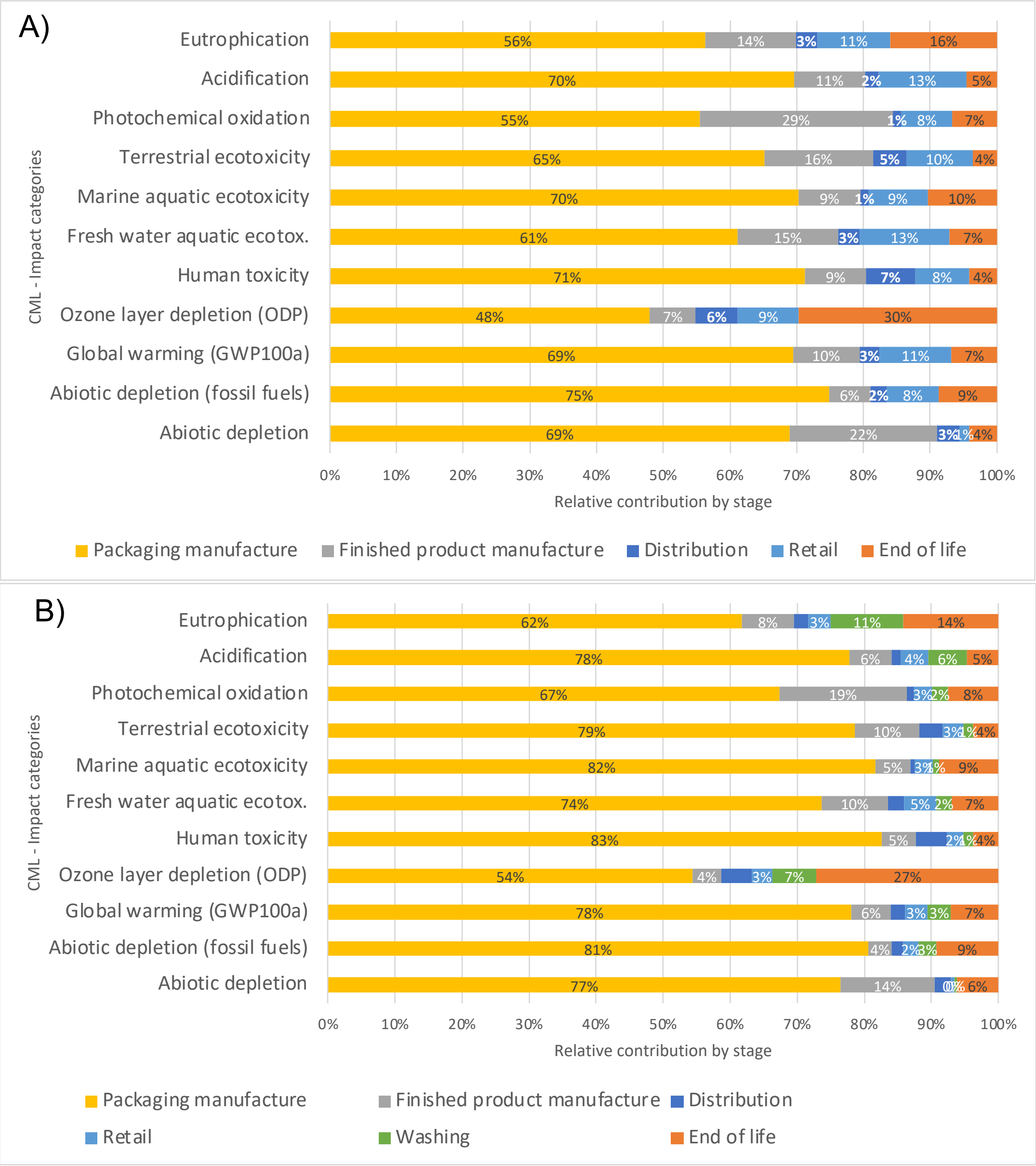


Figure 11: CML impact categories characterization for A) NRPET, B) REFPET, C) RGB and D) CAN packaging systems by stage.

- **REFPET system**

Since REFPET shares the same raw materials and manufacturing processes as NRPET, similar results have been obtained. Therefore, packaging manufacture was the main contributor to GWP, representing 78% (231.24 kg CO_2eq.) of the total emissions (296.14 kg CO_2 eq.), as seen in ***Figure 11-B***.

When comparing NRPET and REFPET systems on a single life cycle scope, the weight of the bottle is decisive for the total environmental impact since the REFPET bottle contains more material than NRPET. Consequently, results showed that NRPET has a better environmental impact as NRPET needs 29.58 kg of PET resin per FU, while REFPET bottle requires 63.5 kg of PET resin per FU.

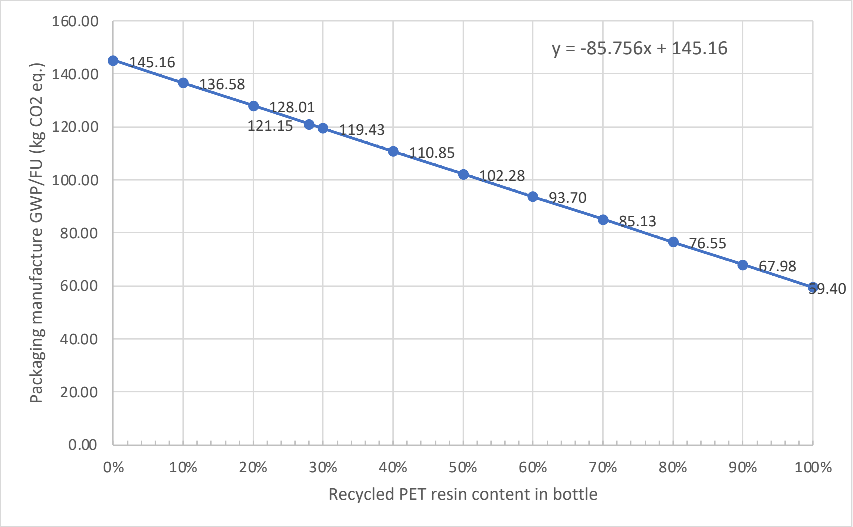


Figure 12: Recycling content contribution to GWP

- **RGB system**

RGB system presents the worst environmental performance with a GWP of 1174.61 kg CO_2eq. The result is aligned with the results from (Meneses et al., 2016; Ponstein et al., 2019; Bonamente et al., 2016). The comparison among these studies is because a single life is quantified. Other studies are far from the obtained results since many different assumptions are considered mainly in the end-of-life stage.

The packaging manufacture stage has an impact of 785.97 kg CO_2 eq, which represents the 67%. Glass manufacture process requires high temperatures for the melting process and blowing bottles; consequently, a heightened energetic consumption takes place. Moreover, the melting process uses fuel oil to reach the temperature required by the process (ECOINVENT, 2017).

Additionally, the RGB end-of-life stage contributes 27% (321.99 kg CO_2 eq). The weight of the bottle is a decisive factor that generates this impact since transport to landfill is 88%, 339% and 648% higher than transport to the landfill for CAN, REFPET and NRPET, respectively. Moreover, the glass recycling process contributes more than NRPET or aluminium recycling process.

- **Aluminium CAN system**

Aluminium CAN has the second-worst environmental impact with a GWP of 497.39 kg CO_2 eq., as seen in ***Figure 13***. As with the rest of the packaging systems, packaging manufacture is the stage that contributes the most with 83.7%, which represents emission for 416.426 kg CO_2 eq. Moreover, the production of virgin Aluminum ingots represents 71.4% of the total emissions of the packaging system, as seen in ***Figure 11-D***.

