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# Comparative Issues in LCA – Applicability to Carbonated Beverage Containers

**Prepared for:**

## Aluminum Association

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## Legal Notice

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# 1.0 Introduction

When choosing materials for a product, modern companies must consider a wide range of options, all of which have inherent positive and negative attributes. Today, more emphasis is being placed on the usage of materials that offer preferable environmental properties, such as a lower carbon footprint. In the packaging space, there is ongoing debate about the relative environmental impacts of materials such as plastic, aluminum, and glass.

While consumers and the general populace may associate certain materials as being more "environmentally friendly" than others, this concept can be vague and subjective, leaving room for interpretation. This paper is intended to address comparative issues assessing the carbon footprint of carbonated beverage containers made of aluminum (Al), glass, and plastic (specifically polyethylene terephthalate, PET). The paper will do so by outlining key concepts pertaining to life cycle assessment (LCA) and product carbon footprint (PCF), as these methodologies often serve as a basis for comparison between different products. Through a literature review process, results from various comparative studies are compiled, scaled to an equivalent basis, and analyzed. A discussion of the findings is presented, with the aim of presenting a clear picture of the carbon footprint of carbonated beverage containers.

# 2.0 Life Cycle Assessment and Product Carbon Footprinting

LCA is a systemic analysis that quantifies the potential life cycle environmental impacts of a product from raw material extraction to the recycling or disposal of the product at end-of-life. The results of an LCA often include a range of impact assessment indicators such as primary energy demand, global warming potential, acidification potential, eutrophication potential, and smog formation potential, among others. This paper focuses on global warming potential (GWP), which is a measure of a product's contribution to climate change and is the unit of measurement for a PCF. GWP is measured in units of carbon dioxide equivalents (kg $CO_2e$). For the purposes of discussion in this paper, GWP and PCF are considered to be equivalent and interchangeable terms.

A product carbon footprint refers to the cumulative climate impact of a product throughout its life cycle, from raw material extraction to recycling or disposal at the end-of-life (EOL). The climate impact is measured and expressed as the global warming potential of greenhouse gas emissions associated with the product – from raw material extraction from the earth through use and end-of-life management.

There are a variety of standards and protocols that guide the quantification and communication of the PCF. One of the most used standards is the ISO 14067 (International Organization for Standardization, 2006). ISO 14067 requires that the quantification of carbon footprint of product must be based on ISO 14040 (International Organization for Standardization, 2006a) and 14044 (International Organization for Standardization, 2006b) standards. These two standards set principles, framework, requirements, and guidelines for LCA studies. There is an intrinsic relationship between PCF and LCA, in which the calculation of PCF should be based on LCA procedures, methodologies, and tools. In other words, any robust disclosure or claim of PCF should be supported by LCA data and studies.

# 3.0 Key Comparability Criteria for Product Comparisons

Comparing PCFs among beverage containers is subject to the issues discussed in this paper. Before diving into those issues, there is a key prerequisite for comparison among products: functionality. Products can be compared only when they perform similar or the same functionality.

For beverage containers, one of the functions is to pack the beverage so that it can be delivered from the manufacturer to consumers. However, the functionality goes beyond packaging for delivery. Beverages are made with predetermined color, taste, nutrition, flavor, and smell, among other attributes. An ideal beverage container protects all these predetermined physical specifications from deteriorating before the beverage is consumed. In addition, almost all beverage containers are designed with a predetermined consumption volume in mind: some are for a single serving, some are for multiple servings, and with a variety of configurations. The differences between beverage categories also lead to variations in packaging material specifications. For instance, to pack carbonated beverages and beer, the container needs to have sufficient strength, rigidity, and seal-tightness to hold the carbonated gases. On the other hand, water doesn't require a high strength or as rigid of a container. As a result, comparing containers with differing applications is difficult since the functionalities of these containers are not directly comparable.

## 3.1 Functional Unit and Reference Container Size

One of the central attributes of an LCA is that the analysis is based on product function and a specified functional unit, which serves as the unit for which process data are scaled and for which the results are presented. ISO 14044 section 3.20 defines a functional unit as the "quantified performance of a product system for use as a reference unit."

Once product functions are determined, it becomes necessary to decide what functional unit may be used as a baseline for comparison. Some studies use a single container as the basis of comparison regardless of its size. Others focus on per-unit-volume of beverage. From a comparability point of view, containers should be compared on a per unit beverage volume (e.g., milliliter, liter, fluid ounce or gallon), since container sizes can differ significantly and since the ultimate function of the container is the delivery of beverage to the consumer.

Even if comparisons are made based on per-unit-volume of beverage, it is still important to compare containers of a similar size. This is important for two reasons. The first reason is the functions of different size containers are different: some are for a single serving and others are for multiple servings. Second, from a material efficiency point of view, larger-sized packaging is more efficient per unit of packed goods compared to a smaller size packaging. Using less material for packaging is a design choice that goes beyond the consideration of material efficiency. It takes into account improved product protection, reduced spoilage, increased shelf-life, and convenience for consumption and delivery. As a result, LCA comparisons should take these differences into consideration – distinct functions and choices that are embedded in the designs of different size containers. The best approach in comparing containers made of different materials is to compare similar size containers.

## 3.2 Boundary of Study

A second issue for LCA comparison is related to mismatching system boundaries. System boundary refers to a product's life cycle stages and processes that are included in a study. The system boundary of an LCA can be cradle-to-gate (e.g., raw material extraction and manufacturing), cradle-to-grave (full life cycle from raw material extraction to end-of-life), or, in some cases, gate-to-gate (representing a single life cycle stage or process step). However, differences between system boundaries make it difficult to compare studies. Studies that include the use and end-of-life stages will have a different emissions profile than cradle-to-gate studies that only include production impacts, and therefore may not be directly comparable. Even in the case of studies that have the same system boundary, say cradle-to-gate, the specific boundaries of the compared products may still be very different from each other. For example, one study may include container filling and distribution in its definition of cradle-to-gate while another study may only consider container manufacturing and exclude downstream process steps.

Extensive debates have been had within the environmental community regarding whether comparisons should be made at the partial life cycle or full life cycle level. For instance, comparisons of carbon footprint of products are usually focused on the cradle-to-gate level, provided that the processes excluded from the system boundaries are the same for the comparative products. However, such a comparison misses a key aspect of life cycle thinking. The fundamental principle for life cycle thinking and life cycle assessment is to address the environmental impact of products from a full life cycle perspective, an approach that can overcome the problem of "burden shifting" of a traditional "compliance and control" approach at the tailpipe. Burden shifting refers to shifting environmental impact from one impact category to another or from one life cycle stage, one location, one time, or one generation, to another. For a product like a beverage container with a very short lifetime, comparisons should be made at a full life cycle level to make sure that the product is not only designed for packaging service but also for waste reduction, reuse, and recycling.

