Case study of alternatives for closing the cycle of food delivery service within the circular economy in Bogotá.

L. Gámez*, F. Salcedo*, Y. Hernández-Charpak **, P. Ortiz*

* Department of Chemical Engineering, Universidad de Los Andes, Bogotá, Colombia
**Department of Mechanical engineering, Universidad de Los Andes, Bogotá, Colombia

(E-mail: l.gamez@uniandes.edu.co; fesalced@uniandes.edu.co; yd.hernandez10@uniandes.edu.co; portiz@uniandes.edu.co)

Abstract

The rapid expansion of food delivery services has significantly increased the consumption of single-use packaging, intensifying waste management challenges in urban contexts such as Bogotá, Colombia. This study presents a comparative life cycle assessment (LCA) of four container alternatives used in food delivery services: expanded polystyrene (EPS), polyethylene-coated kraft paper, compostable sugarcane bagasse, and a reusable stainless steel system. The assessment was conducted following ISO 14040/14044 guidelines, applying the ReCiPe 2016 Midpoint (H) methodology across 18 impact categories, and modeled using both SimaPro and openLCA with the ecoinvent database. The functional unit was defined as the delivery of a single food portion in a home delivery service, contained in a packaging with an approximate capacity of 32 ounces, and a cradle-to-cradle system boundary was applied under Bogotá-specific logistical and waste management conditions. Results indicate that kraft paper consistently exhibited the highest environmental burdens across most impact categories, driven primarily by raw material production and anaerobic degradation in landfills. EPS showed comparatively lower impacts due to its reduced material intensity, while sugarcane bagasse displayed intermediate performance. The reusable stainless steel container demonstrated the lowest per-use impacts when sufficient reuse cycles are achieved. Sensitivity and uncertainty analyses confirmed the statistical robustness of the comparative ranking and identified transport logistics as the most influential parameter across the evaluated system. These findings underscore the importance of adopting full life cycle perspectives rather than relying on material perception alone when assessing the environmental performance of packaging alternatives.

Keywords: life cycle assessment; food delivery packaging; circular economy; expanded polystyrene; sugarcane bagasse; reusable containers

1. Introduction

The 2022 Sustainable Development Goals Report, issued by the United Nations (UN), highlights that rapid urban growth has led to a proportional increase in municipal solid waste generation. The lack of adequate collection and inefficient management of this waste pose significant risks to public health, increase plastic pollution, and contribute to the intensification of greenhouse gas emissions [1]. In fact, various estimates indicate that the waste sector is responsible for approximately 11% of global anthropogenic methane emissions, derived from processes such as collection, transport, recycling, and final disposal in landfills, where the anaerobic decomposition of organic waste is the main generating process [2]. In Latin America and the Caribbean, the waste collection rate reaches 82.6%, but only 56.5% is managed in facilities with adequate control conditions [1].

In Colombia, it is estimated that 32.53 million tons of solid waste are generated annually, of which 59% comes from industry and 41% from households [3]. In Bogotá, the Bogotá Environmental Observatory reported that in 2024 the city generated 3.967.682 tons of waste, of which only 43.88% was recycled, while 52.12% was disposed of at the Doña Juana Innovation Park (PIDJ)[4]. The Environmental and Public Health Legal Clinic

(MASP) of the University of the Andes and Greenpeace Colombia, together with the Mayor's Office of Bogotá, pointed out that approximately 56% of the waste generated in the city corresponds to plastics of different types, which highlights the magnitude of the challenge associated with its management [5] .

In this context, the United Nations Development Program warns that plastic food packaging accounts for about 40% of total plastic waste and that its recycling faces significant technical limitations due to contamination from labels, food residues, and other materials that deteriorate the quality of the recovered material and affect the operability of recycling processes [6], [7]. This problem has intensified with the expansion of home delivery services, which have evolved from traditional telephone orders to sophisticated digital platforms, significantly increasing the consumption of single-use plastic packaging for food delivery and, at the same time, establishing themselves as a key source of income for the restaurant sector [8]. Projections for 2025 estimate 2.5 billion users and an annual growth rate of 7.64% until 2030 [9], [10]. As for the waste generated by this activity, recent studies estimate that in South Korea, plastic packaging from online food orders in 2020 accounted for 2.55% of the country's household plastic waste that year[11]. Similarly, in Osaka, Japan, it was estimated that the annual plastic waste load from packaging associated with food delivery services during the pandemic reached 6.15 kt, generating 47,033 tons of CO_2 from its manufacture and treatment [12].

In Colombia, the sustained growth of the food delivery market and the entry into force of Law of 2022 have driven a transition toward replacing single-use plastic materials, such as expanded polystyrene (EPS), with alternatives such as polyethylene (PE)-coated kraft paper, biodegradable or compostable materials, and reusable options [13]. However, despite the rapid adoption of these new materials, there has been no rigorous assessment of whether this substitution represents a real environmental improvement, nor have any comparison factors or sustainability indicators been established to determine whether the change has been positive or whether, on the contrary, it has shifted the impacts to other stages of the life cycle.

The objective of this project is to conduct a comparative life cycle assessment (LCA) between different types of packaging commonly used in the food delivery sector. Through this assessment, we seek to quantify and compare the environmental impacts associated with each option, based on Bogotá, Colombia conditions and realities.

2. Materials and methods

2.1. Materials

EPS, widely used for its low cost, lightness, and insulating capacity, is a product derived from petroleum, characterized by an atomic structure of carbon and hydrogen characterized by the presence of the styrene ring [14], [15]. It has limited recyclability due to its low density and volume, which makes its collection and transport expensive and generates significant impacts due to its inadequate final disposal [16]. PE-coated kraft paper, although perceived as a more sustainable alternative, poses challenges for recycling, such as the plastic layer fragments during repulping, clogs screens, and can release microplastics [17] . Additionally, its manufacture involves high consumption of forest resources (Zhuo et al., 2023).

Added to this are biodegradable and compostable alternatives derived from renewable sources [8], [18]which, although they represent a step towards more sustainable materials, have limitations associated with the need for controlled conditions for their degradation or their low competitiveness in the market, which restricts their adoption and management within conventional waste systems. In the particular case of materials based on plant fibers such as sugarcane bagasse or bamboo, they have gained popularity because they are considered more environmentally friendly options, as they can be composted under natural conditions and in relatively short periods of time. However, their cost remains higher than that of other alternatives, and their adoption in the market is still limited, mainly due to the still-small scale of production [8].