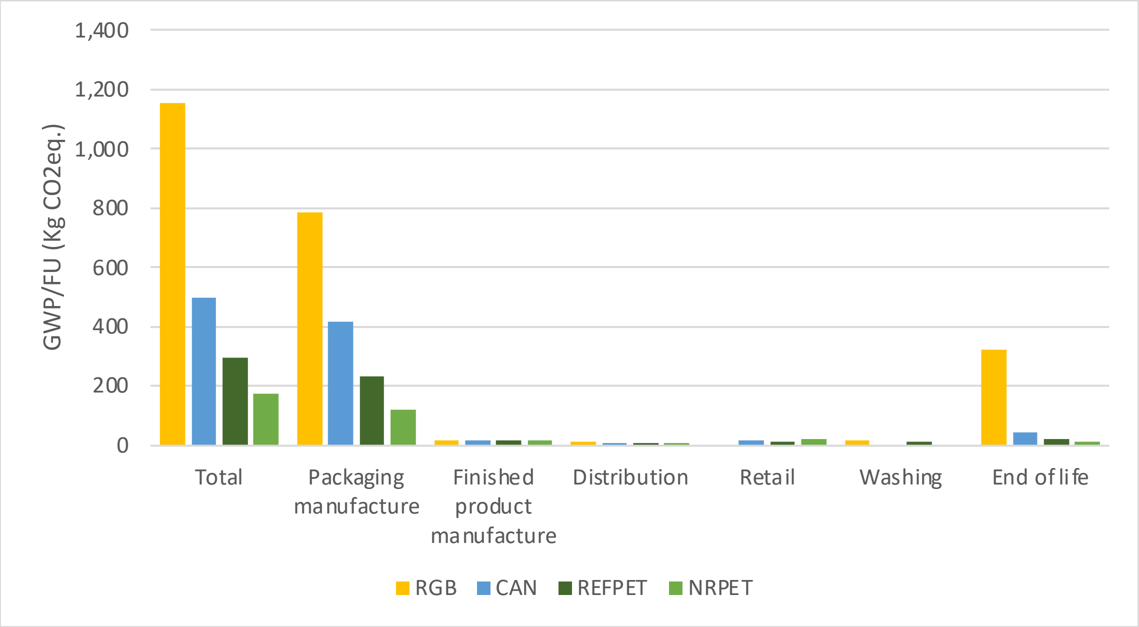


Figure 13: GWP comparison of selected packaging systems

Finished product manufacture, distribution and washing stages discussion

The finished product manufacture stage did not generate a significant difference between packaging systems since the energetic matrix was assumed to be the same for all systems. Moreover, water and energy consumption at the beverage company facility was considered the same according to the environmental indicators registered by beverage companies in their annual reports.

Additionally, the distribution is the stage that contributes less to GWP for all packaging systems, representing less than 3% of the total emissions.

The washing stage for refillable systems contributes to GWP of 16.97 and 10.65 kg CO_2 eq for RGB and REFPET, respectively. Once again, the weight of the bottle is a factor to consider since bottles require additional transportation from retail to beverage company facilities. Therefore, the lighter the bottle, the less contribution to GWP.

Retail stage discussion

On the other hand, emissions derived from the cooling system used at the retail stage are comparable to the findings (Amienyo et al., 2012). The difference between both studies is related to the number of bottles that fit in the cooling system and the leakage of refrigerant considered by the author.

At this stage, NRPET (18.8 kg CO_2eq.) and aluminium CAN (17.3 kg CO_2eq.) systems have almost the same impact, while REFPET (10.08 kg CO_2eq.) has a lower impact.

The number of units that fit in the cooling system is a determining factor since, depending on the capacity, more cooling systems are needed to hold the necessary amount of NRPET, CAN or REFPET products. Consequently, more energy is consumed due to more cooling systems being used by FU. Finally, the energetic matrix used for the model is also a crucial factor to consider since the most of primary energy is obtained from fossil fuels, according to the data from ECOINVENT (ECOINVENT, 2017)

End of life stage discussion

Finally, the end-of-life stage is impacted the most by the waste fraction treated on the landfill, as seen in ***Figure 14***. Landfill contribution to total GWP of EoL stage represents 48%, 56% and 64% for RGB, NRPET and REFPET systems, respectively. An exception for the CAN system is highlighted as the more significant contributor is the recycling process due to two factors: i) the recycling rate and ii) the energy requirements of the recycling process. Moreover, the municipal collection service, which is strongly related to the waste fraction which ends on landfills, is the second contributor to GWP for NRPET and REFPET. However, the recycling process is the second for CAN and RGB, as explained previously.

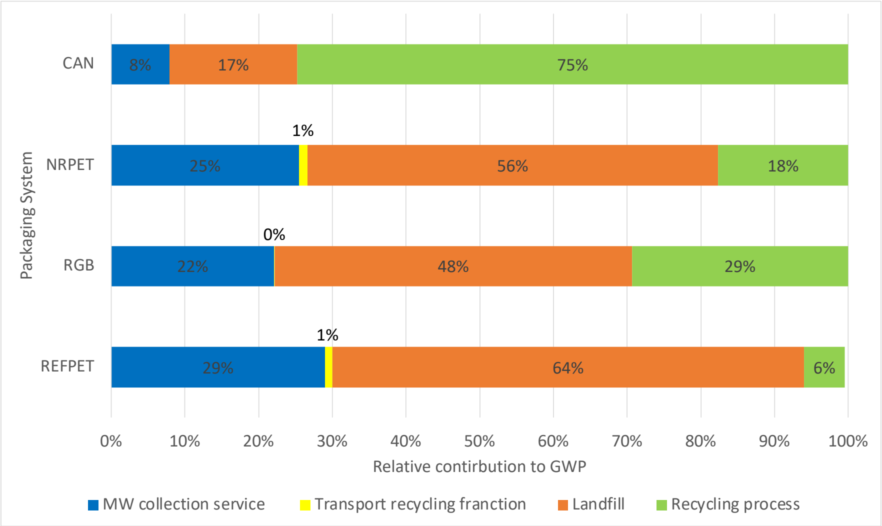


Figure 14: EoL activities relative contribution to GWP

4.3.2 Water Footprint and Cumulative Energy Demand

Water Footprint (WF)

Aligned with the results obtained for GWP, the stage with the most significant impact on WF is the packaging manufacture. Packaging manufacture represents at least 44% of the total WF for all packaging systems. Specifically, the extraction and processing of virgin raw materials (PET resin, aluminium and components for glass) have the most significant contribution to WF.

Table 5 presents the results obtained for each packaging system. The main findings to notice are:

- The washing stage in refillable alternatives is not representative of a single cycle.
- Refillable systems have the largest WF among all.
- RGB packaging manufacture stage represents 87% of the total WF.
- For a single life cycle, the weight of the bottle for the REFPET system generates an impact that doubles the NRPET water footprint in the packaging manufacture stage.
- The impact of distribution and retail stages impact is related to electricity and fuel consumption.
- In contrast, the EoL stage has a positive impact derived from the recycling process.

Table 5: Packaging Systems water footprint by stage

Packaging system	Unit	Packaging manufacture	Finished product manufacture	Distribution	Retail	Washing	EoL	Total
NRPET	m^3/FU	45.50	43.67	0.3551	1.889	-	0.2474	91.66
CAN	m^3/FU	54.72	43.69	0.3560	1.737	-	30.68	131.19
REFPET	m^3/FU	93.94	43.69	0.4115	1.013	0.7909	2.153	142.01
RGB	m^3/FU	241.99	43.69	0.7022	-	1.2371	-9.499	278.12

Cumulative energy demand (CED)

As seen in ***Figure 15***, CED analysis determined that fossil fuels are the model's predominant primary energy source. Although beverage companies' energetic matrix has a configuration with renewable energy predominance, the rest of the supply chain, especially the packaging manufacture stage, has a fossil-based energetic matrix. Consequently, on average renewable energy represents between 4% and 8% of the energetic requirements for each packaging system.

Furthermore, energy and fuel consumption are relevant to determine WF and GWP impact:

- WF is impacted since fossil fuels demand more water for their process than renewable energy.

- GWP is also affected because of the high energetic demand for virgin materials extraction and transformation, along with the energy matrix available in the public network.

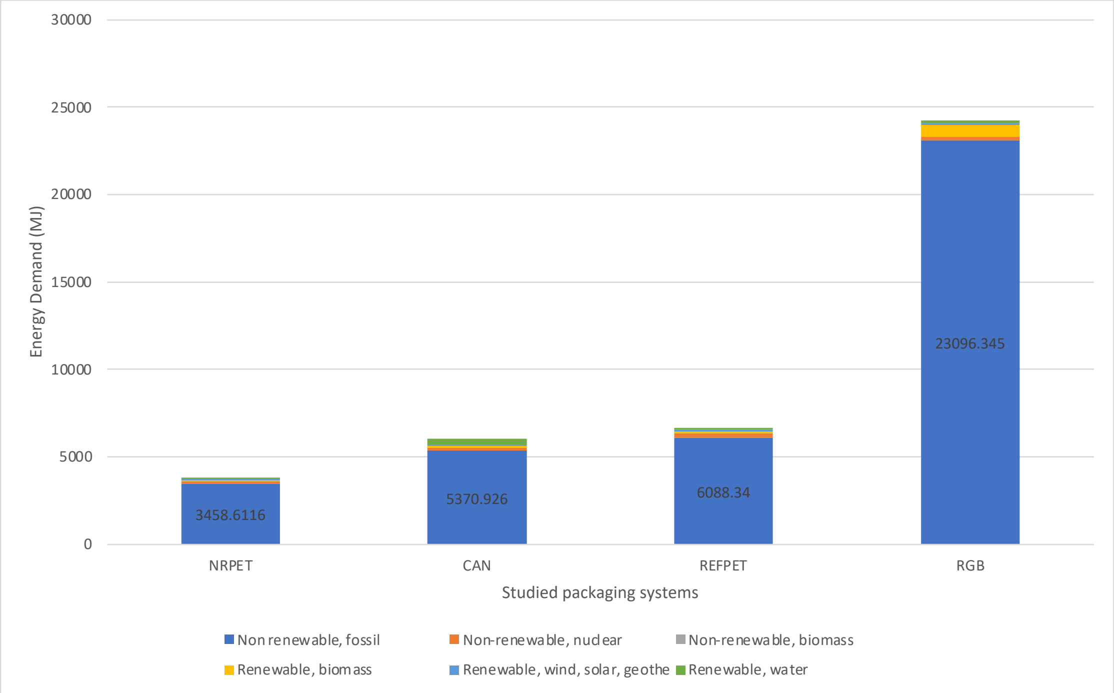


Figure 15: CED by the packaging system

Other impact categories discussion

Finally, the following observations from the rest ten impact categories from CML IA are highlighted:

- RGB performs worse than other systems in 8 categories: Abiotic depletion (fossil fuels), Ozone layer depletion, Human toxicity, Freshwater aquatic ecotoxicity, Terrestrial ecotoxicity, Photochemical oxidation, Acidification and Eutrophication.

- CAN system has the worst performance in Abiotic depletion and Marine aquatic ecotoxicity impact categories; moreover, this is the packaging system with the second-worst performance overall categories.

- NRPET has the best performance in the ten categories if a single cycle is computed.

- Aligned with GWP and WF, the packaging manufacture stage was the main contributor to the environmental impact in all impact categories, as seen in ***Table 6***.

Table 6: LCA results for each environmental impact category by FU

Impact category	Unit	RGB	CAN	REFPET	NRPET
Abiotic depletion	kg Sbeq	8E-04	63E-04	1.05E-05	6.55E-06
Abiotic depletion (fossil fuels)	MJ	23,095.8	5,368.7	6,087.2	3,456.5
Global warming potential	kg CO2eq	1,152.9	497.4	296.6	174.4
Ozone layer depletion	kg CFC-11eq	2E-04	2.62E-05	2.63E-05	1.63E-05
Human toxicity	kg 1,4-DBeq	699.8	316.45	45.22	25.01
Fresh water aquatic ecotox.	kg 1,4-DBeq	15.85	3.74	2.92	1.92
Marine aquatic ecotoxicity	kg 1,4-DBeq	64,889.7	2,988.15	74,832.5	41,564.2
Terrestrial ecotoxicity	kg 1,4-DBeq	1.127	0.7938	0.1865	0.1093
Photochemical oxidation	kg C2H4eq	0.3621	0.2021	0.0869	0.0571
Acidification	kg SO2eq	6.165	2.971	1.357	0.8011
Eutrophication	kg PO4-eq	0.8629	0.2768	0.1413	0.0812

4.3.3 Returnability scenario

For this scenario, it was considered that the bottle is disposed of at the end of each cycle. For instance, if the RGB system is disposed at the first cycle, the results compute the effects of each stage. However, if RGB last until cycle 15, the impacts generated by the packaging manufacture and end-of-life stages were computed only once, but the returnability effect (includes washing stage, finished product manufacture and distribution stages) was calculated 15 times. The same procedure was applied for REFPET.

In contrast, to compute an additional cycle of non-refillable systems, the whole LC's environmental impacts were considered since a new packaging system is required for each cycle.

The returnability scenario results can be observed in ***Figure 16***. Oppositely with the results obtained by comparing and applying LCA for a single cycle, the effect of multiple cycles for refillable systems changes conclusions completely:

- RGB had the worst performance for a single cycle.
- Aluminium CAN had the most significant impact on GWP for multiple cycles since this system needs only 3 “cycles” to perform worse than any other system.
- REFPET became a better alternative than NRPET since the second cycle.

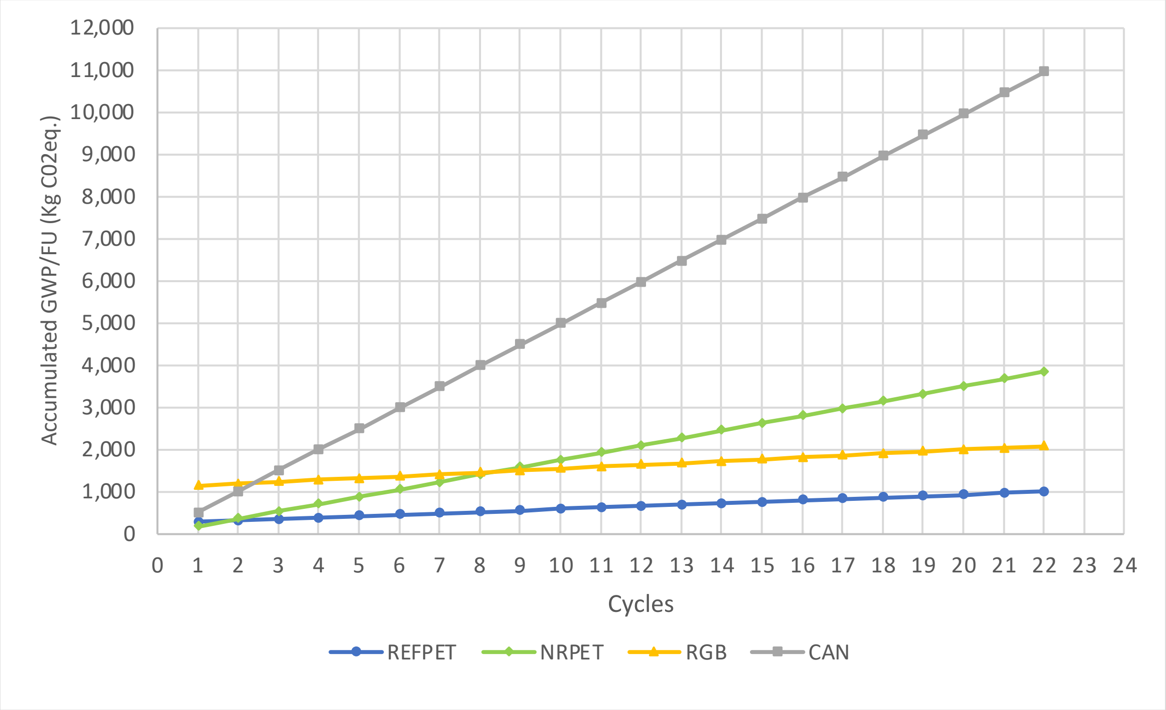


Figure 16: Accumulated GWP for multiple cycles by packaging system

- The NRPET system became the second-worst system after the ninth cycle. Nowadays is possible to reach GWP goals detailed only for NRPET if refillable bottles do not last for a reasonable number of cycles.

- The difference between REFPET and RGB impact is derived from the material and weight of the bottle. Therefore, considering multiple cycles, the best alternative is REFPET.

- If the total amount of GWP emissions is divided to calculate the average impact per cycle for refillable systems, it can be observed that after the tenth cycle, REFPET and RGB systems have a GWP lower than the NRPET bottle with at least 50% of recycled content, as is seen in ***Figure 17***. Nowadays is possible to reach GWP goals detailed only for NRPET if refillable bottles last for a reasonable number of cycles.

4.3.3 Summary of results

The results showed that NRPET (174.45 kg CO_2eq) has the best environmental performance on the GWP impact category if a single life is considered. The results are comparable with the studies made by (Ferrara et.al., 2021) - 191.9 kg CO_2eq; (Kuczenski et.al., 2012) - 178.8 kg CO_2eq; (Bertolini et.al., 2016) - 165 kg CO_2eq; (Nessi et.al., 2012) - 156.48 kg CO_2eq and (Amienyo et.al., 2013) - 151 kg CO_2eq.