## 3.3 Data Quality and Representativeness

Data are the foundation for product LCA and PCF studies. The quality of data and data representativeness are directly linked to the robustness of results. When comparisons are made, it is the highest priority for practitioners to make sure that the quality and representativeness of data for different materials is aligned.

Data quality assessment includes a review of the preciseness, completeness, consistency, reproducibility, and representativeness of the data. Preciseness refers to whether the data are from directly measured data at production sites, or whether data are calculated, drawn from literature references, or estimated. Completeness refers to whether all inputs and outputs of a unit process, and all relevant unit processes, are included. Consistency refers to alignment between modeling choices and data sources. It is important to ensure that differences in results reflect actual differences between product systems, not due to inconsistencies in modeling choices, data sources, emission factors, or other artifacts. Reproducibility refers to the degree to which third parties would be able to reproduce the results of a study based on the information contained in the study itself. To that end, a high level of transparency is also necessary in reporting.

Data representativeness is also part of the data quality assessment. It refers to the degree to which the data matches the geographical, temporal, and technological requirements defined in a study's goal and scope. When comparisons are made between beverage containers of different materials, the ideal situation is that the data selected represent the same or similar geographical, temporal, and technological scope.

## 3.4 Methodology for End-of-Life Treatment

As mentioned in section 3.2, the environmental impact of packaging products with a very short lifetime should be studied at the full life cycle level to ensure that natural resources extracted from the earth can be efficiently and effectively utilized through waste reduction and material reuse and recycling. To achieve this goal, different methodological choices can be made in the modeling of material recycling and disposal. The process is often known as end-of-life allocation. Recycling may help to preserve natural resources and avoid the need to produce new virgin materials. Therefore, some credits or burdens should be allocated to the recycling of materials at the end of a product's life. Methodological choices made for allocation can have a significant impact on the results of a study. In addition, there should be burdens or credits allocated to other material disposal options such as waste-to-energy or landfilling. Note that the difference in results for choosing differing allocation methods for waste-to-energy or landfilling are typically not as significant as that for recycling.

There are two main methods typically used for recycling allocation. One method is known as the cut-off method (other names include recycled content, 100:0). The other is known as substitution (other names include avoided burden, 0:100).

The cut-off method assigns no upstream virgin material environmental burden to recycled material used in a product, and ignores any benefits of any additional recovery of materials at the end of a product's life that can be used by other products or in the next generation of products.

The substitution method assigns credits for the use of recycled material in a product, and gives credit for additional recovered materials that can be used by other products. In the case where a product uses more recycled material than the amount of material recovered at end-of-life, an upstream virgin material burden is assigned to the deficit proportion of the material recovery. The method is also called a net scrap approach.

The net scrap approach is an appropriate method for allocation for recycling in the case of beverage containers due to the use of recycled material, the improvement of recycling recovery rates and processes, and the relatively short time span in which the products are produced and disposed of. It is important to note that both cut-off and substitution methods are acceptable modeling approaches, and they are both ISO-compliant.

## 3.5 Transparency and Critical Review

Given the complexity of LCA studies and the uniqueness of materials and products, ISO 14040 and 14044 standards set strict requirements on transparency and reporting. This is particularly important when it comes to studies that are intended to make comparative assertions and public claims. For comparative assertions disclosed to the public, a detailed report must be developed and a critical review must be conducted by a panel of independent experts. This is to make sure that the quality of a study and the legitimacy of claims are robust, verifiable, and unbiased.

# 4.0 Literature Review and Analysis of Comparative Issues

Focusing on the PCF of single use carbonated beverage containers, we conducted a literature review of various publicly available or publicly communicated studies to examine the quality of the studies and the robustness of their conclusions and claims. The goal of the review and analysis is to inform the public about the complexities behind the claims of carbon footprint of these products. The studies were identified either through a detailed literature review or collection of published reports and papers.

Several considerations were applied to the selection criteria for the studies. The first was to select studies sponsored or conducted by industry groups and trade associations. This is to ensure that the product and its environmental footprint represent an industry average profile instead of the performance of a specific manufacturer. Industry groups and trade associations are in the best position to examine the environmental performance of their own products because these groups can access and collect real production data from manufacturers. In applying this criterion, two exceptions were made in the case of the Owen-Illinois 2010 study and the Ball Corporation sponsored 2020 study. The selection of these two works was because both studies were largely using industry average data instead of company specific data, and both were focused on comparisons.

The second consideration was to select the most recent studies since very old ones may not represent today's manufacturing technology and operations. However, the availability of new studies is limited for some materials, like glass. The latest publicly available industry study for glass bottles was published in 2010.

A third criterion for selecting studies involves considering third-party research. This refers to studies that are sponsored and conducted by organizations without any affiliation to a specific beverage container manufacturing industry. The rationale behind this criterion is to prioritize a sense of neutrality. Third-party studies may encounter data quality issues that can arise when relying on data from public databases that may not accurately represent the current state of materials, technologies, and manufacturing efficiencies.

It is important to note that our review focused on studies about **common carbonated beverage containers**. Thus, noncarbonated containers and noncommon containers such as water bottles, cartons, aluminum bottles, reusable glass bottles and reusable PET bottles are excluded. In addition, the review also prioritizes information for products manufactured and sold in the North American region in cases where a study contains information for multiple geographic regions.

## 4.1 Detailed Reporting and Critical Review

For a PCF based on LCA, the process of calculating such footprints is based on the process of life cycle assessment, which follows procedures and requirements outlined in the ISO 14040 and 14044 standards. This is particularly important when it comes to studies that are intended to make comparative assertions and claims. A detailed study report is required and also requires a critical review process. The critical review process is carried out by an independent third party and is only required if the study is comparative and the results are being shared with the public. However, critical review can be a beneficial part of any LCA study - it can help improve the quality of the study and thereby increase stakeholder confidence and acceptance. The quality of a LCA and the legitimacy of claims relies on the level of detail in the background report, which can be made more robust through review by an unbiased expert reviewer or review panel. A study that publishes a detailed LCA report and goes through third-party review may nevertheless be biased – but from a credibility perspective, a transparent and critically reviewed LCA ranks much higher than a non-transparent and non-reviewed study.