Finally, reusable systems have emerged as one of the main alternatives to single-use packaging. Currently, in Bogotá, a reuse scheme for food delivery services has been implemented in which restaurants provide customers with reusable stainless steel containers for takeaway and home delivery orders [19]. After use, the containers are collected from consumers' households, returned to the restaurants, and washed before being reintroduced into the system. The main limitation of this model lies in the additional logistical requirements imposed on participating restaurants, which must implement systems for tracking, collecting, and managing the return flow of containers throughout the reuse cycle.

2.2. Life cycle assessment

The life cycle assessment (LCA) conducted in this study was carried out in accordance with ISO 14040, which requires that the assessment be structured with a defined objective and scope, specify the functional unit, describe the life cycle inventory, apply appropriate impact assessment methods, and interpret the results using sensitivity and uncertainty analyses.

2.2.1. Goal and scope definition

This research comparatively evaluated the environmental performance of four alternative containers for home delivery services: polyethylene-coated kraft paper, expanded polystyrene (EPS), a compostable alternative, and a reuse system. The study was conducted to inform the decision-making of stakeholders involved in promoting responsible consumption of materials associated with home delivery services: end users, restaurants, material producers, and delivery platforms, considering the conditions and realities of the Bogotá context. The functional unit was defined as the delivery of a single food portion in a home delivery service, contained in packaging with an approximate capacity of 32 ounces (≈1000 mL), this volume being the most representative and consistent across the evaluated alternatives. For the reusable alternative, the reference flow is expressed as the fraction 1/N, where N represents the effective number of uses of the packaging. Se decide establecer 1000 como el numero de usos efectivo con el fin de tomar un valor medio entre los 5000 usos que indica la ficha técnica del contenedor y la cantidad de usos efectivos utilizados en literatura [19], [20], [21].

The possibility of estimating the number of containers required to meet the demand for food delivery services in the city of Bogotá was evaluated. However, it was determined that the functional unit used in this study allows greater comparability with previous studies and facilitates the scalability or projection of the results under different scenarios or conditions. For further details regarding the estimation of the number of deliveries, please refer to the Supplementary material.

This analysis was conducted in accordance with the guidelines established by the standard, using the openLCA 2.6 and SimaPro 10.2.0.3 software, along with the ecoinvent 3.7.1 and ecoinvent 3.10 databases, respectively. The ReCiPe 2016 methodology, specifically its H (Hierarchical) perspective, was selected as the primary tool for the assessment. This methodology allows for the evaluation of impact categories at the midpoint level. The entire life cycle (cradle-to-cradle) of the container alternatives for home delivery service in Bogotá was evaluated, covering raw material extraction, manufacturing, transportation, use, final disposal, and return to the chain. Since the dimensions of the containers remain constant for all alternatives, the difference lies in the amount of material required to manufacture each type of container according to its composition and material properties.

2.2.2. System Boundaries

Figure 1 illustrates the system boundaries considered for each container alternative. It is important to note that, for the EPS, PE-coated kraft paper, and compostable containers, the use phase includes transportation from the distribution point to a representative restaurant and from the restaurant to an arbitrarily located end user. In the case of the reusable container system, this stage additionally includes the water consumption required for washing and the return transport from the user back to the restaurant.

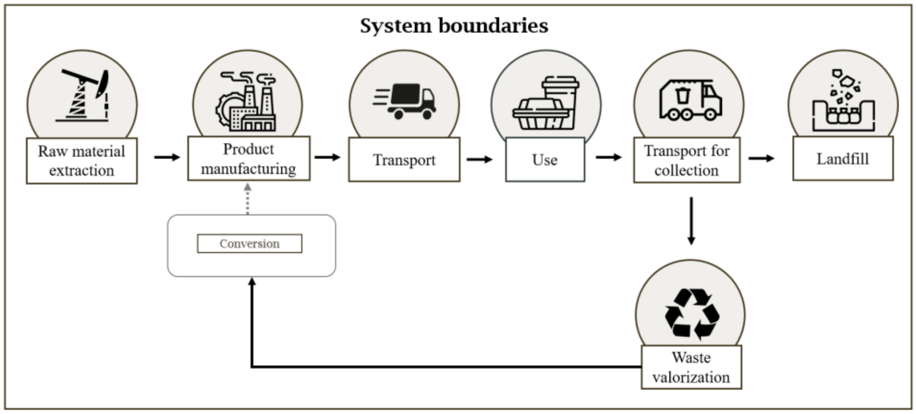

Figure 1. System boundaries

More specifically, the life cycle of expanded polystyrene containers begins with their manufacture, which consists of several stages. In the pre-expansion of expanded polystyrene, the beads are placed in an expansion chamber where steam at a temperature of 80-100°C is applied, allowing the pentane inside to volatilize and cause expansion. After expansion, the beads are left to rest in a drying and stabilization silo, where they reach a uniform and consistent size. After this, the beads are taken to the container mold, where steam and pressure are applied, causing the beads to expand slightly more and fuse together [22]. The production of expandable polystyrene, the manufacture of the EPS container, transport to distribution, use, transport to final disposal, and final disposal as the end of the life cycle are part of the system study boundaries. The production and use of pentane are outside the system boundaries.

On the other hand, to obtain a laminated kraft paper container commonly used in home delivery services, kraft paper is used as the raw material. This is subjected to a lamination process in which low-density polyethylene plastic is used. The kraft paper and plastic layer pass through the laminating machine, which applies pressure and heat, causing the plastic to adhere to the surface of the kraft paper. After this, the laminated material is cut into patterns to assemble the container and is fed into a die-cutting machine. Finally, the laminated pieces are passed through a folding or molding machine where they take on the desired shape [23]. The procurement of kraft paper, the manufacture of the kraft paper container, its use, transport to distribution, transport to final disposal, and final disposal are all part of the system study boundaries.

In the case of compostable material made from sugarcane bagasse, the life cycle begins with sugarcane bagasse as the raw material. Sugarcane bagasse is the fibrous, pulpy residue left over after extracting juice from the cane in sugar mills or alcohol plants, accounting for approximately 30% of the total processed [24]. It is a cellulosic material that, although generally considered waste, has multiple applications thanks to its high cellulose content [25]. It undergoes a process of washing, pulping, molding, and drying for the production of a container. The collection of bagasse, the manufacture of the container, its use, transport to distribution, transport to final disposal, and final disposal are also part of the system study boundaries.

