LIFE CYCLE ASSESSMENT OF CORRUGATED CONTAINERS AND REUSABLE PLASTIC CONTAINERS FOR PRODUCE TRANSPORT AND DISPLAY

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Study Undertaken on Behalf of:

Corrugated Packaging

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Executive Summary

This report conducted for the Corrugated Packaging Alliance (CPA) is an update to a 2019 ISO-compliant LCA by Quantis that compared corrugated containers (CCs) to reusable plastic containers (RPCs) used to transport and display fresh produce in the U.S.

The analyses described in this study rely on data from 2020 for single-use corrugated fiberboard while the reusable plastic data remained unchanged. Like the earlier study, this LCA seeks to compare the relative environmental performance of these two container systems. The objectives of this study are unchanged from those in the 2019 study, [2] which were outlined as follows:

I. Establish credible and transparent profiles of the life cycle potential environmental impacts of corrugated containers and reusable plastic containers utilizing appropriate and recognized databases and LCIA characterization factors according to ISO 14040 and 14044:2006;
II. Identify the magnitude and confidence of comparative environmental advantages of either system; and
III. Ensure compliance of results with ISO 14044 (clause 6) and ISO 14040 (clause 7) to support a public comparative claim, including critical review by a panel of interested parties.

The functional unit of this study is defined as the provision of containment for 907,185 kg (1,000 short tons) of eight varieties of produce (apples, carrots, grapes, head lettuce, oranges, onions, tomatoes and strawberries) grown and purchased in the United States. The study boundaries include filling the containers, transportation, and display at retail, all while ensuring the produce is maintained at a level suitable for sale and safe for human consumption. The study is "cradle-to-grave," as such, it includes all life cycle stages from raw materials extraction through end-of-life. As in the 2019 Quantis study, most data for this study are based on CPA's own research. Other data sources included published LCAs on CCs and RPCs and confidential information provided by representatives of the CC and RPC industries.

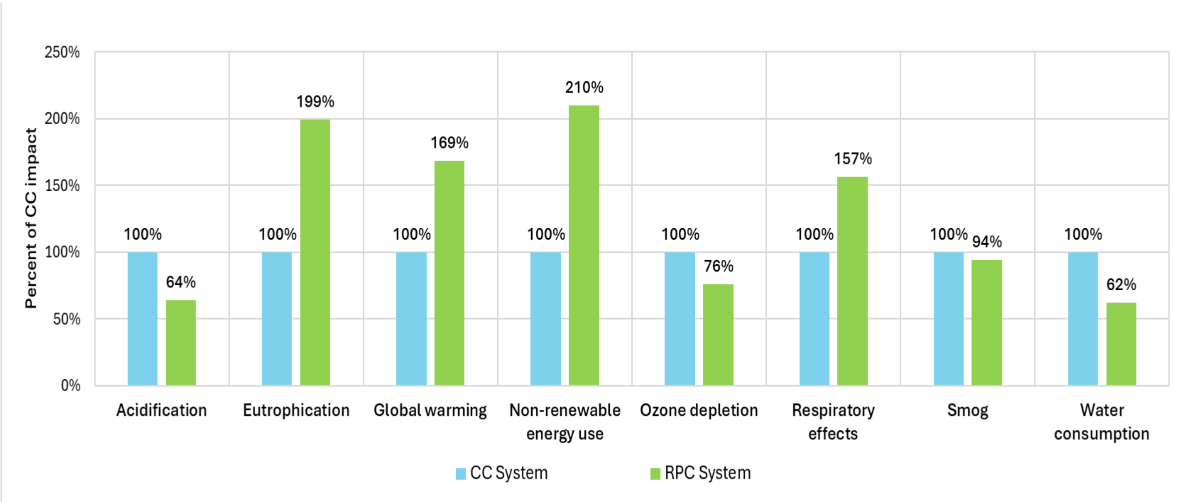
To facilitate comparisons to the 2019 study, the same seven impact categories were evaluated: acidification, eutrophication, global warming, non-renewable energy, ozone depletion, respiratory effects, and smog formation along with an eighth category: water consumption. SimaPro software was employed to perform calculations, and neither normalization nor weighting of results was employed. An external panel has been commissioned to conduct a review in accordance with ISO 14040.