The studies identified in the literature review varied widely in the type of report that is publicly available and the type of critical review performed. Some study reports were freely available on company websites or in academic journals, while for some only summary documentation and communications were published. When detailed background reports are not published, this lack of transparency makes the evaluation of the quality of the work more difficult or impossible. Table 1 shows the details of the reviewed studies in terms of the availability of a report and the critical review process. A peer review is an evaluation process by experts in a particular field, ensuring the quality and validity of the article before publication (typically in an academic journal). A critical review is an analysis and assessment of an LCA for conformance to ISO 14040/14044, providing an opinionated evaluation of its strengths, weaknesses, and overall merit.

*Table 1. Study attributes and critical review*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Comparative Study? | Background Report Published? | Critical Review or Peer Review |
|---|---|---|---|---|
| 1 | Aluminum Association 2010 (PE International) | No | Yes | Critical review |
| 2 | Aluminum Association 2014 (thinkstep) | No | Yes | n/a* |
| 3 | Aluminum Association 2021 (Sphera) | No | Yes | Critical review |
| 4 | Owen-Illinois 2010 | Yes | No | Unknown |
| 5 | PET Resin Association 2009 (Franklin Associates) | Yes | Yes | Critical review |
| 6 | Ball 2020 (Sphera) | Yes | Yes | Critical review |
| 7 | Carbon Trust 2022 | Yes | Yes (summary) | Unknown |
| 8 | Glass Packaging Institute 2010 | No | Yes (summary) | Critical review |
| 9 | University College Dublin 2015 | Yes | Yes | Peer review |
| 10 | The Energy and Resource Institute 2022 | Yes | Yes | Unknown |
| 11 | University of Salerno 2021 | Yes | Yes | Peer review |
| 12 | University of Maribor 2020 | Yes | Yes | Peer review |
| 13 | Carbon Trust 2010 (Reuters) | Yes | No | Unknown |
| 14 | McKinsey 2021 | Yes | Yes (summary) | Critical review |
| 15 | NAPCOR 2023 (Franklin Associates) | Yes | Yes | Critical review |

*The AA 2014 study was an update of the 2010 study and the report was in the form of a memo. No critical review was conducted due to the nature of the study.

Among the studies reviewed, two comparative pieces are deemed to have the lowest creditability because of the black box nature of the claims and the lack of a published background report. These include Owen-Illinois 2010 and Carbon Trust 2010 (Reuters).

## 4.2 Product Functions and Functional Unit

The assessment of functions and functional units of the studies focused on identifying the sizes of the underlying containers and the functional units used. Table 2 shows the differences in functional units and the sizes of the underlining containers for each study considered in the literature review. Across studies, both the container sizes and functional units differ. The Aluminum Association uses 1,000 containers representing a market mix of different sizes, while the Glass Packaging Institute uses 1 kg of mass – without defining the size of the container – as the functional unit. For studies comparing containers made of different materials, most were based on a certain volume of packaged beverage, although the volume and measuring unit differed between studies.

Many comparative studies did not use similar size containers as a base for comparison for different materials. **This is considered problematic in terms of comparability**. For instance, the 2023 NAPCOR study compared PET bottles of 2-liter, 20-oz, and 16.9-oz sizes with 12-oz and 16 oz aluminum cans and 12 oz glass bottles. The study compares single-serving containers to larger multiple-serving containers, which leads to a mismatch in the function of the containers studied. In addition, the large range of container sizes may lead to a misrepresentation of the comparability of the study results.

*Table 2. Study functional unit and container volume*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Functional Unit in Study | Single Container Volume (mL)* |
|---|---|---|---|
| **1** | Aluminum Association 2010 (PE International) | 1,000 cans | Al can: 384**<br>Glass bottle: n/a<br>PET bottle: n/a |
| **2** | Aluminum Association 2014 (thinkstep) | 1,000 cans | Al can: 384**<br>Glass bottle: n/a<br>PET bottle: n/a |
| **3** | Aluminum Association 2021 (Sphera) | 1,000 cans | Al can: 408**<br>Glass bottle: n/a<br>PET bottle: n/a |
| **4** | Owen-Illinois 2010 | 355 mL container | Al can: unknown<br>Glass bottle: 355<br>PET bottle: unknown |
| **5** | PET Resin Association 2009 (Franklin Associates) | Primary packaging of 100,000 ounces of soft drink | Al can: 355<br>Glass bottle: 237<br>PET bottle: 592 |
| **6** | Ball 2020 (Sphera) | 1 gallon of fill volume of small to medium size, single use beverage packaging at point of sale | Al can: 355, 474<br>Glass bottle: 355, 500<br>PET bottle: 355, 500 |
| **7** | Carbon Trust 2022 | 330 mL containers | Al can: 330<br>Glass bottle: 330<br>PET bottle: 330 |
| **8** | Glass Packaging Institute 2010 | 1 kg of glass produced | - |
| **9** | University College Dublin 2015 | Packaging and delivery of 1000 L beer to customer | Al can: 500<br>Glass bottle: 500<br>PET bottle: n/a |
| **10** | The Energy and Resource Institute 2022 | 1 L of fill volume of beverage and accordingly number of units of each product category needed | Al can: 250, 500<br>Glass bottle: 330, 650<br>PET bottle: 200, 600 |
| **11** | University of Salerno 2021 | Packaging needed for bottling and distribution of 1 L of natural mineral water and 1 L of sparkling mineral water | Al can: n/a<br>Glass bottle: 1000<br>PET bottle: 1000 |
| **12** | University of Maribor 2020 | Packaging necessary for distribution of 1,000 L of beverage | Al can: 500<br>Glass bottle: 500<br>PET bottle: 500 |
| **13** | Carbon Trust 2010 (Reuters) | 330 mL container | Al can: 330<br>Glass bottle: 330<br>PET bottle: 330 |
| **14** | McKinsey 2021 | 100,000 oz of soft drink | Al can: 355<br>Glass bottle: 355<br>PET bottle: 592 |
| **15** | NAPCOR 2023 (Franklin Associates) | 1,000 gallons of beverage delivered | Al can: 355, 474<br>Glass bottle: 355<br>PET bottle: 500, 592, 2000 |

*For studies that included multiple container sizes, all sizes included are listed.

**The size of the aluminum can in the AA studies reflects a weighted average of all size cans shipped to the market in a particular year, weighted based on the shares of each size and each manufacturer. Correspondingly, the mass of the can under study is also a weighted average.