For the reuse system, a stainless-steel container currently implemented in reuse schemes in Bogotá was evaluated. The container is manufactured in China and subsequently transported to Bogotá for integration into the reuse system. The manufacturing process includes the production of molten metal from raw materials through stages such as sintering, iron production, and steel manufacturing, followed by continuous casting, rolling, and deep drawing processes for the final shaping of the container [26], [27]. System boundaries also include scrap production and recovery, molten metal production, container manufacturing, the use phase, transportation to distribution points, transportation to end-of-life management, and final disposal.

2.2.3. Life cycle inventory

Expanded polystyrene

The inventory data and quantities for the EPS container life cycle are taken from the values reported by Cruz, who compiled data on the manufacturing stage of 1 kg of EPS from the Colombian manufacturer and distributor Aislapor S.A.S [22]. Based on this data, it was decided to apply a treatment that would allow for the production of a container with a set capacity. Similarly, it was decided to apply the study to the dimensions of a container commonly distributed in the country by the company Darnel.

Regarding transportation, the starting point for the EPS container system was defined as the polystyrene production and petrochemical complex of Darnel (Ajover), located in Cartagena de Indias, Colombia. From this location, the containers are transported to a distribution and commercialization center in Bogotá. According to Veritrade, the United States is the main source of styrene monomer imports into Colombia, with Ajover identified as the country's second-largest importer of this raw material [28]. Based on this information, the "PS production" dataset was adapted to include the maritime transport of 1 kg of styrene monomer by container ship from the Port of Houston, Texas, one of the main petrochemical export hubs in the United States, to the Port of Cartagena, where the Darnel (Ajover) facilities are located.

Kraft Paper

In the case of the PE-coated Kraft paper container, the container inventory data is taken from data reported in a study conducted in the United States [29]. In this case, it was also decided to apply the data to the manufacture of a container made of this material commonly found in the country of the Darnel company. The calculations of containers dimensions are available in the Supplementary material.

The Darnel (Ajover) production and logistics facility located in Madrid, Colombia, was defined as the starting point for the transportation stage. From this site, the containers are distributed to a commercialization center in Bogotá. Additionally, raw material transport was incorporated into the inventory, including the transport of 1 kg of kraft paper from the Smurfit Westrock production plant in Yumbo (Valle del Cauca) to Madrid (Cundinamarca). Since approximately 99% of the forest plantations supplying this company originate from Santa Catarina (Brazil) and Valle del Cauca (Colombia), these flows were also included within the raw material modeling framework [29]. Furthermore, the transport of low-density polyethylene (LDPE) from the Ecopetrol production plant in Barrancabermeja to Madrid was incorporated into the system boundaries.

Sugarcane Bagasse (Compostable material)

For the compostable sugarcane bagasse container, production-stage inventory data were obtained from the study by Fan and Bussracumpakorn, developed in China using environmental impact assessment reports from companies, industrial process records, and databases such as ecoinvent and CLCD [30]. The container weight was estimated based on a commercially available 32 oz product distributed by Darnel (Ajover). As with the previous alternative, the Darnel (Ajover) plant and logistics center in Madrid, Colombia, was selected as the transportation starting point. Containers were then transported to a distribution and commercialization center in Bogotá. In both cases, the destination corresponded to a distributor facility belonging to the same company, ensuring consistency in the logistical conditions of the evaluated system. The inventory also incorporated the transportation of sugarcane bagasse from Valle del Cauca, considering that this region concentrates a substantial proportion of Colombia's sugar mills, according to the Sociedad de Agricultores de Colombia[31].

Stainless steel (Reusable material)

The inventory data for the stainless steel reusable container were obtained from a study developed in China, which modeled the production of molten steel considering five different scrap-content scenarios[26]. To better represent the evaluated system, these data were interpolated to adjust the raw material composition to 75% scrap content, consistent with the conditions of the case study. According to S&P Global Commodity Insights, China was the world's largest importer of iron ore in 2025, with Australia as its primary supplier. Consequently, maritime transport of iron ore was incorporated into the raw material dataset [32].

For the continuous casting, hot rolling, and deep drawing stages, data from the ecoinvent database were used in combination with energy consumption information reported for the steel industry [27], ensuring consistency with internationally recognized LCA sources. The transportation stage included the shipment of the finished container from China to Bogotá, considering its distribution to the logistics center defined within the system boundaries.

When simulating the current reality of container disposal, we decided to contact the Bogotá Recycling Association (ARB), which comprises 14 of the 382 professional recycling organizations active in Bogotá and 2,600 of the 26,159 professional recyclers registered in Bogotá[33]. Based on these conversations, it was concluded that in Bogotá, 100% of all materials are sent to landfills for final disposal. This is due to difficulties related to separating them for recycling because they are coated, in the case of kraft paper, because of the cost of storage, in the case of EPS, or because of a lack of defined routes, in the case of compostable materials.

For the end-of-life analysis of single-use containers (EPS, kraft paper, and compostable) in landfills, the degradation rate of each material under the anaerobic conditions typical of this type of disposal will be taken into account.

Table 1. Inventory kraft paper -PE

INPUT/ OUTPUT	QUANTITY	UNIT
	INPUT	
Electricity P-L	0,00657	MJ
Electricity P-C	0,00045972	MJ
Electricity P-T	0,0384984	MJ
Electricity P-M	0,035064	MJ
Kraft Paper	0,04661	kg
LDPE	0,000048	kg
Treatment of paper waste, sanitary landfill	0,04661	kg
Treatment of polyetylene waste, sanitary landfill	0,000048	kg

Table 2. Inventory expanded polystyrene (EPS)

INPUT/ OUTPUT	**QUANTITY**	**UNIT**
	INPUT	
Charcoal P-PE	0,000107	kg
Charcoal P-M	0,000107	kg
Electricity P-PE	0,0107028	MJ
Electricity P-M	0,0100728	MJ
Electricity P-S	0,054144	MJ
Polystyrene	0,01994	kg
Steam P-PE	0.0474	kg
Steam P-PM	0.0474	
Water P-PE	0,00168	kg
Water P-M	0,00168	kg
Treatment of polystyrene waste, sanitary landfill	0.01749	kg
	OUTPUT	
Carbon dioxide	0.000421	kg
Carbon monoxide	0.000115	kg
Nitric oxide	0.000064	kg
Nitrogen dioxide	0.000008	kg
Particulate matter	0.0000155	kg
Sulfur dioxide	0.0000039	kg
Sulfur trioxide	0.0000003	kg