[2] Thorbecke, M., A. Pike, J. Dettling, and D. Eggers. Life cycle assessment of corrugated containers and reusable plastic containers for produce transport and display. Quantis. February 28, 2019.

Results

Market-Weighted Results

Analysis showed that the RPCs create higher impacts in 4 of the 8 damage categories assessed (eutrophication, global warming, non-renewable energy use, and respiratory effects) but lower impacts in 3 categories (acidification, ozone depletion, and water consumption, ES Figure 1). For smog, the difference between CC and RPC systems is less than 10%, which is not significant enough to be considered as an advantage for either system. The magnitude of the difference between the CC and RPC is greatest for the categories of eutrophication, global warming, and non-renewable energy use, where the RPC results are 69-110% larger than those for the CC system.



ES Figure 1: Market-weighted average results for the baseline analysis

Commodity-Specific Results

Commodity-specific results demonstrate similar trade-offs between the container systems (ES Table 1). Regardless of the commodity, RPCs perform better than CCs in three damage categories (acidification, ozone depletion, and water consumption); and CCs perform better than RPCs in four damage categories (eutrophication, global warming, non-renewable energy use, and respiratory effects). For smog formation, RPCs show lower smog impacts for carrots, lettuce, onions, and grapes, no difference for apples, and higher smog impacts for strawberries, tomatoes, and oranges.

ES Table 1. Baseline results for the 8 produce types in this study. Commodities are ordered from the greatest to least functional unit mass ratio. Each bar is shown relative to the system of greatest impact for that impact category and commodity.