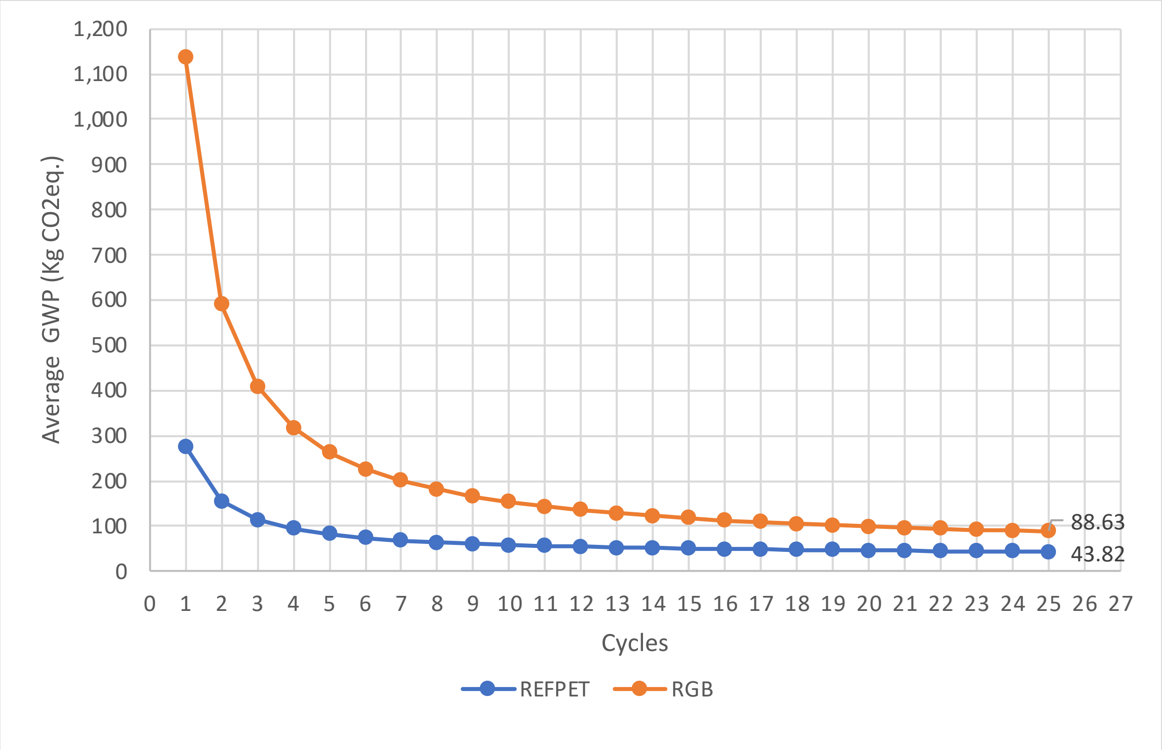


Figure 17: GWP average by cycle for refillable systems

On the contrary, RGB system (1152.95 kg CO_2eq) had the worst performance among the studied packaging systems. The results are comparable with (Meneses et.al., 2016) - 1268 kg CO_2eq; (Boutros et.al., 2021) - 354 kg CO_2eq; Bonamente, et.al., 2016) - 1426.67 $_2$; (Ferrara et.al., 2021) - 166.1 $_2$; (Amienyo et.al., 2013) - 555 kg CO_2eq.

The effect of returnability on the environmental performance was noted as REFPET (548.99 kg CO_2eq) and RGB (1495.87 kg CO_2eq) became a better option compared with NRPET (1570.06 kg CO_2eq) if the packaging last for nine cycles at least.

It was found that non-renewable energy sources concentrate more than 90% of the total energy requirements. Moreover, raw material extraction and packaging manufacture are the stages with the most significant energetic consumption.

The hot spots detected on the life cycle of beverage packaging systems are related to the virgin raw material extraction and packaging manufacturing stage. This stage is responsible for 68% to 84% of the total GWP, depending on the packaging system. Virgin raw materials and fossil fuel energy sources have the most significant environmental impact on WF and GWP.

Section 5: Conclusions and further work

5.1 General conclusions

This study compared the environmental impact of four packaging systems offered by beverage companies in Mexico through their whole life cycle. Moreover, a recent literature review was carried out to compare the results obtained within an international scope.

From the literature review, it was possible to determine that the most studied beverage packaging system is the NRPET. Moreover, the authors considered a single life cycle when comparing packaging systems such as RGB, Al-CAN and NRPET. Only a few articles considerer multiple life cycles and the conclusions are different against the results obtained when a single cycle is considered.

The results obtained by this study are statistically similar to the ones found in the literature. When a single life cycle is considered, NRPET has the best environmental performance, followed by REFPET, Al-CAN and RGB packaging systems. In this sense, it is a good result since industrial practices are not worse according to public information. Nevertheless, it implies a call to stay ahead of technological evolution and regulations. Improving environmental performance could be very useful if local regulations related to single-use packaging thrive.

On the other hand, when multiple cycles are considered, REFPET becomes the best alternative, followed by RGB, NRPET and Al-CAN. It is essential to mention that refillable alternatives can be better only if they reach a minimum number of cycles. In this case, the results showed that nine cycles are required.

As found in literature, beverage companies have set strategical public commitments related to the recycled content in their packaging. If beverage companies reach their goals reduce in GWP emissions can be saved. The case of NRPET is modelled in this study. The results showed that this reduction could be about 0.857kg CO_2eq per FU for each additional 1% of recycled content in the bottle.

Aligned with literature, the hot spots of the life cycle of beverage packaging are focused on the raw material extraction and packaging manufactures stage.

5.2 Recommendations

The application of the LCA methodology allowed the detection of clear hot spots and consequently the following recommendations should be considered by companies to adapt the supply chain of the packaging systems studied in the Mexican beverage industry:

Recycled raw materials: Aligned with the Circular Economy framework, the results revealed a clear tendency to improve the environmental impact of packaging systems by increasing the recycled content of raw materials in the packaging.

Although this study considered an average of recycled content, the environmental impact of the beverage packaging could de lower because of the actual rate of recycling materials used in the products.

For beverage companies, it is urgent to achieve public objectives and the recycled content set by each company. However, this objective should not be only for NRPET bottles but for the rest of the packaging systems and elements like the cap or the label.

Moreover, Mexican companies and governments should consider increasing infrastructure related to collecting and recycling materials to increase the national offer of recycled raw materials. This point should be considered essential since global supply chains face a scarcity of raw materials (Girtan et al., 2021). For further work, it is critical to quantify the national dependency on foreign recycling materials and the financial and economic costs of different scenarios.

On the other hand, beyond including recycling raw materials, it is essential to increase materials collection and recycling rates. Particular attention should focus on glass, BOPP and HDPE, as they have the lowest rates among the materials evaluated, according to (Monteverde, M. 2020).

Refillable packaging: Beverage companies should consider increasing the share of refillable packaging systems to decrease their GWP impact. However, an effort should be made to ensure refillable bottles last enough cycles. On the contrary, the effect will not be the desired, derived from the packaging manufacture stage due to the transformation process and raw materials. Besides, if recycled materials were added to refillable systems, the positive effect of multiple cycles would increase.

Stakeholders engagement and collaboration: Considering the packaging manufacture stage as the most significant contributor of GPW and WF, beverage companies and suppliers should collaborate.

It would be hardly recommended for all stakeholders involved in the beverage industry to improve the environmental performance of the whole supply chain. As stated by Hedstrom (2018), some of the solutions can be solved within the boundaries of a single actor. However, most of them shall need the collaboration of multiple parties and require long term planning and execution.

Renewable energy: As CED results indicate, one of the most significant improvements to consider should be to increase the amount of primary renewable energy in the system.

Water footprint: Consistent with GWP, increasing refillable alternatives and increasing recycling content and the recycling fraction on the EoL could improve the performance of WF for all packaging systems.

5.3 Limitations and further work

As it was mentioned in Section 4.3, one of the most challenging steps of this study was to build Life Cycle Inventory. To model the case study of Mexico, it was necessary to use data from not conventional sources such as companies´ public annual reports. This was done since there is not enough data from reviewed sources such as peer-reviewed articles or specific data on the ECOINVENT database.

Using data from annual reports is novelty of this work and it represents a good step for this kind of studies since it is possible to know about the environmental performance of companies. Consequently, to model a more precise case study.

However, thinking on other complementary studies related with Life Cycle tools, it could be possible to do not find data from public sources. To overcome this problem and as the best-case scenario count with commercial software would simplify and increase the quality of the study. However, this kind of software might represent a high investment for companies, the public sector or even academia that not many organizations can do.

Therefore, fixing research projects between academia and companies could be the most effective alternative to build a data inventory with the best possible quality. To make it possible, companies need to know the benefits that this kind of studies bring to them. Moreover, it is crucial to design institutional academic-business collaboration frameworks that set the directives for a win-win arrangement.

Additionally, take leverage from the digitalization of the supply chain can be an additional benefit for companies, as they could track with more pression their impacts and used them to build an inventory with higher quality.

For future work, it is necessary to complement this study with other Life Cycle Assessment tools such as Life Cycle Costing and Social Life Cycle Assessment. Those studies will give a far-reaching scope of the situation and to detect areas of improvement.