Table 3. Inventory sugarcane bagasse

INPUT/ OUTPUT	**QUANTITY**	**UNIT**
	INPUT	
Sugarcane bagasse	0,043575	kg
Biomass fuel	0,02901	kg
Water	0,125243	kg
Treatment of paper waste, sanitary landfill	0.04150	kg
	OUTPUT	
Particulate matter	0,0000087	kg
Sulfur dioxide	0,000025	kg
Nitrogen oxides	0,000030	kg

Table 4. Inventory stainless steel FU

INPUT/ OUTPUT	**QUANTITY**	**UNIT**
	INPUT	
Steel	0,000336	kg
Electricity P-CC	0,00011007	MJ

Electricity P-L	0,00010282	MJ
Electricity P-EP	0,00004028	MJ
Compressed air P-EP	0,000000148	m3
Water (use)	0,15680	kg
Treatment of steel waste, incineration	0,000336	kg

2.2.4. Limitations of life cycle impact assessment

2.2.4.1. Uncertainty assessment

Uncertainty assessment is an essential component of LCA studies according to ISO 14044, as it allows the reliability of results to be quantified and determines whether the differences observed between alternatives are statistically significant. The assessment of uncertainty associated with LCA results was developed using a probabilistic approach based on Monte Carlo simulations, running 10,000 Monte Carlo simulations for each modeled scenario. This approach allows us to capture the variability inherent in life cycle inventories, as well as the epistemological uncertainty derived from the quality of the data used.

To statistically characterize inventory flows, the Pedigree matrix of the Weidema–Müller–Ciroth–Leisner method, incorporated in openLCA, was used (Table S1 in Supplementary material). This method assigns uncertainty factors based on data quality, considering five dimensions:

- Analytical reliability,
- Completeness,
- Temporal representativeness,
- Geographical representativeness, and
- Technological representativeness.

Each of these dimensions is translated into a log-normal uncertainty value using an Uncertainty Factor (UF), which is then combined with the base value of the flow to define a lognormal probability distribution (Ciroth et al., 2016).

2.2.4.2. Sensibility assessment

In order to evaluate the robustness of the life cycle assessment results and determine the influence of key system parameters, a sensitivity analysis was performed on the inventory flows with the greatest contribution to the impact categories assessed using the ReCiPe 2016 method. The selected parameters corresponded to those considered the most uncertain within the system, as they strongly depend on logistical conditions, operational practices, and local characteristics of the evaluated context. In particular, the analysis focused on transportation within the system boundaries, raw material transportation, and the energy required for container processing and manufacturing.

For each parameter, baseline values were individually modified by ±20% for energy consumption, ±50 km for transportation within the system boundaries, and ±200 km for raw material transportation, while keeping all other model variables constant. To avoid biases associated with the baseline inventory, absolute variation scenarios were defined for the transportation parameters instead of percentage-based changes, establishing common distance variations across all alternatives. This approach enabled the evaluation of how plausible variations in critical inventory parameters could influence the final LCA outcomes, providing insight into the sensitivity of the model to data uncertainty and changes in operating conditions.

3. Results

3.1. Comparative analysis of results across software programs

Figure 2 is an Observed vs. Predicted Plot to evaluate the consistency of the results obtained with the LCA softwares SimaPro and openLCA. In this analysis, SimaPro results were used as the reference values (predicted), while openLCA outputs were treated as observed values.

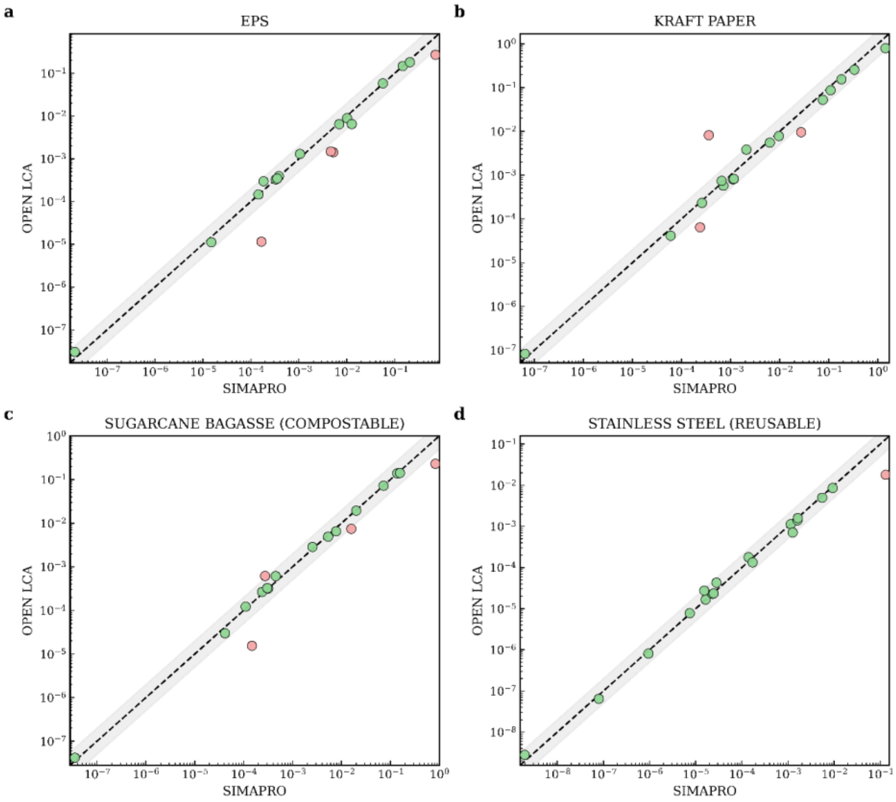

Figure 2. Comparison of SimaPro and OpenLCA Results. SimaPro results were used as the reference values (predicted), while openLCA outputs were treated as observed values. Each point represents an impact category assessed using the ReCiPe 2016, allowing a direct comparison between both tools. The diagonal line indicates the ideal 1:1 agreement between results, while a dispersion band was included to visualize the degree of concordance.