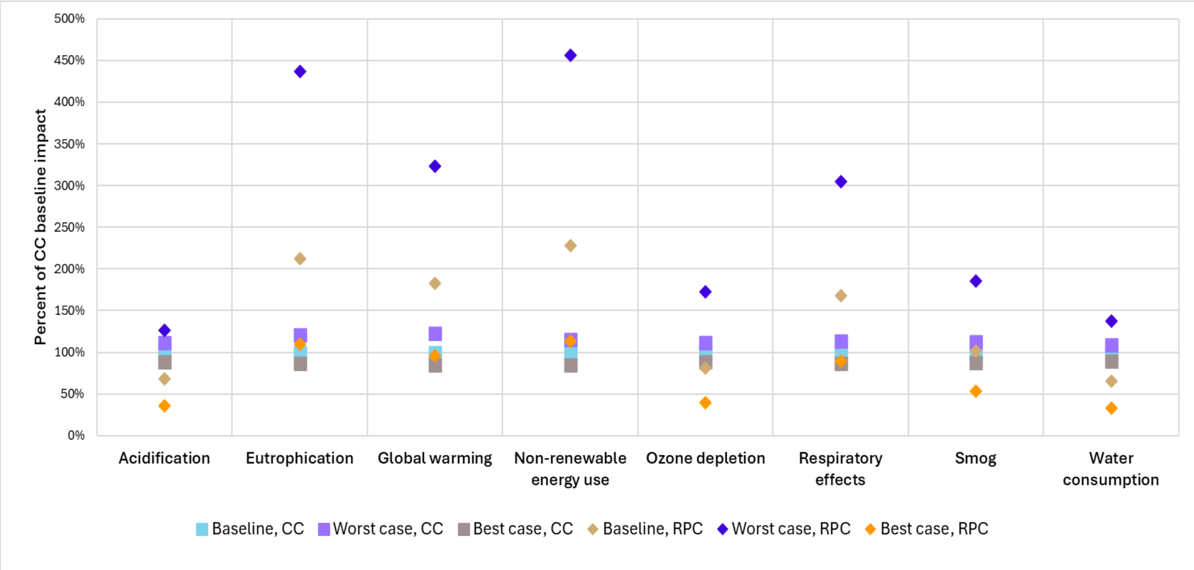
Impact category	Unit	System	Onions	Grapes	Lettuce	Carrot	Apple	Oranges	Tomatoes	Strawberries
Acidification	(kg SO2 eq)	CC	4.9E+02	7.1E+02	4.3E+02	3.5E+02	4.2E+02	4.1E+02	4.3E+02	9.8E+02
		RPC	2.3E+02	4.0E+02	2.4E+02	2.2E+02	2.9E+02	2.9E+02	3.3E+02	7.9E+02
Eutrophication	(kg N eq)	CC	8.4E+01	1.2E+02	7.3E+01	5.9E+01	7.1E+01	7.0E+01	7.3E+01	1.7E+02
		RPC	1.2E+02	2.1E+02	1.3E+02	1.2E+02	1.5E+02	1.5E+02	1.7E+02	4.2E+02
Global warming	(kg CO2 eq)	CC	7.7E+04	1.1E+05	6.7E+04	5.4E+04	6.5E+04	6.5E+04	6.7E+04	1.6E+05
		RPC	9.4E+04	1.6E+05	1.0E+05	9.3E+04	1.2E+05	1.2E+05	1.3E+05	3.3E+05
Non-renewable energy use	(MJ)	CC	1.2E+06	1.7E+06	1.0E+06	8.2E+05	9.8E+05	9.7E+05	1.0E+06	2.4E+06
		RPC	1.8E+06	3.1E+06	1.9E+06	1.7E+06	2.2E+06	2.3E+06	2.5E+06	6.1E+06
Ozone depletion	(kg CFC-11 eq)	CC	3.8E-03	5.5E-03	3.4E-03	2.7E-03	3.3E-03	3.2E-03	3.3E-03	7.7E-03
		RPC	2.1E-03	3.7E-03	2.3E-03	2.1E-03	2.7E-03	2.7E-03	3.0E-03	7.2E-03
Respiratory effects	(kg PM2.5 eq)	CC	4.8E+01	6.9E+01	4.2E+01	3.4E+01	4.1E+01	4.0E+01	4.2E+01	9.8E+01
		RPC	5.5E+01	9.5E+01	5.8E+01	5.4E+01	6.8E+01	6.9E+01	7.8E+01	1.9E+02
Smog	(kg O3 eq)	CC	4.8E+03	6.9E+03	4.2E+03	3.4E+03	4.1E+03	4.0E+03	4.2E+03	9.7E+03
		RPC	3.3E+03	5.7E+03	3.5E+03	3.2E+03	4.1E+03	4.2E+03	4.7E+03	1.1E+04
Water consumption	(m3)	CC	8.5E+02	1.2E+03	7.4E+02	6.0E+02	7.3E+02	7.1E+02	7.4E+02	1.7E+03
		RPC	3.9E+02	6.7E+02	4.0E+02	3.7E+02	4.7E+02	4.8E+02	5.4E+02	1.3E+03

Best- and Worst-Case Results

The best- and worst-case scenarios substantiate these conclusions. In the case of the apple system as depicted in ES Figure 2, the best-case scenario for the RPC system includes the highest reuse rate, lowest break/loss rate, greatest amount of recycled content, shortest transport distances (from growers to retailers, retailers to servicing and servicing back to growers) and state-of-the-art cleaning technology. The worst-case for RPCs applies the opposite ends of these values (e.g., lowest reuse rate), except for the cleaning technology, for which the baseline assumption (composite technology) is used. This is a conservative (favorable) assumption for RPCs.

The best-case for the CC system includes the least container weight, highest recovery rate and shortest transport distances (from growers to retailers); the worst-case evaluates the heaviest container, least amount of recovery and longest transport distances (from growers to retailers). The biogenic carbon accounting scheme and the biogenic carbon storage parameter are excluded from the best- and worst-case scenarios because the purpose of the test is to understand the relative results of RPCs and CCs under varying industry conditions, and the biogenic carbon topics are methodological choices, rather than industry variables.