Additionally, a financial comparison between business as usual and sustainable alternative scenario. The results can lead to strategical and ordered transition related to infrastructure capabilities investments.

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ANNEXES

Annexe 1 - Life Cycle inventory for NRPET system

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	Referencia
Package Manufacture (Montaje 1)	NRPET (Empty bottle)	Material (Escenario RA)	Resina PET Virgen (g)	Polyethylene terephthalate, granulate, bottle grade {RoW}| production | Alloc Def, U	72%	*	*	12.78	21,300.00	Promedio Reportes anuales (RA) KOF y ARCA
			Recina PET Reciclada (g)	polyethylene terephthalate production, granulate, bottle grade, recycled - {MX}	28%	*	*	4.97	8,283.33	
		Material (Escenario 2030)	Resina PET Virgen (g)	Polyethylene terephthalate, granulate, bottle grade {RoW}| production | Alloc Def, U	50%	*	*	8.875	14,791.67	Promedio RA KOF y ARCA
			Recina PET Reciclada (g)	polyethylene terephthalate production, granulate, bottle grade, recycled - {MX}	50%	*	*	8.875	14,791.67	
		Proceso	Soplado (g)	Blow moulding {MX}| production | Alloc Def, U	*	*	*	17.75	29,583.33	Reporte Anual ALPLA
			Inyección (g)	Injection moulding {MX}| processing | Alloc Def, U	*	*	*	17.75	29,583.33	Reporte Anual ALPLA
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	10.6 km x 17.75 g	*	0.18815	313.58	RA CULTIVA
	Cap	Material	LDPE (g)	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	Virgen	*	*	2.4	4000	Weighted
		Proceso	Inyección (g)	Injection moulding {MX}| processing | Alloc Def, U	*	*	*	2.4	4000	ECOINVENT
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	828 km x 2.4 g	*	1.9872	3312	RA CULTIBA
	Label	Material	BOPP	Polypropylene, granulate {GLO}| market for | Alloc Def, U	Virgen	*	*	0.0223614	37.269	Weighted
		Proceso	Extrucción	Extrusion, plastic film {RoW}| production | Alloc Def, U	*	*	*	0.0223614	37.269	ECOINVENT
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	10.6 km x 0.0223614 g	*	0.000237031	0.3950514	RA CULTIBA

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Llenado (Montaje 2)	Consumo energético (Escenario RA)	Elctricidad	CFE (MJ)	Electricity, medium voltage {MX}| market for | Alloc Def, U	20%	0.055055	0.011011	0.011010989	18.35	RA KOF
			Eólica(MJ)	Electricity, high voltage {MX}| electricity production, wind, 1-3MW turbine, onshore | A	35.2%	0.055055	0.019379	0.019379341	32.30	RA KOF
			Biomasa (MJ)	Heat, district or industrial, other than natural gas {GLO}| treatment of bagasse, from su	44.8%	0.055055	0.024665	0.024664615	41.11	RA KOF y ARCA
		Termica	Gas Natural (MJ)	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale,	37%	0.052088	0.019273	0.019272527	32.12	RA KOF y ARCA
			Gas LP (MJ)	Heat, central or small-scale, other than natural gas {GLO}| market group for | Alloc Def	13%	0.052088	0.006771	0.006771429	11.29	RA KOF
			Madera (MJ)		1%	0.052088	0.000521	0.000520879	0.87	RA KOF
			Combustoleo (MJ)		16%	0.052088	0.008334	0.008334066	13.89	RA KOF
			Vapor (MJ)		16%	0.052088	0.008334	0.008334066	13.89	RA KOF
	Agua	Agua	Pozo (L)	Water, well, in ground, MX	84%	10,101,935.00	8,485,625.40	0.750960000	750.96	Calculado RA KOF y ARCA
			Tap (kg)	Tap water {RoW}| market for | Alloc Def, U	16%	10,101,935.00	1,616,309.60	0.143040000	143.04	Calculado RA KOF y ARCA
	Emisiones directas	Suelo	Residuos sólidos (kg)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	Landfill	*	*	0.00744	12.4	RA KOF
		Agua	Agua sin tratar (L)	Waste water/m3	5%	*	*	0.008762265	14.60	RA ARCA
			Agua tratada (L)	Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Alloc Def, U	95%	*	*	0.177863161	296.44	RA ARCA

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Distribución (Mnotaje 3)	Transporte (Escenario KOF)	T1	Transporte producto terminado (kgkm)	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	Beverage-Custumer	*	*	39.45	23.67	Calculated with Maps

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Retail (Mnotaje 4)	Refrigeración	Electricidad	Modelo G3-19(kWh)	Fridge 1p	41%	26.01778616	10.77110734	0.003763014	6.27	Calculated with most common models in market
			Modelo G3-26 (kWh)	Fridge 2p	34%	26.01778616	8.896064876	0.005223815	8.71	Calculated with most common models in market
			Modelo G3-42(kWh)	Fridge 3p	24%	26.01778616	6.350613943	0.006623842	11.04	Calculated with most common models in market

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
End of Life (Montaje 5)	Escenario RA	Reciclado	PET (g)	polyethylene terephthalate production, granulate, bottle grade, recycled {MX}	56%	17.75	*	9.94000000	16,566.67	ANPRAC
			HDPE (g)	Mixed plastics (waste treatment recycling) {MX}	36.9%	2.40	*	0.8856	1,476.00	ECOCE
			BOPP (g)		3.5%	0.02	*	0.0008	1.30	ECOCE
		Landfill	BOTTLE (g)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	44%	17.75	*	7.81	13,016.67	ANPRAC
			CAP + LABEL (g)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	63% + 96%	2.4 + 0.0223614	*	1.54	2,559.96	Calculation
	Trasnporte	Transporte	Landfill (kgkm)	Municipal waste collection service by 21 metric ton lorry {MX}| processing | Alloc Def, U	Municipal Collection	60.90 km x 9.35 g	*	0.569131164	948.5519406	Inventario de RS CDMX
			Recycling (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Collection-recycling	76.225 km x 10.83 g	*	0.825241017	1375.401696	Calculated with Maps

Annexe 2 – Life Cycle inventory for REFPET system

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	Referencia
Package Manufacture (Montaje 1)	NRPET (Empty bottle)	Material (Escenario RA)	Resina PET Virgen (g)	Polyethylene terephthalate, granulate, bottle grade {RoW}| production | Alloc Def, U	100%	*	*	127	50,800.00	Promedio Reportes anuales (RA) KOF y ARCA
		Material (Escenario 2030)	Resina PET Virgen (g)	Polyethylene terephthalate, granulate, bottle grade {RoW}| production | Alloc Def, U	50%	*	*	63.5	25,400.00	Promedio RA KOF y ARCA
			Recina PET Reciclada (g)	polyethylene terephthalate production, granulate, bottle grade, recycled - {MX}	50%	*	*	63.5	25,400.00	
		Proceso	Soplado (g)	Blow moulding {MX}| production | Alloc Def, U	*	17.75	*	127	50,800.00	Reporte Anual ALPLA
			Inyección (g)	Injection moulding {MX}| processing | Alloc Def, U	*	17.75	*	127	50,800.00	Reporte Anual ALPLA
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	74.8 km x 127 g	*	9.4996	3,799.84	RA CULTIBA (Calculated with Maps)
	Cap	Material	LDPE (g)	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	Virgen		*	2.4	960	Weighted
		Proceso	Inyección (g)	Injection moulding {MX}| processing | Alloc Def, U	*	*	*	2.4	960	ECOINVENT
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	828 km x 2.4 g	*	1.9872	794.88	RA CULTIBA (Calculated with Maps)
								0.099835165		

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Llenado (Montaje 2)	Consumo energético (Escenario RA)	Elctricidad	CFE (MJ)	Electricity, medium voltage {MX}| market for | Alloc Def, U	20%	0.229396	0.045879	0.045879121	18.35	RA KOF
			Eólica(MJ)	Electricity, high voltage {MX}| electricity production, wind, 1-3MW turbine, onshore | A	35.2%	0.229396	0.080747	0.080747253	32.30	RA KOF
			Biomasa (MJ)	Heat, district or industrial, other than natural gas {GLO}| treatment of bagasse, from su	44.8%	0.229396	0.102769	0.102769231	41.11	RA KOF y ARCA
		Termica	Gas Natural (MJ)	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale,	37%	0.217033	0.080302	0.080302198	32.12	RA KOF y ARCA
			Gas LP (MJ)	Heat, central or small-scale, other than natural gas {GLO}| market group for | Alloc Def	13%	0.217033	0.028214	0.028214286	11.29	RA KOF
			Madera (MJ)		1%	0.217033	0.002170	0.002170330	0.87	RA KOF
			Combustoleo (MJ)		16%	0.217033	0.034725	0.034725275	13.89	RA KOF
			Vapor (MJ)		16%	0.217033	0.034725	0.034725275	13.89	RA KOF
	Agua	Agua	Pozo (L)	Water, well, in ground, MX	84%	10,101,935.00	8,485,625.40	3.124303195	1,249.72	Calculado RA KOF y ARCA
			Tap (kg)	Tap water {RoW}| market for | Alloc Def, U	16%	10,101,935.00	1,616,309.60	0.600696805	240.28	Calculado RA KOF y ARCA
	Emisiones directas	Suelo	Residuos sólidos (kg)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	Landfill	*	*	0.31	124	RA KOF
		Agua	Agua sin tratar (L)	Waste water/m3	5%	*	*	0.036509439	14.60	RA ARCA
			Agua tratada (L)	Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Alloc Def, U	95%	*	*	0.741096505	296.44	RA ARCA