## 4.3 System Boundary

For system boundary, this review focused on identifying if a study is cradle-to-gate in scope, cradle-to-grave, or contained information for both. In addition, attention was paid to make sure that even in the case of studies that have the same system boundary, say cradle-to-gate, the specific boundaries of the compared products are indeed comparable. For example, one study may include container filling and distribution in its definition of cradle-to-gate while another study may only consider container manufacturing and exclude downstream process steps.

Table 3 breaks out the studies included in this review into comparable system boundaries.

*Table 3. Study system boundaries*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Cradle-to-Grave | Cradle-to-Gate |
|---|---|---|---|
| 1 | Aluminum Association 2010 (PE International) | X | X |
| 2 | Aluminum Association 2014 (thinkstep) | X | X |
| 3 | Aluminum Association 2021 (Sphera) | X | X |
| 4 | Owen-Illinois 2010 | X* | |
| 5 | PET Resin Association 2009 (Franklin Associates) | X | |
| 6 | Ball 2020 (Sphera) | X | X |
| 7 | Carbon Trust 2022 | X | |
| 8 | Glass Packaging Institute 2010 | X* | |
| 9 | University College Dublin 2015 | | X |
| 10 | The Energy and Resource Institute 2022 | X | |
| 11 | University of Salerno 2021 | X | |
| 12 | University of Maribor 2020 | X | |
| 13 | Carbon Trust 2010 (Reuters) | X | |
| 14 | McKinsey 2021 | X | |
| 15 | NAPCOR 2023 (Franklin Associates) | X | X |

*Cradle-to-cradle, which is understood to be an expansion upon cradle-to-grave scope to account for material flows into subsequent product systems. It should be noted that ISO standards do not define ‘cradle-to-cradle’ as a system boundary.

A challenge for the review is when a study did not contain system boundary information. Some works provided no statement about its system boundary. Others may make statements that are not in compliance with the ISO standards. For instance, both the Glass Packaging Institute 2010 and the Owen-Illinois 2010 studies state that they are cradle-to-cradle LCAs, which is not defined in the ISO 14040 and 14044 standards. It is unclear how the “cradle-to-cradle approach” was modeled since the publicly available reports contained only a few pages of images and high-level summary points.

Overall, the majority of the comparative studies used a cradle-to-grave system boundary as a basis for comparison. This is considered a meaningful comparison for the reasons stated previously. For packaging products with a very short lifetime, comparisons should be made at a full life cycle level to make sure that the product is not only designed for packaging service but also for optimizing end-of-life recapture and recycling. Only one work, The University College Dublin 2015 study, made comparisons between aluminum cans and glass bottles at the cradle-to-gate level, which can provide an incomplete picture about the total impacts as it excludes downstream life cycle stages.

From a technical perspective, the cradle-to-gate footprint of a product should be an integral part of a cradle-to-grave study. Thus, it is always convenient and beneficial for researchers to present results for both the cradle-to-gate and cradle-to-grave perspectives since they shed light on the manufacturing processes of a product. On the other hand, the take-away messages of a study and the basis for comparison among different products need to be made at the cradle-to-grave level.

Among the works reviewed, the Aluminum Association aluminum can studies presented both cradle-to-gate and cradle-to-grave results; NAPCOR 2023 is a cradle-to-grave study that also presented cradle-to-gate information as part of a sensitivity analysis under the cut-off end-of-life allocation approach. Two of the studies, Owen-Illinois 2010 and Carbon Trust 2010 (Reuters), did not publish a report and thus could not be evaluated.

## 4.4 Data Representation

The review of data representation focused on two aspects: the representativeness of the mass of the containers, and the representativeness of the background data of the materials.

The material compositions of the containers and their respective masses are considered some of the most critical data points for LCAs of beverage containers. This is because the environmental footprint of a product is proportional to the mass of the materials used to make the product: in general, the lighter a product, the lower the footprint; the heavier a product, the higher the footprint. Table 4 lists the masses of the containers in the studies. The masses align with the respective container sizes listed in Table 2.

*Table 4. Study container mass*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Single Container Mass (g) |
|---|---|---|
| 1 | Aluminum Association 2010 (PE International) | Al can: 13.34*<br>Glass bottle: n/a<br>PET bottle: n/a |
| 2 | Aluminum Association 2014 (thinkstep) | Al can: 13.04*<br>Glass bottle: n/a<br>PET bottle: n/a |
| 3 | Aluminum Association 2021 (Sphera) | AL can: 13.04*<br>Glass bottle: n/a<br>PET bottle: n/a |
| 4 | Owen-Illinois 2010 | Al can: not reported<br>Glass bottle: not reported<br>PET bottle: not reported |
| 5 | PET Resin Association 2009 (Franklin Associates) | Al can: 13.2<br>Glass bottle: 208.3<br>PET bottle: 27.3 |
| 6 | Ball 2020 (Sphera) | Al can: 12.68, 14.61<br>Glass bottle: 229, 290<br>PET bottle: 21.4, 24.53 |
| 7 | Carbon Trust 2022 | Al can: 12<br>Glass bottle: 190<br>PET bottle: 21.5 |
| 8 | Glass Packaging Institute 2010 | 1 kg of glass produced |

| No. | Study Commissioner, Year, and Practitioner/Publisher | Single Container Mass (g) |
|---|---|---|
| 9 | University College Dublin 2015 | Al can: 18<br>Glass bottle: 388<br>PET bottle: n/a |
| 10 | The Energy and Resource Institute 2022 | Al can: 8.09, 12.4<br>Glass bottle: 305, 510<br>PET bottle: 15.9, 22.2 |
| 11 | University of Salerno 2021 | Al can: n/a<br>Glass bottle: 454<br>PET bottle: 27.6 |
| 12 | University of Maribor 2020 | Al can: 17.1<br>Glass bottle: 483<br>PET bottle: 28.5 |
| 13 | Carbon Trust 2010 (Reuters) | Al can: not reported<br>Glass bottle: not reported<br>PET bottle: not reported |
| 14 | McKinsey 2021 | Al can: 13<br>Glass bottle: 208<br>PET bottle: 27 |
| 15 | NAPCOR 2023 (Franklin Associates) | Al can: 12.7, 15.1<br>Glass bottle: 208<br>PET bottle: 22.1, 22.2, 43.9 |

*The mass of the can in the AA studies is a weighted average of all size cans shipped to the market in a particular year. Correspondingly, the size of the can under study is also a weighted average.