The results offer a sense for the range of results that could be obtained under various combinations of the different assumptions. One system's worst-case scenario doesn't necessarily have to be preferable to the others' best-case scenario for conclusions to be drawn.



ES Figure 2: Baseline, best and worst-case scenarios for RPCs and CCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

Conclusions

In line with the 2019 report which concluded "without prioritizing types of impact, it is not possible to say from the present assessment that one of these systems is an overall better environmental performer than the other in the US market," results from the current study do not indicate that either system is clearly a superior overall environmental performer. It remains true that it is not appropriate to use a count of the number of indicators in which a container system shows less impact to determine the comparative advantage between container types and that the only overarching conclusion that can be made is that there are trade-offs between the systems.

The same opportunities for improvement for the container systems studied exist today as when the 2019 study was undertaken. Impacts from the CC system can be reduced by lowering container weight and enhancing recovery rates. Impacts from the RPC system can be reduced by increasing reuse, incorporating recycled content, minimizing breakage and losses, and reducing transport distances. Reducing transportation distances would reduce impacts for both CCs and RPCs.

Among the factors analyzed, CC weight and RPC transportation distances emerge as the most significant in determining the relative performance of the two container systems. However, even under market conditions that might appear to favor one system over the other, the findings suggest that neither system demonstrates a definitive environmental advantage for most commodity systems.

The findings indicate that variations exist in the comparative results across the assessed impact categories. For a given commodity, the environmental trade-offs between container systems can be predicted based on analyzing the ratio of the container masses required to fulfill the functional unit for each container system. The disparity in container mass needed to transport a specific quantity of produce determines which environmental indicators favor one system over the other.

Both container systems present opportunities for environmental improvement. The CC system can reduce its impact by lowering container weight and enhance recovery rates. Similarly, the RPC system can improve its environmental performance by increasing reuse and recycled content, minimizing breakage and losses, and reducing transport distances.

This study assumes a steady-state market where the containers under evaluation maintain consistent weights and dimensions throughout their functional use. However, it is important to acknowledge that these characteristics may change over time. Furthermore, while not analyzed in this study, custom container designs tailored for specific retailers can lead to inventories of containers with remaining service life when the designs are no longer required. If a system stops operating before the containers reach their useful service lifespan, a larger share of the production and disposal impacts is attributed to that system. Consequently, the impact per container increases, as the associated environmental and resource costs are distributed across fewer usage cycles.

A significant knowledge gap pertains to the proportion of RPCs in the float[3] system. This study adopts a conservative approach, assuming that float constitutes a minimal share (<1%) of the total crate mass in the system. Under this assumption, the environmental impact attributed to float is considered negligible. However, if float represents a substantially larger proportion of the total mass, its contribution to environmental impact could become significant and should be accounted for in studies of this nature.

When integrating the findings of this study with those of other LCAs comparing CCs and RPCs, the overarching conclusion is that environmental trade-offs do indeed exist between the RPC and CC systems. Additionally, market characteristics- subject to regional variations- play a crucial role in shaping these trade-offs. Given the close alignment of outcomes between the two systems in certain impact categories and the sensitivity of the results to certain factors, it is clearly important to model in detail the specific market in question.

[3]Float refers to the quantity of excess RPCs that exist in the total system. These excess RPCs are required to assure the flexibility to respond to surges in system demand or extended time in the return loop.