Creating this type of graph enables both a visual and statistical assessment of the agreement between the results obtained using different modeling tools. The graph was constructed considering a ±20% admissible deviation range around the line of equality, meaning that differences between both tools within this interval were considered acceptable given the inherent variability and uncertainty associated with LCA modeling, database adaptation, and software implementation. Most of the data points were located close to the equality line and within the established admissible range, indicating that the observed differences were generally limited and did not alter the overall trend of the results.

This comparison was performed for the four evaluated materials, and the impact categories that repeatedly exceeded the ±20% admissible range across more than one case were identified. Terrestrial ecotoxicity, freshwater eutrophication, and carcinogenic human toxicity were the categories that most consistently fell outside the established threshold. Consequently, these categories were excluded from the interpretation of results and the formulation of conclusions in order to avoid potential misinterpretations or biased comparisons between alternatives.

These discrepancies may be associated with differences between the versions available for each modeling tool, including variations in characterization factors, background datasets, and calculation procedures. Nevertheless, future studies should conduct a more detailed evaluation of the origin of these inconsistencies, particularly regarding methodological differences between software platforms and the influence of database-version updates on impact assessment results.

3.2. Life cycle impact assessment

Figure 3 presents the contribution analysis for the four food delivery container alternatives evaluated: sugarcane bagasse, expanded polystyrene (EPS), kraft paper with polyethylene coating, and reusable stainless steel, using both openLCA and SimaPro. The figure presents the results obtained for the 18 impact categories assessed using the ReCiPe 2016 Midpoint (H) methodology, and each alternative is normalized relative to the one with the highest impact, allowing for the identification of the relative performance among the materials analyzed.

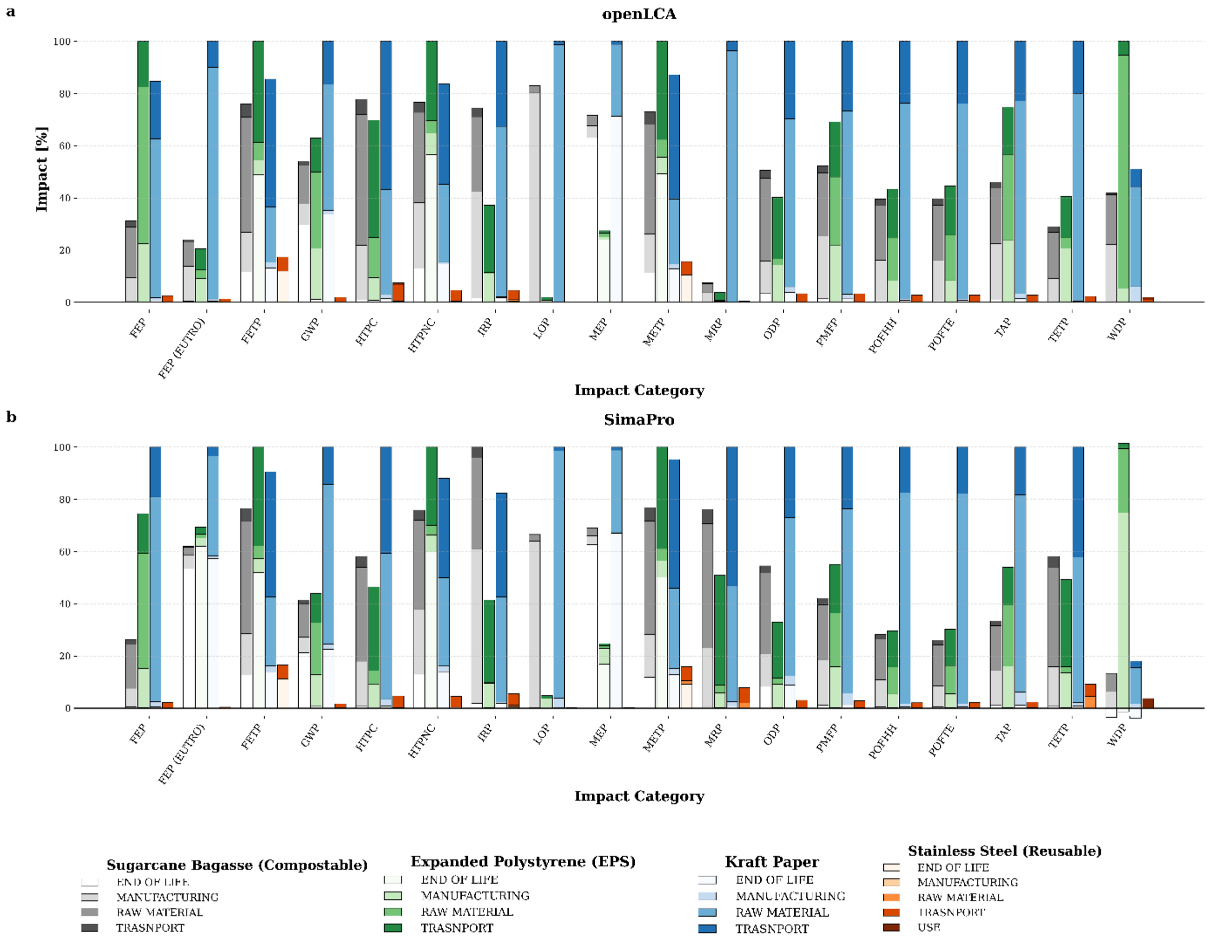

Figure 3. Impact category results. a) OpenLCA results. b)SimaPro results

NOTE: TAP: Terrestrial acidification. GWP: Climate change. FETP: Freshwater ecotoxicity. METP: Marine ecotoxicity. TETP: Terrestrial ecotoxicity. FEP: Depletion of fossil energy resources. FEP (Eutro): Freshwater eutrophication. MEP: Marine eutrophication. HTPc: Human carcinogenic toxicity. HTPnc: Human non-carcinogenic toxicity. IRP: Ionizing radiation. LOP: Land use. MRP: Depletion of mineral and metal resources. ODP: Ozone layer depletion. PMFP: Particulate matter formation. POFhh: Formation of photochemical oxidants (human health). POFte: Formation of photochemical oxidants (terrestrial ecosystems). WDP: Water use or depletion

Consistent with the findings of the previous direct comparison between the two software programs, the overall differences in the results are not significant. Overall, both software platforms showed consistent trends across the evaluated impact categories, indicating good methodological agreement despite minor differences in the magnitude of individual contributions. FEP (Depletion of fossil energy resources) and IRP (Ionizing radiation) categories are the only exceptions, where the results differ between the software programs. These differences can be attributed to variations in process implementation or to differences in the database versions used for the assessment. In this regard, tools such as uncertainty analysis allow for a more robust evaluation of the significance of these differences and strengthen the comparative interpretation.