Upon comparison, the masses of the containers included in each of the studies vary significantly from each other. Given the fact that most of the studies, particularly comparisons, may be used to influence the choice of beverage manufacturers and consumers, the mass of containers should reflect the average of the products in the market. The modeled mass of the container has a substantial impact on the final carbon footprint of the product. The Aluminum Association's studies use a national weighted average container mass, which is a good representation of the reality in which consumers are purchasing aluminum cans. PET Resin Association 2009, Ball 2020 and NAPCOR 2023 are based on a sampling of beverage containers purchased by the study authors. This approach is not considered representative of the marketplace but rather of specific products manufactured by specific manufacturers. Other studies reviewed did not disclose where they got their container mass data and whether such data were representative with respect to the goal and scope. These include University College Dublin and University of Salerno.

A lack of data availability may prevent researchers from obtaining representative information of the larger market. In such cases, the researchers should communicate the limitations and non-representativeness of the study as part of the take-away message.

For the representativeness of the background data for materials, the review focused on identifying which geographic area and for what reference year the studies were focused on. In addition, attention was paid to whether key background data (for raw materials: aluminum, glass, and PET) represent the latest available data at the time of publication. Not all studies we examined disclosed their data source and data representativeness.

Table 5 shows the results of the data representation assessment. Few of the works reviewed strictly followed the requirements on data quality from the ISO standards. This is particularly true when it comes to comparative studies. For instance, NAPCOR's 2023 and PET Resin Association's 2009 study used outdated aluminum data even though researchers could access new data at the time of the study.

*Table 5. Study geography, reference year, and technology*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Geography* | Reference Year | Products Under Study | Background Material Data Year** |
|---|---|---|---|---|---|
| 1 | Aluminum Association 2010 (PE International) | North America | 2008 | Aluminum Can | Aluminum: 2005 |
| 2 | Aluminum Association 2014 (thinkstep) | North America | 2010 | Aluminum Can | Aluminum: 2013 |
| 3 | Aluminum Association 2021 (Sphera) | North America | 2016 | Aluminum Can | Aluminum: 2016 |
| 4 | Owen-Illinois 2010 | North America (also Latin America, Western Europe, Asia) | Unknown | Aluminum Can<br>Glass Bottle<br>PET Bottle | Aluminum: unknown<br>Glass: unknown<br>PET: unknown |
| 5 | PET Resin Association 2009 (Franklin Associates) | North America | 2007 | Aluminum Can<br>Glass Bottle<br>PET Bottle | Aluminum: 1997<br>Glass: 1997<br>PET: 2003 |
| 6 | Ball 2020 (Sphera) | North America (also Europe and Brazil) | 2018 | Aluminum Can<br>Glass Bottle<br>PET Bottle | Aluminum: 2016<br>Glass: 2016-2019<br>PET: 2016-2019 |
| 7 | Carbon Trust 2022 | Europe | Unknown | Aluminum Can<br>Glass Bottle<br>PET Bottle | Aluminum: unknown<br>Glass: unknown<br>PET: unknown |
| 8 | Glass Packaging Institute 2010 | North America | 2007 | Glass Bottles | Glass: 2007 |
| 9 | University College Dublin 2015 | Europe, North America | 2010 | Aluminum Can<br>Glass Bottles | Aluminum: 2013<br>Glass: 2003 |
| 10 | The Energy and Resource Institute 2022 | India | 2021 | Aluminum Can<br>Glass Bottle<br>PET Bottle | Aluminum: 2018<br>Glass: 2018<br>PET: 2018 |
| 11 | University of Salerno 2021 | Europe | 2019 | Glass Bottle<br>PET Bottle | Glass: 2017<br>PET: 2019 |
| 12 | University of Maribor 2020 | Europe | 2019 | Aluminum Can<br>Glass Bottle<br>PET Bottle | Aluminum: 2016<br>Glass: 2010<br>PET: 2015 |
| 13 | Carbon Trust 2010 (Reuters) | Unknown | Unknown | Aluminum Can<br>PET Bottle | Aluminum: unknown<br>PET: unknown |
| 14 | McKinsey Global 2021 | North America | 2020 | Aluminum can<br>Glass Bottle<br>PET Bottle | Aluminum: 2010 (EPA WARM Model)<br>Glass: 2003 (EPA WARM Model)<br>PET: 2011/2018 (EPA WARM Model) |
| 15 | NAPCOR 2023 (Franklin Associates) | North America | 2021 | Aluminum Can<br>PET Bottle<br>Glass Bottle | Aluminum: 2013/2014<br>Glass: unknown<br>PET: 2020 |

*Additional geographic regions included in the studies are listed as secondary in parentheses.
**For the background material data year, this review focused on identifying the actual production year of the materials. However, in some cases, the studies referred to the publication years of the data instead of production years.

## 4.5 End-of-life Allocation

Our review of the methodological choices on allocation for recycling **focused on identifying which method was used for the baseline cases in each study** (i.e., excluding any scenario analyses done on end-of-life allocation). As discussed in section 3.4, this is only applicable for studies that are cradle-to-grave in boundary. Table 6 shows the methodological choices made by each of the studies. It is worth noting that the Carbon Trust 2022 study used a hybrid method, which is a combination of cut-off and substitution (50:50 for PET and 20:80 for aluminum and glass).

*Table 6: Study end-of-life allocation methods*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Cut-off | Substitution | Hybrid | Unknown |
|---|---|---|---|---|---|
| 1 | Aluminum Association 2010 (PE International) | | X | | |
| 2 | Aluminum Association 2014 (thinkstep) | | X | | |
| 3 | Aluminum Association 2021 (Sphera) | | X | | |
| 4 | Owen-Illinois 2010 | | | | X |
| 5 | PET Resin Association 2009 (Franklin Associates) | | X | | |
| 6 | Ball 2020 (Sphera) | X | | | |
| 7 | Carbon Trust 2022 | | | X | |
| 8 | Glass Packaging Institute 2010 | X | | | |
| 9 | University College Dublin 2015 | | | | |
| 10 | The Energy and Resource Institute 2022 | X | | | |
| 11 | University of Salerno 2021 | X | | | |
| 12 | University of Maribor 2020 | X | | | |
| 13 | Carbon Trust 2010 (Reuters) | | | | X |
| 14 | McKinsey Global 2021 | X | | | |
| 15 | NAPCOR 2023 (Franklin Associates) | | X | | |

## 4.6 Harmonized Study Results

To determine the approximate life cycle carbon footprint of various beverage containers, we aligned the functional unit of each study under review and scaled the results accordingly. Results are scaled to a theoretical container that holds 1 liter of beverage. The amount of material required for this theoretical container is proportionally scaled up (or down) from the material mass of the original container(s) used in each of the studies. Note that the material requirement for a 1-liter theoretical container may not be proportional (i.e., have a linear relationship) to the masses of other size containers. For example, a container that holds 0.5 L of beverage may not have a mass that is half of a container that holds 1 L of beverage. Thus, the assumptions made in this exercise may not be realistic in practice. The harmonized results may be viewed as an estimate.