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Abbreviations and Acronyms

AF&PA	The American Forest and Paper Association
BTU	British Thermal Unit = 1,060 joules (j)
CC	Corrugated container
CH4	Methane
CO2	Carbon dioxide
CPA	Corrugated Packaging Alliance
DQIs	Data Quality Indicators
EOL	End-of-life
FBA	Fibre Box Association
GHG	Greenhouse gas
GMA	Grocery Manufacturer's Association
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Control
ISO	International Organization for Standardization
kg	Kilogram = 1,000 grams (g) = 2.2 pounds (lbs.)
kWh	Kilowatt-Hour = 3,600,000 joules (j)
lb	Pounds = 0.45 kilograms (kg)
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Mega joules = 1,000,000 joules (j)
NCASI	National Council for Air and Stream Improvement, Inc.
PP	Polypropylene
ReCiPe	Impact assessment method developed by: RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft
RPC	Reusable plastic container
Tonne-km	Tonne-kilometer; 1 metric ton traveling 1 kilometer
Ton-mi	Ton-mile; 1 short ton traveling 1 mile
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts

1 Introduction

Corrugated Packaging Alliance (CPA) seeks to understand the relative environmental performance of corrugated containers (CCs) to reusable plastic containers (RPCs) used to transport and display fresh produce in the U.S. To update a work originally conducted by Quantis in 2019, CPA engaged Anthesis to undertake an ISO-compliant comparative life cycle assessment (LCA) of CCs and RPCs. As this report replicates the 2019 report with updated numbers, large portions of this report—specifically background information and recommendations—replicate text from the original report. Instances where methods, results, conclusions, or recommendations have changed are clearly indicated.

1.1 Background

Consumers have become increasingly aware of the need to reduce the environmental impact of food waste and food packaging in recent years.[4] In response, retailers and producers of food and food packaging are turning to life cycle assessments (LCA) to quantify impacts and inform improvement efforts.

LCA is a decision support tool that enables scientifically rigorous and transparent quantification of a range of environmental impacts for different product systems and is a framework defined by the International Organization for Standardization (ISO) 14040 and 14044 standards (ISO 2006a; ISO 2006b). This report and the study it describes adhere to the four-stage iterative process detailed in the ISO standards and represented in Figure 1:

1. **Goal and scope definition:** The first stage of LCA is to define the goal and scope of study to understand the objectives and intended applications, the boundaries of what is being assessed and the performance requirement that the product fulfils.

2. **Inventory analysis:** The second stage is inventory analysis, where an inventory of flows to and from nature is created, usually using a combination of primary and secondary data collected for each unit process of the product system.

3. **Impact assessment:** The third stage is impact assessment, which is where inventory data are applied to characterization factors to generate the main results and determine the environmental impacts.

4. **Interpretation:** The final stage is interpretation, which is where conclusions are drawn, sensitivity and uncertainty analyses are performed, and recommendations made.

[4] WRAP. Reducing household food waste and plastic packaging. February 2022. https://www.wrap.ngo/sites/default/files/2022-02/WRAP-Reducing-household-food-waste-and-plastic-packaging-Full-report.pdf.