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Distribución (Montaje 3)	Transporte (Escenario KOF)	T1	Transporte producto terminado (kgkm)	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	Beverage-Custumer	*	*	192.7174907	481.79	Calculated with Maps

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Retail (Montaje 4)	Refrigeración	Electricidad	Modelo G3-19(kWh)	Fridge 1p	*	*	*	0.009031234	3.61	Calculated with most common models in market
			Modelo G3-26 (kWh)	Fridge 2p	*	*	*	0.013432667	5.37	Calculated with most common models in market
			Modelo G3-42(kWh)	Fridge 3p	*	*	*	0.012419705	4.97	Calculated with most common models in market

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Lavado (Montaje 5)	Energía	Elctricidad	CFE (Wh)	Electricity, medium voltage {MX}| market for | Alloc Def, U	20%	14.8	2.96	2.9600	1,184.0000	Ferrara, C. et.al., (2021)
			Eólica(Wh)	Electricity, high voltage {MX}| electricity production, wind, 1-3MW turbine, onshore | A	35.2%	14.8	5.2096	5.2096	2,083.8400	Ferrara, C. et.al., (2021)
			Biomasa (Wh)	Heat, district or industrial, other than natural gas {GLO}| treatment of bagasse, from su	44.8%	14.8	6.6304	6.6304	2,652.1600	Ferrara, C. et.al., (2021)
		Termica	Diesel (MJ)	Diesel, burned in building machine {GLO}| market for | Alloc Rec, U	*	*	*	0.24	96.00	Boutros, M. et.al., (2021)
	Agua	Agua	Fuente desconocida (L)	Water, unspecified natural origin, MX	*	*	*	0.001756	0.7024	Boutros, M. et.al., (2021)
	Materiales	Aditivos	Hidróxido de Sodio (g)	Sodium hydroxide, production mix, at plant/RNA	*	*	*	0.004	1.6	Boutros, M. et.al., (2021) /USLCI
			Nitrógeno (g)	Nitrogen, liquid {RoW}| market for | Alloc Def, U	*	*	*	0.000472	0.1888	Boutros, M. et.al., (2021)
			Phosphorous chloride (g)	Phosphorous chloride {GLO}| market for | Alloc Def, U	*	*	*	0.000472	0.1888	Boutros, M. et.al., (2021)
	Transporte	Transporte	Transporte producto vacio (kmkg)	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	Consumer-Beverage	73.293 km x 129.4 g	*	9.48411	3,793.64568	Calculated with Maps

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
End of Life (Montaje 6)	Escenario RA	Reciclado	PET (g)	polyethylene terephthalate production, granulate, bottle grade, recycled {MX}	56%	127.00	*	71.12000000	28,448.00	ANPRAC
			HDPE (g)	Mixed plastics (waste treatment recycling) {MX}	37%	2.40	*	0.8856	354.24	ECOCE
		Landfill	BOTTLE (g)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	44%	127.00	*	55.88	22,352.00	ANPRAC
			CAP (g)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	63%	2.40	*	1.51	604.80	Calculation
	Trasnporte	Transporte	Landfill (kgkm)	Municipal waste collection service by 21 metric ton lorry {MX}| processing | Alloc Def, U	Municipal Collection	60.90 km x 57.39 g	*	3.49505	1398.0204	Inventario de RS CDMX
			Recycling (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Collection-recycling	76.225 km x 72.01 g	*	5.48896	2195.5849	Calculated with Maps

Annexe 3 – Life Cycle inventory for Al-CAN system

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	Referencia
Package Manufacture (Montaje 1)	CAN Body	Materiales	Aluminio Virgen (g)	Aluminium, primary, ingot {RoW}| market for | Alloc Def, U	38%	10	3.78105	3.78105	10650.84507	Niero, M. et.al. (2016) / RA NOVELIS
			Aluminio Reciclado (g)	Aluminium scrap, post-consumer {GLO}| aluminium scrap, post-consumer, Recycled C	59%	10	5.91395	5.91395	16659.01408	Niero, M. et.al. (2016) / RA NOVELIS
			Magnesio (g)	Magnesium {GLO}| market for | Alloc Def, U	1.050%	10	0.105	0.105	295.7746479	Niero, M. et.al. (2016)
			Hierro (g)	Pig iron {GLO}| market for | Alloc Def, U	0.350%	10	0.035	0.035	98.5915493	Niero, M. et.al. (2016)
			Cobre (g)	Copper {GLO}| market for | Alloc Def, U	0.125%	10	0.0125	0.0125	35.21126761	Niero, M. et.al. (2016)
			Manganeso (g)	Manganese {GLO}| market for | Alloc Def, U	1.250%	10	0.125	0.125	352.1126761	Niero, M. et.al. (2016)
			Silicio (g)	Silicon, metallurgical grade {GLO}| market for | Alloc Def, U	0.125%	10	0.0125	0.0125	35.21126761	Niero, M. et.al. (2016)
			Zinc (g)	Zinc {GLO}| market for | Alloc Def, U	0.150%	10	0.015	0.015	42.25352113	Niero, M. et.al. (2016)
		Proceso	Sheet rolling (g)	Sheet rolling, aluminium {GLO}| market for | Alloc Def, U	*	*	*	10	28,169.01	Niero, M. et.al. (2016)
		Energía	Electricidad (MJ)	Electricity, high voltage, aluminium industry {RoW}| market for | Alloc Def, U	*	*	*	12.79	36,028.17	Niero, M. et.al. (2016)
			Térmica (MJ)	Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel o	*	*	*	128.5	361,971.83	Niero, M. et.al. (2016)
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	80.1 km x 10 g	*	0.18815	530.00	RA CULTIVA / Calculated with Maps
	Can Lid	Materiales	Aluminio Virgen (g)	Aluminium, primary, ingot {RoW}| market for | Alloc Def, U	94.575%	2.5	2.364375	2.364375	6660.211268	Niero, M. et.al. (2016)
			Hierro (g)	Pig iron {GLO}| market for | Alloc Def, U	0.175%	2.5	0.004375	0.004375	12.32394366	Niero, M. et.al. (2016)
			Manganeso (g)	Manganese {GLO}| market for | Alloc Def, U	0.350%	2.5	0.00875	0.00875	24.64788732	Niero, M. et.al. (2016)
			Silicio (g)	Silicon, metallurgical grade {GLO}| market for | Alloc Def, U	0.100%	2.5	0.0025	0.0025	7.042253521	Niero, M. et.al. (2016)
			Cobre (g)	Copper {GLO}| market for | Alloc Def, U	0.075%	2.5	0.001875	0.001875	5.281690141	Niero, M. et.al. (2016)
			Cromo (g)	Chromium {GLO}| market for | Alloc Def, U	0.050%	2.5	0.00125	0.00125	3.521126761	Niero, M. et.al. (2016)
			Titanio (g)	Titanium dioxide {RoW}| market for | Alloc Def, U	0.050%	2.5	0.00125	0.00125	3.521126761	Niero, M. et.al. (2016)
			Zinc (g)	Zinc {GLO}| market for | Alloc Def, U	0.125%	2.5	0.003125	0.003125	8.802816901	Niero, M. et.al. (2016)
			Magnesio (g)	Manganese {GLO}| market for | Alloc Def, U	4.500%	2.5	0.1125	0.1125	316.9014085	Niero, M. et.al. (2016)
		Proceso	Sheet rolling (g)	Sheet rolling, aluminium {GLO}| market for | Alloc Def, U	*	*	*	2.5	7042.253521	Niero, M. et.al. (2016)
		Transporte	Transporte material (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Supplier-Beverage	80.1 km x 2.5 g	*	1.9872	5597.746479	RA CULTIVA / Calculated with Maps
		Energía	Electricidad (MJ)	Electricity, high voltage, aluminium industry {RoW}| market for | Alloc Def, U	*	*	*	0.81	2281.690141	Niero, M. et.al. (2016)
			Térmica (MJ)	Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel o	*	*	*	6.66	18760.56338	Niero, M. et.al. (2016)
	Laquer	Aditives	Resina Epóxica (g)	Epoxy resin, liquid {GLO}| market for | Alloc Def, U	20%	0.32	0.064	0.064	180.2816901	Niero, M. et.al. (2016)
			Poliester (g)	Polyester resin, unsaturated {GLO}| market for | Alloc Def, U	40%	0.32	0.128	0.128	360.5633803	Niero, M. et.al. (2016)
			Varnís (g)	Acrylic varnish, without water, in 87.5% solution state {RER}| acrylic varnish productio	40%	0.32	0.128	0.128	360.5633803	Niero, M. et.al. (2016)