Table 7 shows the GWP values converted from each study's original functional unit to a normalized functional unit of 1 Liter of beverage. Note that for studies that reported results for multiple container sizes, an average is taken for the purposes of this review.

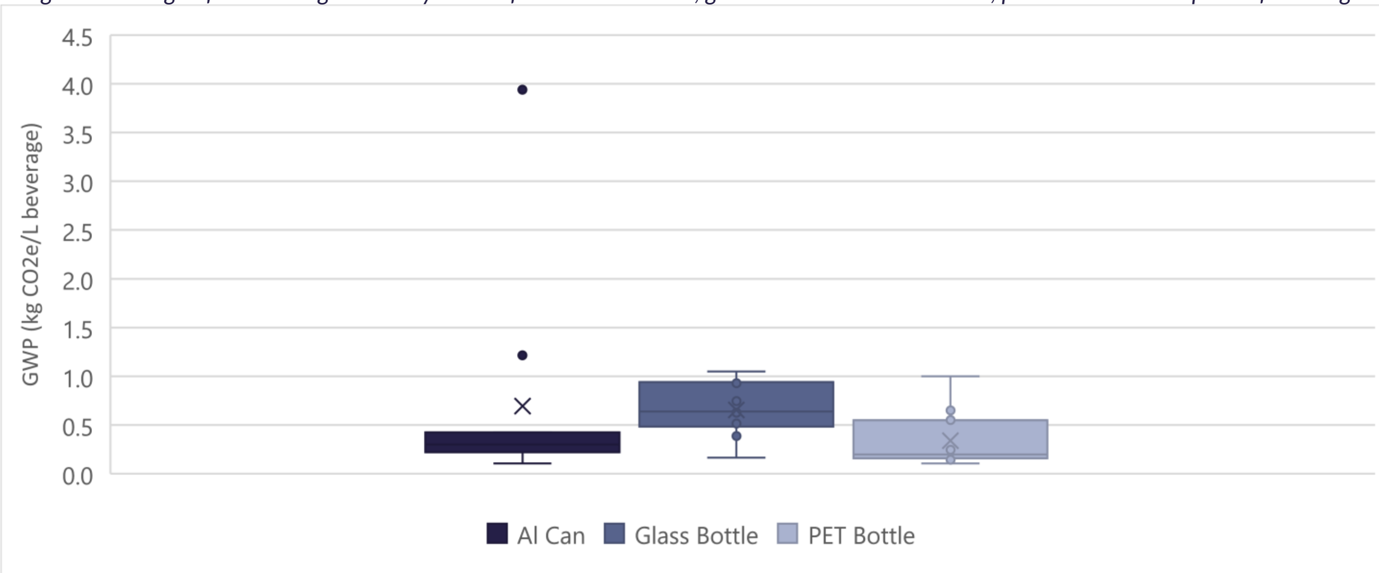
*Table 7. Cradle-to-Grave GWP converted to the unit of kg CO2e per 1 L of beverage*

| No. | Study Commissioner, Year, and Practitioner/Publisher | Baseline GWP ($kg\ CO_2e$/1 L of Beverage)[1] | | | Sensitivity Range of GWP, if available ($kg\ CO_2e$/1 L of Beverage)[2] | | |
|---|---|---|---|---|---|---|---|
| | | Al Can | Glass Bottle | PET Bottle | Al Can | Glass Bottle | PET Bottle |
| 1 | Aluminum Association 2010 (PE International) | 0.371 | - | - | - | - | - |
| 2 | Aluminum Association 2014 (thinkstep) | 0.295 | - | - | - | - | - |
| 3 | Aluminum Association 2021 (Sphera) | 0.241 | - | - | 0.104 – 0.368 | - | - |
| 4 | Owen-Illinois 2010 | 1.21[3] | 0.518[3] | 0.648[3] | - | - | - |
| 5 | PET Resin Association 2009 (Franklin Associates) | 0.424 | 0.744 | 0.173 | - | - | - |
| 6 | Ball 2020 (Sphera) [4] | 0.219 | 0.970 | 0.306 | - | - | - |
| 7 | Carbon Trust 2022 | 0.182[4] | 0.506[4] | 0.212[4] | 0.067 – 0.724 | 0.367 – 0.864 | 0.082 – 0.330 |
| 8 | Glass Packaging Institute 2010 | - | 0.650 | - | - | - | - |
| 9 | University College Dublin 2015[5] | - | - | - | - | - | - |
| 10 | The Energy and Resource Institute 2022[4] | 0.300 | 1.05 | 0.550 | - | - | - |
| 11 | University of Salerno 2021 | - | 0.167 | 0.192 | - | - | - |
| 12 | University of Maribor 2020 | 0.419 | 0.930 | 0.246 | - | - | - |
| 13 | Carbon Trust 2010 (Reuters) | - | - | - | 0.106 – 3.94 | - | 0.106 – 1.00 |
| 14 | McKinsey 2021 | 0.301 | 0.387 | 0.145 | - | - | - |
| 15 | NAPCOR 2023 (Franklin Associates) | 0.292 | 0.625 | 0.160 | 0.259 - 0.292 | 0.614 - 0.625 | 0.078 - 0.160 |

1) Baseline results reflect the situation in which the key parameters used to build the LCA model match the reality of a particular market.
2) Sensitivity analysis usually builds off assumptions that reflect an ideal world scenario – for instance, 100% recycling rate.
3) The scope and system boundary by the Owen-Illinois 2010 study do not match with the harmonized scope and boundary of this review. The numbers are adopted from the study “as is.”
4) Ball 2020, Carbon Trust 2022 and The Energy and Resource Institute 2022 studies did not explicitly provide numerical values for results – rather, results were presented in a figure. These numerical values are estimated based on the figures.
5) The University College Dublin 2015 study reports cradle-to-gate results only, and therefore is excluded from the review of cradle-to-grave studies presented here.

Figure 1 presents the range of results per liter of beverage for the cradle-to-grave system boundary. **The range of each container material plotted in the figure reflects the baseline results of all relevant studies, if the baseline results were presented by the reports of the studies**. Outlier results (extremely low or high values) are plotted as outliers.