Across most impact categories, kraft paper exhibited the highest environmental burdens, particularly in categories associated with climate change (GWP), terrestrial acidification (TAP), and marine eutrophication (MEP). These impacts were primarily dominated by the raw material production stage, and the anaerobic biodegradation in the sanitary landfill, suggesting that the manufacturing of virgin paper fibers and associated processing activities of its final disposal strongly influence the overall environmental profile of the system. In contrast, the lower material requirement for manufacturing EPS containers reduces environmental burdens associated with both material production and energy consumption. EPS generally presented lower impacts than kraft paper in most categories. Despite its petrochemical origin, EPS consistently showed lower contributions in several categories related to land occupation, water consumption, and eutrophication, highlighting the importance of considering the full life cycle rather than material perception alone.

Sugarcane bagasse showed intermediate behavior between EPS and kraft paper. The environmental profile of this alternative was strongly influenced by the raw material stage and End of Life due to the anaerobic biodegradation. In categories such as land occupation, and ozone depletion, the contribution of agricultural activities associated with sugarcane cultivation became more significant.

The reusable stainless steel container exhibited a markedly different environmental profile. Although the manufacturing stage generated relatively high contributions in several impact categories due to the energy-intensive production of stainless steel, these impacts were distributed over multiple use cycles. Consequently, the use phase showed comparatively small contributions, supporting the potential environmental advantages of reusable systems when sufficient reuse rates are achieved.

When comparing the contribution breakdown between SimaPro and openLCA, differences are observed in the relative distribution of impacts across life-cycle stages. In some impact categories, the dominant stage varies between tools. For example, in Depletion of mineral and metal resources, results from SimaPro indicate that the largest contribution arises from Kraft Paper container raw material,whereas openLCA attributes the main contribution to transport. A similar pattern is observed for Water Depletion, where openLCA identifies EPS raw material extraction as the primary contributor, while SimaPro highlights the manufacturing stage. These differences underline the need for further examination of potential causes, including variations in database implementation, modelling assumptions, and flow allocation within the life cycle inventory.

3.3. Uncertainty assessment

The application of the Pedigree matrix in each of the input flows of the alternatives evaluated and the detailed results obtained from the Monte Carlo simulation are available in Supplementary material (Table S2, S3, S4 and S5). Overall, the distributions for both alternatives show a right-skewed pattern, which is consistent with the lognormal distributions generated through the Pedigree matrix implemented in openLCA to characterize uncertainty in life cycle inventory parameters.

The Monte Carlo uncertainty analysis provides additional insight into the robustness and statistical stability of the comparative LCA results among kraft paper, EPS, sugarcane bagasse, and reusable stainless steel containers. For example, beyond the deterministic comparison, the probability distributions shown in Figure 4 and 5 allow evaluation of the variability, overlap, and relative separation between alternatives in ionizing radiation and climate change respectively, which are critical for determining whether the observed environmental differences are statistically meaningful or potentially sensitive to inventory uncertainty.

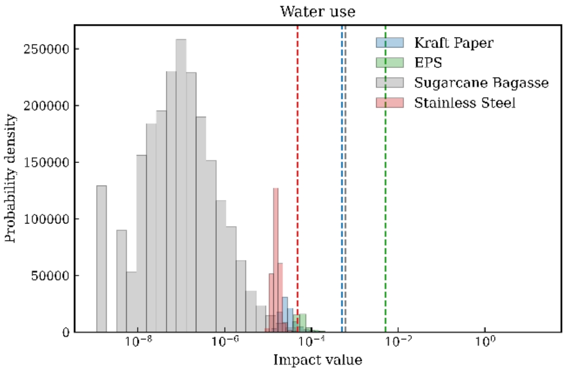

Figure 4. Monte Carlo Water use

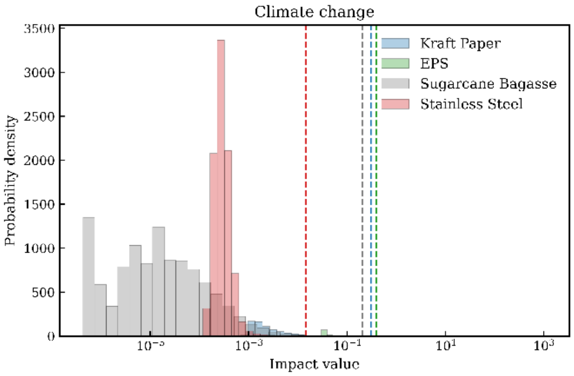

Figure 5. Monte Carlo Climate change

For climate change, EPS and kraft paper exhibit distributions systematically shifted toward higher impact values, with their central tendency lines located several orders of magnitude to the right of sugarcane bagasse and stainless steel. The limited overlap between these distributions indicates a low probability of result inversion, meaning that the ranking between alternatives is statistically stable rather than dependent on isolated inventory values. This is highly relevant for the LCA interpretation because it increases confidence that the lower impacts observed for bagasse and reusable stainless steel are not artifacts of deterministic assumptions but persist under uncertainty conditions. Additionally, kraft paper and EPS present broader distributions and longer tails, reflecting greater uncertainty propagation from upstream processes such as raw material production and energy consumption, which is consistent with the contribution analysis previously identified.

The main difference between both figures lies in the relative separation and dispersion of the distributions. In the climate change category, the distributions are more clearly separated, particularly between high-impact materials (EPS and kraft paper) and low-impact alternatives (bagasse and stainless steel), indicating stronger statistical differentiation and more robust comparative conclusions. In contrast, the water use category shows a greater degree of proximity between kraft paper, EPS, and stainless steel, suggesting that this indicator is more sensitive to inventory variability and therefore presents higher uncertainty in the comparative ranking. Another important distinction is the behavior of sugarcane bagasse, which exhibits extremely low impact values and highly concentrated distributions in both categories, indicating low variability and high stability of results. From an LCA perspective, this contributes significantly to the reliability of the environmental interpretation, as alternatives with narrow and consistently low distributions provide stronger evidence for environmentally preferable performance than systems characterized by broad and highly dispersed uncertainty ranges.