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Llenado (Montaje 2)	Consumo energético (Escenario RA)	Elctricidad	CFE (MJ)	Electricity, medium voltage {MX}| market for | Alloc Def, U	20%	0.032574	0.006515	0.006514835	18.35	RA KOF
			Eólica(MJ)	Electricity, high voltage {MX}| electricity production, wind, 1-3MW turbine, onshore | A	35.2%	0.032574	0.011466	0.011466110	32.30	RA KOF
			Biomasa (MJ)	Heat, district or industrial, other than natural gas {GLO}| treatment of bagasse, from su	44.8%	0.032574	0.014593	0.014593231	41.11	RA KOF y ARCA
		Termica	Gas Natural (MJ)	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale,	37%	0.030819	0.011403	0.011402912	32.12	RA KOF y ARCA
			Gas LP (MJ)	Heat, central or small-scale, other than natural gas {GLO}| market group for | Alloc Def	13%	0.030819	0.004006	0.004006429	11.29	RA KOF
			Madera (MJ)		1%	0.030819	0.000308	0.000308187	0.87	RA KOF
			Combustoleo (MJ)		16%	0.030819	0.004931	0.004930989	13.89	RA KOF
			Vapor (MJ)		16%	0.030819	0.004931	0.004930989	13.89	RA KOF
	Agua	Agua	Pozo (L)	Water, well, in ground, MX	84%	10,101,935.00	8,485,625.40	0.443651054	443.65	Calculado RA KOF y ARCA
			Tap (kg)	Tap water {RoW}| market for | Alloc Def, U	16%	10,101,935.00	1,616,309.60	0.085298946	85.30	Calculado RA KOF y ARCA
	Emisiones directas	Suelo	Residuos sólidos (kg)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	Landfill	*	*	0.04402	124	RA KOF
		Agua	Agua sin tratar (L)	Waste water/m3	5%	*	*	0.005184340	14.60	RA ARCA
			Agua tratada (L)	Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Alloc Def, U	95%	*	*	0.105235704	296.44	RA ARCA

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Distribución (Mnotaje 3)	Transporte (Escenario KOF)	T1	Transporte producto terminado (kgkm)	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	Beverage-Custumer	*	*	23.67534733	8.40	Calculated with Maps

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Retail (Mnotaje 4)	Refrigeración	Electricidad	Modelo G3-19(kWh)	Fridge 1p	41%	26.01778616	10.77110734	0.002257809	6.36	Calculated with most common models in market
			Modelo G3-26 (kWh)	Fridge 2p	34%	26.01778616	8.896064876	0.003134289	8.83	Calculated with most common models in market
			Modelo G3-42(kWh)	Fridge 3p	24%	26.01778616	6.350613943	0.003104926	8.75	Calculated with most common models in market

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
End of Life (Montaje 5)	Escenario RA	Reciclado	Recolección (g)	Aluminium scrap, post-consumer {RoW}| treatment of, by collecting, sorting, cleaning,	70%	12.50	*	8.75	24,647.89	Niero, M. et.al. (2016) / RA NOVELIS
			Fundición (g)	Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium	70%	12.50	*	8.75	24,647.89	Niero, M. et.al. (2016) / RA NOVELIS
		Landfill	Tratamiento (g)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	30%	CAN + Lacquer	*	4.07	11,464.79	Niero, M. et.al. (2016) / RA NOVELIS
	Trasnporte	Transporte	Landfill (kgkm)	Municipal waste collection service by 21 metric ton lorry {MX}| processing | Alloc Def, U	Municipal Collection	60.90 km x 4.07 g	*	0.247846042	698.1578638	Inventario de RS CDMX

Annexe 4 – Life Cycle inventory for RGB system

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	Referencia
Package Manufacture (Montaje 1)	NRPET (Empty bottle)	Material (Escenario RA)	Vidrio Virgen (g)	Packaging glass, white, without cullet | Alloc Def, U	80%	280	224	224	630,985.92	Weighted / RA VITRO
			Vidrio Reciclado (g)	Glass cullet, sorted {MX}| market for | Alloc Def, U	20%	280	56	56	157,746.48	Weighted / RA VITRO
	Cap	Material	Corcholata (g)	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U	Virgen		*	2	5633.802817	Weighted /Boutros, M., 2021
			Liner (g)	PVC film E				0.19	535.2112676	Weighted /Boutros, M., 2021

0.014176593

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Llenado (Montaje 2)	Consumo energético (Escenario RA)	Elctricidad	CFE (MJ)	Electricity, medium voltage {MX}| market for | Alloc Def, U	20%	0.032574	0.006515	0.006514835	18.35	RA KOF
			Eólica(MJ)	Electricity, high voltage {MX}| electricity production, wind, 1-3MW turbine, onshore | A	35.2%	0.032574	0.011466	0.011466110	32.30	RA KOF
			Biomasa (MJ)	Heat, district or industrial, other than natural gas {GLO}| treatment of bagasse, from su	44.8%	0.032574	0.014593	0.014593231	41.11	RA KOF y ARCA
		Termica	Gas Natural (MJ)	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale,	37%	0.030819	0.011403	0.011402912	32.12	RA KOF y ARCA
			Gas LP (MJ)	Heat, central or small-scale, other than natural gas {GLO}| market group for | Alloc Def	13%	0.030819	0.004006	0.004006429	11.29	RA KOF
			Madera (MJ)		1%	0.030819	0.000308	0.000308187	0.87	RA KOF
			Combustoleo (MJ)		16%	0.030819	0.004931	0.004930989	13.89	RA KOF
			Vapor (MJ)		16%	0.030819	0.004931	0.004930989	13.89	RA KOF
	Agua	Agua	Pozo (L)	Water, well, in ground, MX	84%	10,101,935.00	8,485,625.40	0.443651054	1,249.72	Calculado RA KOF y ARCA
			Tap (kg)	Tap water {RoW}| market for | Alloc Def, U	16%	10,101,935.00	1,616,309.60	0.085298946	240.28	Calculado RA KOF y ARCA
	Emisiones directas	Suelo	Residuos sólidos (kg)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	Landfill	*	*	0.04402	124	RA KOF
		Agua	Agua sin tratar (L)	Waste water/m3	5%	*	*	0.005184340	14.60	RA ARCA
			Agua tratada (L)	Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Alloc Def, U	95%	*	*	0.105235704	296.44	RA ARCA

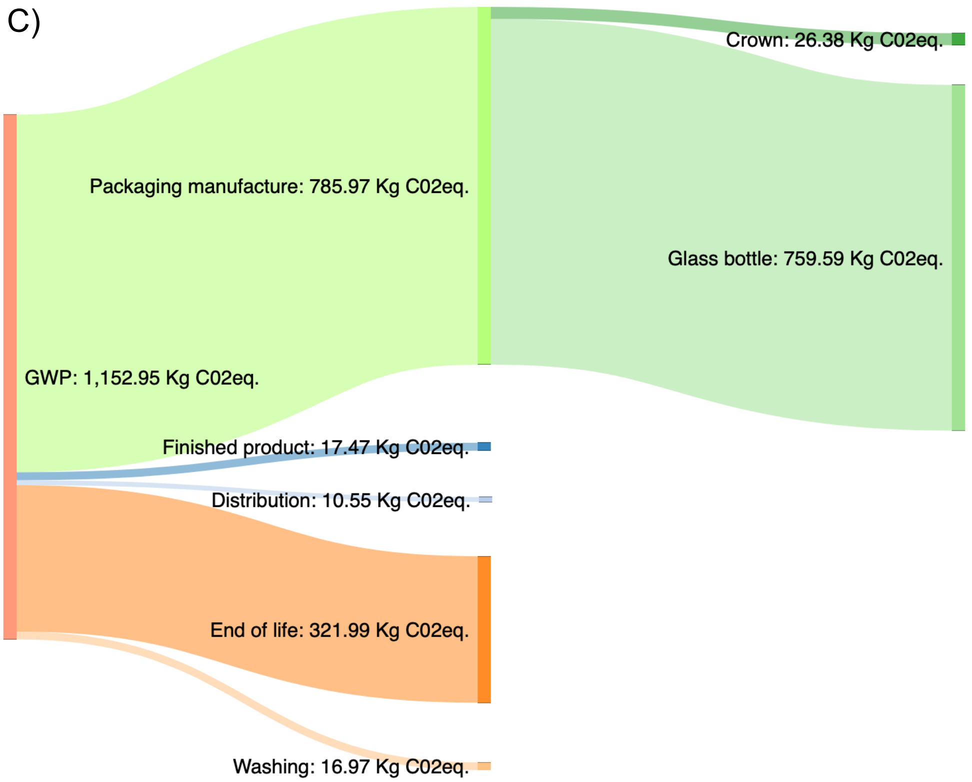
			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Distribución (Montaje 3)	Transporte (Escenario KOF)	T1	Transporte producto terminado (kgkm)	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	Beverage-Custumer	*	*	46.70177907	16.58	Calculated with Maps