*Figure 1*. Range of cradle-to-grave study results for aluminum cans, glass bottles and PET bottles, presented as GWP per L of beverage.*




*Data points for this figure are based on the baseline case of each study except for Carbon Trust 2010 (Reuters), which only reported sensitivity ranges. Thus, the figure contains two data points for each container for the Carbon Trust 2010 (Reuters) work: a minimum value and a maximum value.

It can be seen from the harmonized results that the cradle-to-grave carbon footprint of 1 L of beverage varies across the studies reviewed.

Excluding outliers, the GWP for **aluminum cans** ranges from **0.106 – 0.512 kg $CO_2$e**, with one outlier study developed by Carbon Trust 2010 (Reuters) reporting a maximum value footprint of 3.94 kg $CO_2$e, and a second outlier by Owen-Illinois 2010 reporting a footprint of 1.21 kg CO2e. The minimum value of the normal range (excluding outliers) is attributed to the high recycled content and high end-of-life recycling rates as scenario analysis assumptions. The maximum value of the normal range (excluding outliers) is attributed to high primary metal content and large transport distances between life cycle stages. For the outliers, as Carbon Trust 2010 (Reuters) has not published an LCA report, it is not possible for this review to further explore the reasons behind the high carbon footprints reported (it is worth to note that the value is an extreme case since it is the maximum value of a range). Similarly, the attribution to the second outlier reported by the Owen-Illinois 2010 study is unknown since no further information is disclosed.  As such we treat these results with extreme caution.

Excluding outliers, the GWP for **glass bottles** ranges from **0.387 – 1.05 kg $CO_2$e**, with outlier studies developed by University of Salerno 2021 reporting a footprint of 0.189 kg $CO_2$e for a reusable glass bottle. The minimum value of the normal range (excluding outliers) is attributed to a reduced mass of the container. The maximum value of the normal range (excluding outliers) is attributed to the energy intensive manufacturing process. The outlier footprint results presented by University of Salerno 2021 are due to the reuse of the container and the small amount of virgin glass used, given that the study models a high secondary content and recycling rate.

Excluding outliers, the GWP for **PET bottles** ranges from **0.106 – 0.648 kg $CO_2$e**, with the outlier study by the Carbon Trust 2010 (Reuters) with a maximum value of 1.00 kg $CO_2$e. The minimum value of the normal range (excluding outliers) is attributed to high recycled content and high end-of-life recycling rate as scenario analysis assumptions. The maximum value of the normal range (excluding outliers) is reported by the Owen-Illinois 2010 study with no further information disclosed. Thus, the drivers of the study footprint are unknown. Similarly, the exact attribution to the high value outlier from Carbon Trust 2010 (Reuters) is not known given the fact that no report is available.

After harmonization, results should still be treated with caution without a better understanding of the representativeness and robustness of each study being considered. This is discussed further in the following sections.

## 4.7 A Comprehensive Evaluation of Selected Comparative Studies

It is worth digging deeper into several comparative studies for a more comprehensive evaluation since these works are very typical of today's landscape in comparative LCA. The goal is to understand the complexity and nuance behind a study's conclusions.

The **first study** of note is by Owens-Illinois, 2010. This study was published by a glass bottle manufacturer, and the conclusions suggest that the glass packaging option has the lowest GWP. However, there are two fundamental aspects of the study that are not aligned with the ISO standards. One of which is the work has no traces of a publicly available report, let alone of a critical review process. As such, it is difficult to verify or substantiate any claims made by Owens-Illinois based on the study. The second issue is the study claimed that it was a "cradle-to-cradle" LCA, which the ISO standards did not define. Again, with further detail provided by a background report, the "cradle-to-cradle" system boundary may be acceptable, however this is not possible to verify at present.

The **second study** to point out is by Carbon Trust 2010 (Reuters). This is a study that was done by a third party with no apparent material industry affiliation. The conclusions of the study have been widely quoted by a range of parties, including by Reuters, one of the world's largest news agencies. As with the case of the Owen-Illinois 2010 study, there is no trace of a publicly available report, and it is unclear whether the study has been critically reviewed (as required by ISO standards for comparative claims).

Given its publicity, it is important to examine the quality of this work. However, in absence of a report, the only way to shed light is to compare its conclusions with those done by industry groups such as the Aluminum Association, the PET Resin Association (PETRA), NAPCOR, and Glass Packaging Institute. What we found was that the maximum value for aluminum cans reported by Carbon Trust 2010 (Reuters) is extremely high compared to those reported by the Aluminum Association. Publication of the LCA background report may help to alleviate some of these concerns.

Carbon Trust has since published an updated study. The 2022 version made improvements in two ways. The first is the availability of a summary report with some limited background information. The second improvement is the provision of "baseline" results, which are labeled as "Europe Typical" by the report for the compared containers based on European market situations. Baseline results of a study are usually calculated based on the reality of a certain market for a product by taking into consideration the representative facts on key life cycle stages including production, use and recycling. In contrast, if a study focuses on communicating the results in a range based on extreme scenario assumptions for a product, just like the Carbon Trust 2010 (Reuters) version, consumers and the public will likely be misinformed because the minimum and maximum values of a range usually are based on assumptions, such as all renewable energy versus fossil fuels, and 0% recycling versus 100% recycling. Information based on extreme scenario assumptions is informative, but it does not inform what the 'real life' footprint of the products are.

Although improvements have been made, there are still issues with the Carbon Trust 2022 version. Completion of a critical review process was not indicated anywhere in the summary. The updated version also did not clearly show how the hybrid recycling allocation approach is implemented. Providing detail on how the allocation methodology is applied and calculated is critical for readers to understand the accuracy of the implementation of the allocation method to ensure that undercounting or double counting of credits and burdens does not occur.

It should also be noted that the studies by Owens-Illinois and Carbon Trust are from 2010, and as such are not considered temporally representative of the present-day situation. However, they are still referenced by businesses and the public in the analysis of beverage container options, therefore they are included in this review.

The **third study** to focus on is by McKinsey 2021. This, again, is done by a reputable third party with no apparent material industry affiliation. The study, however, is written to promote the role of plastics in "enhancing use efficiencies and reducing greenhouse gas emissions". It details the "climate benefits" of plastics across most of its applications, including packaging, building and construction, automotive and others, by comparing these plastics with alternative materials. Soft drink container packaging is only one category of products evaluated by the study.