3.4. Sensibility assessment

The results of the sensitivity analysis are presented in Supplementary material, evaluating the effect of varying three key system parameters: raw material transport distance (DMP), processing energy demand (E), and transport within the system expressed in ton-kilometers of the functional unit. This analysis was conducted for all impact categories assessed using the ReCiPe 2016 to identify the parameters with the greatest influence on the LCA results. For example, Figure 6 shows the sensitivity analysis for Land Use reveals that energy demand (E) is the most influential parameter, particularly for EPS, which shows variations of up to ±16–18% — the widest range among all materials. This indicates that the LCA results for EPS are highly sensitive to changes in processing energy consumption, meaning that energy efficiency improvements could substantially alter its environmental performance in this category. Sugarcane Bagasse also exhibits moderate but consistent sensitivity across both E and raw material transport distance (DMP), while Kraft Paper and Stainless Steel display notably narrow bars across all three parameters (below ±0.3%), confirming the robustness and reliability of their relative positions in the LCA.

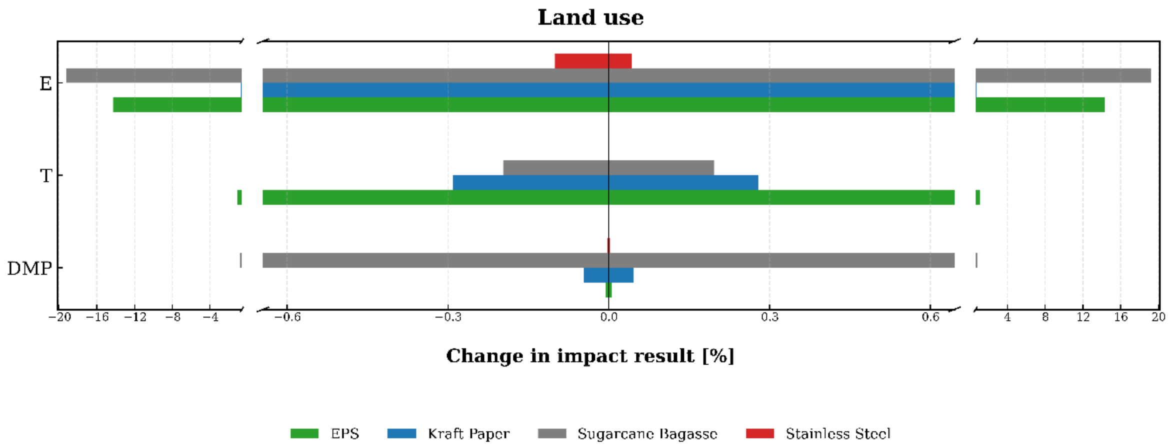

Figure 6. Tornado chart Land use

The findings indicate that transport within the system is the most influential parameter across most impact categories, highlighting the strong effect that variations in transport distance or load can have on overall environmental impacts. Similarly, the distance associated with raw material supply (DMP) also shows a notable influence in several categories, reflecting the sensitivity of the system to the geographic location of suppliers. In contrast, variations in processing energy demand have a comparatively smaller effect within the tested range. Overall, these results emphasize the importance of accurately characterizing logistical conditions in LCA studies, as relatively small changes in transport assumptions can significantly affect impact estimates and should be considered when interpreting results or extrapolating them to other geographical contexts

4. Conclusion

The comparison of results obtained using SimaPro and openLCA indicates that the overall differences in estimated environmental impacts are not significant. This finding supports the use of either tool for life cycle assessment modeling, with SimaPro being more common in academic research and openLCA widely adopted in industry due to its open-source and free-access nature. Consequently, software selection can be guided by the specific needs, resources, and context of the user. However, the comparison also highlights opportunities for further research to better understand discrepancies in the distribution of impacts across life cycle stages.

The study also demonstrates the strong influence of material intensity on the environmental performance of the evaluated containers. Due to the smaller amount of material required, the EPS container shows a comparative advantage across several impact categories. Sensitivity and uncertainty analyses further helped identify impact categories that require cautious interpretation and the parameters that most strongly influence results, emphasizing the importance of considering the specific context of production, distribution, use, and end-of-life management when interpreting LCA outcomes.

Finally, the transition toward more sustainable packaging systems requires coordinated action among multiple stakeholders. Producers can support this transition by developing alternative materials supported by comprehensive environmental assessments. Consumers can influence market demand by selecting establishments that adopt environmentally preferable packaging options. Restaurants and delivery platforms also play a key role by integrating and promoting more sustainable packaging solutions within their operations. At the policy level, governments are essential in establishing technical criteria and regulatory frameworks based on robust methodologies such as life cycle assessment, ensuring consistent and evidence-based decision-making for sustainable material management.

Acknowledgments

The authors have no acknowledgments to declare.

Appendix A. Supplementary material

Supplementary data to this article can be found online at …

References

[1] ONU, “Informe de los Objetivos de Desarrollo Sostenible.”

[2] EPA, “Best Practices for Solid Waste Management: A Guide for Decision-Makers in Developing Countries. Solid Waste Management and Climate Change.”

[3] DANE, “Cuenta Ambiental y Económica de Flujos de Materiales de Residuos Sólidos (CAEFM-RS) 2022 – 2023 provisional.”

[4] Secretaría Distrital de Ambiente, “Porcentaje de Generación de Residuos Aprovechables por Tipo de Material en el Sector Público Distrital. - PIGARESIDUOS.”

[5] Universidad de los Andes - Facultad de Derecho, “Casi el 60 % de la basura diaria de Bogotá es desecho plástico.”

[6] United Nations Development Programme, “Why aren’t we recycling more plastic?”

[7] M. Florencia Melo, “The World Is Flooded With Plastic Waste.”

[8] J. I. B. Janairo, “Unsustainable plastic consumption associated with online food delivery services in the new normal,” *Cleaner and Responsible Consumption*, vol. 2, p. 100014, Jun. 2021, doi: 10.1016/j.clrc.2021.100014.