			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
Lavado (Montaje 4)	Energía	Elctricidad	CFE (Wh)	Electricity, medium voltage {MX}| market for | Alloc Def, U	*	*	*	0.5254	1,480.0000	Ferrara, C. et.al., (2021)
			Eólica(Wh)	Electricity, high voltage {MX}| electricity production, wind, 1-3MW turbine, onshore | A	*	*	*	0.9247	2,604.8000	Ferrara, C. et.al., (2021)
			Biomasa (Wh)	Heat, district or industrial, other than natural gas {GLO}| treatment of bagasse, from su	*	*	*	1.1769	3,315.2000	Ferrara, C. et.al., (2021)
		Termica	Diesel (MJ)	Diesel, burned in building machine {GLO}| market for | Alloc Rec, U	*	*	*	0.04	120.00	Boutros, M. et.al., (2021)
	Agua	Agua	Fuente desconocida (L)	Water, unspecified natural origin, MX	*	*	*	0.00031169	0.878	Boutros, M. et.al., (2021)
	Materiales	Aditivos	Hidróxido de Sodio (g)	Sodium hydroxide, production mix, at plant/RNA	*	*	*	0.00071	2	Boutros, M. et.al., (2021) /USLCI
			Nitrógeno (g)	Nitrogen, liquid {RoW}| market for | Alloc Def, U	*	*	*	0.00008378	0.236	Boutros, M. et.al., (2021)
			Phosphorous chloride (g)	Phosphorous chloride {GLO}| market for | Alloc Def, U	*	*	*	0.00008378	0.236	Boutros, M. et.al., (2021)
	Transporte	Transporte	Transporte producto vacio (kmkg)	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	Consumer-Beverage	73.293 km x 282.19 g	*	20.68265	58260.9739	Calculated with Maps

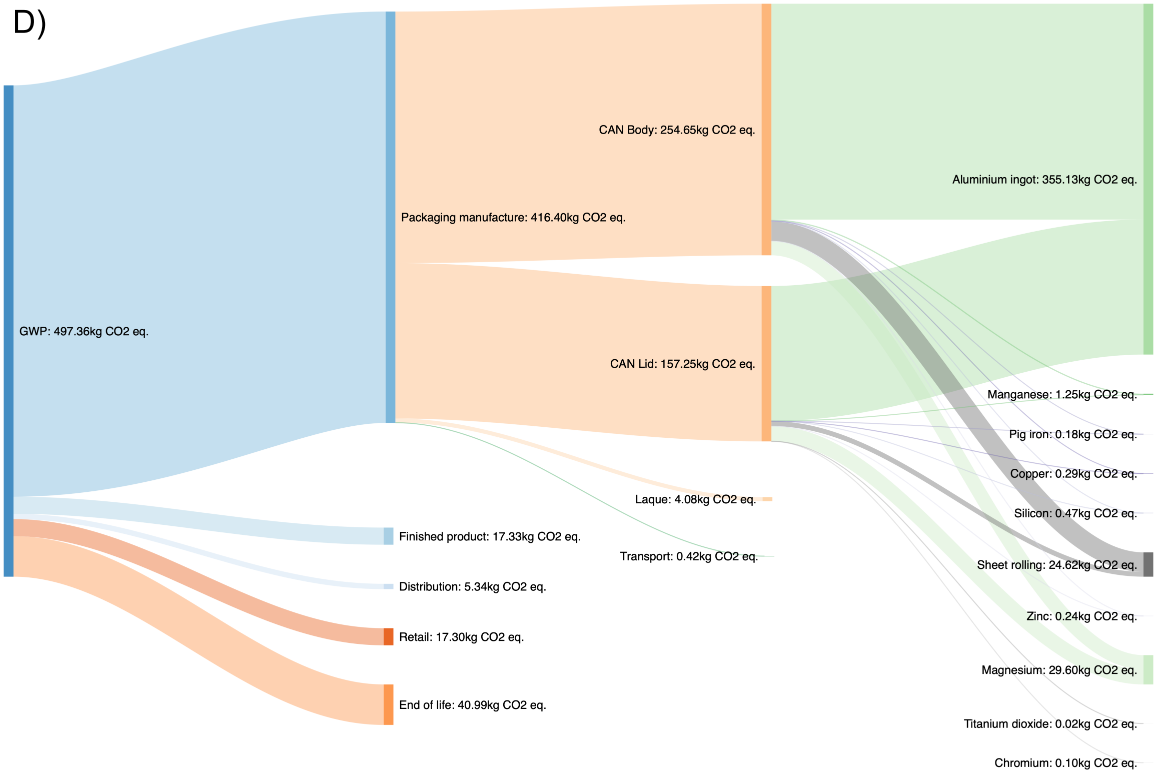
			Concepto	ECOINVENT Name	Especificación	Consumo (Bruto)	Allocation	Unitario	Normalización (1000L)	
End of Life (Montaje 5)	Escenario RA	Reciclado	Botella (g)	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | A	23.5%	280.00	*	65.80000000	185,352.11	Informe de la situación actual del medio ambiente en México 2015
		Landfill	Botella (g)	Municipal solid waste {MX}| treatment of, sanitary landfill | Alloc Def, U	76.5%	280.00	*	214.20	603,380.28	Informe de la situación actual del medio ambiente en México 2015
			Corcholata		100%	2.19	*	2.19	6,169.01	Informe de la situación actual del medio ambiente en México 2015
	Trasnporte	Transporte	Landfill (kgkm)	Municipal waste collection service by 21 metric ton lorry {MX}| processing | Alloc Def, U	Municipal Collection	60.90 km x 216.39 g	*	13.17815	37121.55211	Inventario de RS CDMX
			Recycling (kgkm)	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Def, U	Collection-recycling	27.51 km x 65.8 g	*	1.81044	5099.830986	DIRECTORIO DE CENTROS DE ACOPIO DE RESIDUOS URBANOS EN LA CDMX

Annexe 5 – Sankey diagram representation of GWP contribution for A) NRPET, B) REFPET, C) RGB and D) CAN packaging systems by stage. Own elaborated figure. Made with Sankeymathic software

C)


Crown: 26.38 Kg C02eq.
Packaging manufacture: 785.97 Kg C02eq.
Glass bottle: 759.59 Kg C02eq.
GWP: 1,152.95 Kg C02eq.
Finished product: 17.47 Kg C02eq.
Distribution: 10.55 Kg C02eq.
End of life: 321.99 Kg C02eq.
Washing: 16.97 Kg C02eq.

D)


CAN Body: 254.65kg CO2 eq.
Aluminium ingot: 355.13kg CO2 eq.
Packaging manufacture: 416.40kg CO2 eq.
GWP: 497.36kg CO2 eq.
CAN Lid: 157.25kg CO2 eq.
Manganese: 1.25kg CO2 eq.
Pig iron: 0.18kg CO2 eq.
Copper: 0.29kg CO2 eq.
Laque: 4.08kg CO2 eq.
Silicon: 0.47kg CO2 eq.
Finished product: 17.33kg CO2 eq.
Transport: 0.42kg CO2 eq.
Sheet rolling: 24.62kg CO2 eq.
Distribution: 5.34kg CO2 eq.
Zinc: 0.24kg CO2 eq.
Retail: 17.30kg CO2 eq.
Magnesium: 29.60kg CO2 eq.
End of life: 40.99kg CO2 eq.
Titanium dioxide: 0.02kg CO2 eq.
Chromium: 0.10kg CO2 eq.