Given the stated intention of the study, the focus of this review is to examine its quality from a technical perspective. The summary style report provides very limited information. We conclude that the report is not ISO conformant because of its summary nature and its very limited disclosure of necessary information. The work does not disclose the system boundaries, detail the LCA models for each product under study, detail methodologies, or show assumptions for parameters and scenarios. For instance, the report claims that the use phase of the products was included in the scope, which leads to increased uncertainty. Use phase details should be disclosed so that readers can judge its robustness. It is noted that the report stated it was critically reviewed by two independent experts, and the reviewers' brief assessments were included.

The **fourth and most recent study** included in this review is by NAPCOR 2023. This study is done by a plastics industry association, and the conclusions favor plastic bottles as a packaging solution. From a procedural and transparency point of view, the study is of high quality. There is a detailed LCA background report that is publicly available, and a rigorous critical review was carried out before publication. The level of detail in the report allows for a deeper dive into the analysis to understand some modeling choices and nuances of the study.

An ideal approach to verify the reasonableness for a report of this quality is to reproduce the study by using the information provided to rebuild the models and run the results. This is not possible given the accessibility of some of the PET data, and the nondisclosure of certain information. Therefore, the focus of this review is to identify the modeling choices that are likely to lead to the conclusions of the study, that favor PET from a GWP perspective. As a result, we identified the following:

- NAPCOR uses recent glass and PET data but does not use the most up-to-date aluminum data – using Aluminum Association data from the 2013 and 2014 publications when data from 2021 (aluminum can) and 2022 (semi-fabricated aluminum products) was readily available. According to the AA 2021 report, the cradle-to-grave carbon footprint of aluminum cans decreased 7%

between the 2014 study and 2021 study, and as such using data from the 2014 publican skews the results to be favorable toward other materials.

- The inclusion of 2-liter PET bottles in the comparison may be considered misleading because the other containers included in the analysis are considered single-serving, while the two-liter bottle is a multiple-serving container. The 2-liter bottle benefits from an improved material efficiency by delivering more beverage volume in one package, and therefore the footprint of the container is lower than that for the single-serving containers.
- Secondary packaging was included in the study but was included inconsistently between the container types. Secondary packaging can include film wrap, pallets used for transport, and cardboard boxes. Secondary packaging may vary depending on the container type, beverage brand (producer), and retail requirements. If it is included in the study, it should be included for all products studied. A selective assessment of secondary packaging can swing the results to favor one container type over another. It is appropriate for a study to include secondary packaging in the analysis, but only if it is included consistently across product systems.
- Additionally, the comparison of results suggests that the 2013 Aluminum Association's aluminum production data were used differently than in Aluminum Association's beverage can LCA reports. It is understood that the NAPCOR study practitioners used different software than the Aluminum Association's contractors, therefore some difference in results is expected, however the results should not vary significantly. The accuracy of the NAPCOR aluminum modeling cannot be further verified without visibility into NAPCOR's LCA model.
- Lastly, the amount of upstream virgin material burden assigned to aluminum cans for the difference between a higher recycled content and a lower EOL recycling rate is not aligned with results from the Aluminum Association's can LCA reports. These results should be consistent since the two studies used similar net scrap approach for EOL recycling allocation. As with the previous point, the aluminum modeling cannot be further verified without visibility into NAPCOR's LCA model.

# 5.0 Conclusion

Harmonized results for the studies considered in this report vary widely since comparative carbon accounting for products is a complex and imprecise process. Various assumptions and inputs can drive vastly different results from study to study, despite many being critically reviewed. Product lifecycle assessment studies attempt to quantify the life cycle environmental impacts of a product from raw material extraction to the recycling or disposal of the product at end-of-life, however there is no gold standard for a single, unified carbon accounting methodology. Having a variety of methodological and modeling choices to use in analyses consequently results in variabilities in environmental and sustainability data.

The 15 studies analyzed featured varying study boundaries; data inputs; methodological approaches; and assumptions about product weight, beverage type and container size, all of which can impact the final results. Despite these differences, results generally found that, in terms of global warming potential (GWP), both aluminum cans and PET bottles significantly outperform glass bottles. When it comes to aluminum cans and PET bottles, the harmonized GWP range is very similar (0.106 – 0.512kg $CO_2$e and 0.106 – 0.648kg $CO_2$e, respectively), with variations largely attributed to the choice of data and assumptions made in each study.

The issues discussed in this report should be approached with care when comparing LCA studies. Inconsistencies in scoping and methodology choices between studies can significantly affect the results and lead to misleading conclusions about the relative environmental performance of the product systems in question.

# References

Carbon Trust. (2010). *Carbon Footprint of Aluminum Can and PET Bottle.* Reuters.

Carbon Trust. (2022). *Carbon footprint of soft drinks packaging.*

Ferrera, C., De Feo, G., & Picone, V. (2021). *LCA of Glass Versus PET Mineral Water Bottles: An Italian Case Study*. University of Salerno.

Franklin Associates. (2009). *Life Cycle Inventory of Three Single Serving Soft Drink Containers.* Praire Village, KS.

Glass Packaging Institute. (2010). *Environmental Overview: Complete Life Cycle Assessment of North American Container Glass.*

International Organization for Standardization. (2006). *ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.* Geneva. Retrieved from https://www.iso.org/standard/71206.html

International Organization for Standardization. (2006a). *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. Geneva.

International Organization for Standardization. (2006b). *ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines.* Geneva. Retrieved from https://www.iso.org/standard/38498.html

Krajnc, D., Kravanja, Z., & Pintaric, Z. N. (2020). *Comparative Life Cycle Assessment of Alternative Packaging Materials for Beverages.* University of Maribor.

McKinsey & Company. (2022). *Climate Impacts of Plastics.*

Nag, R. (2015). *Life Cycle Assessment on Aluminum Can and Glass Bottle for Packaging of 500 mL Beer.* Dublin, Ireland: University of Dublin.

Owens-Illinois. (2010). *When it Comes to Carbon Footprints, are you getting the full picture? The Complete Life Cycle Assessment.*

PE Americas. (2010). *Life Cycle Impact Assessment of Aluminum Beverage Cans.*

Sphera. (2020). *Comparative Life Cycle Assessment: North America.*

Sphera. (2022). *Environmental Footprint of Semi-Fabricated Aluminum Products in North America.*

TERI. (2022). *Sustainable Beverage Packaging Options in India.* New Delhi: The Energy and Resources Institute.

The National Association for PET Container Resources (NAPCOR). (2023). *Life Cycle Assessment of Predominant U.S. Beverage Container Systems for Carbonated Soft Drinks and Domestic Still Water.*

thinkstep. (2014). *Update to the Aluminum Can LCA Study.*