[9] Statista, “Number of users of the online food delivery market worldwide from 2017 to 2030, by segment.”

[10] Statista, “Online Food Delivery - Worldwide.”

[11] Y. Jang, K. Nam Kim, and J. Woo, “Post-consumer plastic packaging waste from online food delivery services in South Korea,” *Waste Management*, vol. 156, pp. 177–186, Feb. 2023, doi: 10.1016/j.wasman.2022.11.036.

[12] M. Limuro and T. Tabata, “Relationship between the demand for food delivery and takeaway services and the associated plastic packaging waste during the COVID-19 pandemic,” *J. Mater. Cycles Waste Manag.*, vol. 26, no. 1, pp. 591–601, Jan. 2024, doi: 10.1007/s10163-023-01861-y.

[13] Congreso de Colombia, *POR LA CUAL SE ESTABLECEN MEDIDAS TENDIENTES A LA REDUCCIÓN GRADUAL DE LA PRODUCCIÓN Y CONSUMO DE CIERTOS PRODUCTOS PLÁSTICOS DE UN SOLO USO Y SE DICTAN OTRAS DISPOSICIONES*. Colombia, 2022.

[14] N. Hijazo Dies, “Diseño de proyecto para reciclaje de poliestireno expandido (EPS) en la ciudad de Huesca,” Universidad de Zaragoza, Zaragoza, 2021.

[15] M. P. Desole, A. Gisario, L. Fedele, C. Aversa, and M. Barletta, “Life cycle assessment of secondary packaging: Expanded polystyrene versus bioplastic-coated corrugated cardboard,” *Sustain. Prod. Consum.*, vol. 46, pp. 11–28, May 2024, doi: 10.1016/j.spc.2024.02.010.

[16] A. J. A. Junior and C. Saron, “Mechanical recycling of expanded polystyrene and tire rubber waste as compatibilized and toughened blends,” *J. Appl. Polym. Sci.*, vol. 140, no. 32, Aug. 2023, doi: 10.1002/app.54267.

[17] N. Triantafillopoulos and A. A. Koukoulas, “The future of single-use paper coffee cups: Current progress and outlook,” *Bioresources*, vol. 15, no. 3, pp. 7260–7287, 2020.

[18] Elllen Macarthur Foundation, “Compostable, biodegradable, and bio-based plastic – what’s the difference?”

[19] S. Duran, “Análisis comparativo del ciclo de vida de un envase de un solo uso de cartón y de un modelo de reuso de un envase de acero inoxidable con el método ISO 14044:2007 usando la herramienta SimaPro. ,” Universidad El Bosque, 2023.

[20] S. C. Greenwood *et al.*, “Many Happy Returns: Combining insights from the environmental and behavioural sciences to understand what is required to make reusable packaging mainstream,” *Sustain. Prod. Consum.*, vol. 27, pp. 1688–1702, Jul. 2021, doi: 10.1016/j.spc.2021.03.022.

[21] L. Camps-Posino *et al.*, “Potential climate benefits of reusable packaging in food delivery services. A Chinese case study,” *Science of The Total Environment*, vol. 794, p. 148570, Nov. 2021, doi: 10.1016/j.scitotenv.2021.148570.

[22] T. Cruz Cuevas and J. Zaldúa Ramírez, “Análisis de ciclo de vida del poliestireno expandido usado en contenedores de alimentos en Colombia.”

[23] F. Shao and Q. Cui, “Comparison of life cycle assessment for takeout meal packaging (kraft paper bowl and plastic bowl) based on Simapro,” *Pigment & Resin Technology*, vol. 53, no. 6, pp. 704–709, Nov. 2024, doi: 10.1108/PRT-10-2022-0113.

[24] D. Michel, B. Bachelier, J.-Y. Drean, and O. Harzallah, “Preparation of Cellulosic Fibers from Sugarcane for Textile Use,” *Conference Papers in Materials Science*, vol. 2013, pp. 1–6, Oct. 2013, doi: 10.1155/2013/651787.

[25] Md. A. Mahmud and F. R. Anannya, “Sugarcane bagasse - A source of cellulosic fiber for diverse applications,” *Heliyon*, vol. 7, no. 8, p. e07771, Aug. 2021, doi: 10.1016/j.heliyon.2021.e07771.

[26] L. Yang, H. Hu, S. Yang, S. Wang, F. Chen, and Y. Guo, “Life cycle carbon footprint of electric arc furnace steelmaking processes under different smelting modes in China,” *Sustainable Materials and Technologies*, vol. 35, p. e00564, Apr. 2023, doi: 10.1016/j.susmat.2022.e00564.

[27] L. D. D. Harvey, “A bottom-up assessment of recent (2016–20) energy use by the global iron and steel industry constrained to match a top-down (International Energy Agency) assessment,” *Energy*, vol. 293, p. 130675, Apr. 2024, doi: 10.1016/j.energy.2024.130675.

[28] Veritrade, “Foreign trade in the last five years: Styrene (HS 290250),” 2024.

[29] Smurfit Westrok, “Sustainability report,” 2025.

[30] M. Fan and C. Bussracumpakorn, “Life Cycle Assessment of Sugarcane Bagasse Takeout Containers: A Case Study in Laibin, Guangxi, China,” *Environ. Nat. Resour. J.*, vol. 24, no. 2, pp. 1–13, Mar. 2026, doi: 10.32526/ennrj/24/20250100.

[31] Sociedad de Agricultores de Colombia, “La agroindustria azucarera busca nuevas fuentes para generar energía, así como obtener otros productos a partir del bagazo.,” *Revista Nacional de Agricultura*, vol. 1016, 2021.

[32] S&P Global Market Intelligence, “Simandou’s first shipment with 200,000-mt high-grade iron ore arrives in China. Commodities at Sea,” 2026, Accessed: May 13, 2026. [Online]. Available: https://www.spglobal.com/energy/en/products-solutions/shipping/commodities-at-sea?utm_source=google&utm_medium=cpc&utm_campaign=q1_2026_global-inbound-website-ad-news_products-services-ferrous&gclid=CjwKCAjwqubPBhBOEiwAzgZX2gj7HR08ibA-YcMCUpc1cKH39qoX_t9LXDoC0VSWHJsBqg1so2J4rhoCMI0QAvD_BwE

[33] UAESP, “INFORME DE GESTIÓN 2024 Versión 2.”