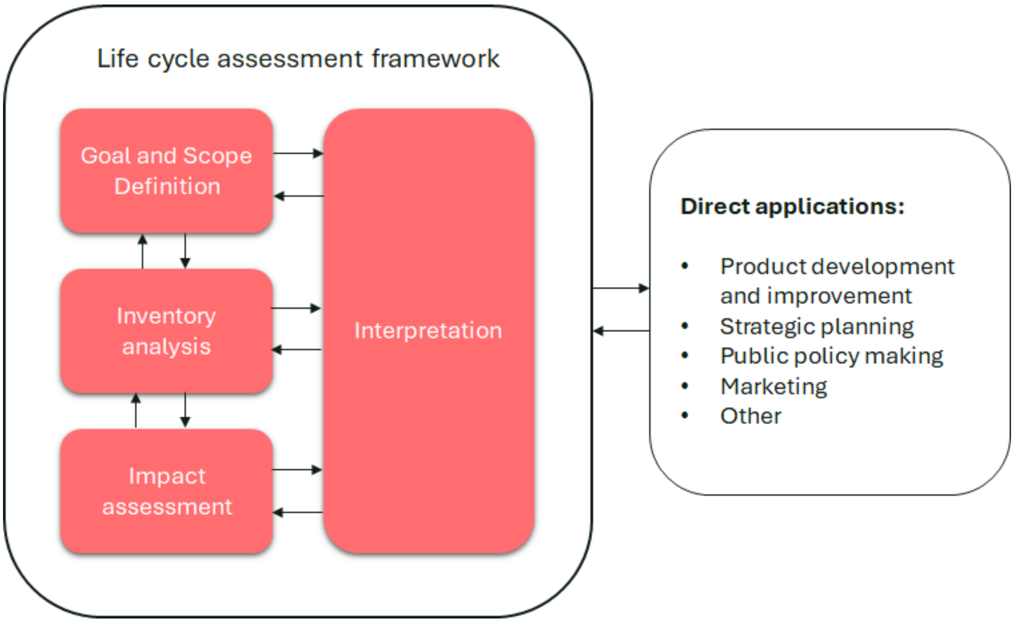

Figure 1: The four stages of LCA as defined by ISO 14040

As indicated by the double arrows in Figure 1, the LCA process is iterative, with feedback loops between the interpretation and all other stages of the LCA, as is the case in this study.

The following LCA practitioners from Anthesis were involved in this project:

- **Caroline Gaudreault, PhD (Project Sponsor)-** Caroline has longstanding experience across the forest products value chain as well as technical expertise in both LCA, and in the treatment of biomass in carbon accounting and goal setting. Caroline provides expert assistance to companies and industry associations across the whole forest products value chain (forest owners, pulp and paper facilities, wood product facilities, biomass fuel producers).

- **Alivia Mukherjee, PhD (Project Support)-** Alivia is a senior consultant with 4 years' experience in Life Cycle Assessments (LCA). She has a PhD in chemical engineering. Alivia has modeled LCAs for a variety of biomass-based products. She has collaborated with government agencies like NRCan and IEA. She has produced 30 plus publications, edited 2 books, and has authored 1 book in the field of hydrogen generations, carbon nanotubes, activated carbon, decarbonization, and renewable energies.

- **Rutika Savaliya (Project Support)-** Rutika is a senior consultant with over 2 years of experience in Life Cycle Assessments (LCA). She has a background in chemical engineering and has experience working on a wide variety of LCA projects, including those focusing on fashion apparel, footwear, packaging, circular businesses, chemicals, and electronics.

The CPA acknowledges the challenges associated with conducting a comparative LCA study and adheres to expert review protocols as stipulated by the ISO standard for public comparative statements.

2 Goal and Scope of the Study

2.1 Objectives

This investigation quantifies and compares the environmental performance of CCs and RPCs used to transport and display produce. More specifically, the objectives of the study are as follows:

1. Quantify the life cycle potential environmental impacts of corrugated containers and reusable plastic containers by employing suitable and recognized databases and LCIA characterization factors in accordance with ISO 14040 and ISO 14044: 2006;
2. Assess the extent and certainty of comparative environmental advantages of either system; and
3. Verify that results adhere to ISO 14044 (clause 6) and ISO 14040 (clause 7) to substantiate a public comparative claim by submitting this report to a critical review by independent experts.

A critical review of an LCA is mandatory by the ISO standards if the results are to be communicated publicly. The purpose of third-party review is to improve quality and credibility, which in turn enhances public acceptance of study.

2.2 Intended audience

The intended audience of this study consists of the stakeholders of the RPC and CC industries such as suppliers of encompassing raw material, container manufacturers, transport providers, farms, produce retailers and produce consumers. The report aims to facilitate public communication of the comparative results. This report may also be utilized by the CPA, American Forest and Paper Association (AF&PA), the Independent Packaging Association (AICC), the Fibre Box Association (FBA), the Technical Association of the Pulp and Paper Industry (TAPPI), plastic industry associations, and by members of these organizations to improve the understanding of their products and to identify opportunities for environmental improvement.

2.3 General Description of the Product Studied

CCs and RPCs are used for the transportation of produce from produce growers to retail markets (e.g., a grocery store) and can also be used to store and display the produce at the point of sale. Although these products provide the same service, they differ in material composition and the rate of container recovery or reuse.

2.3.1 Corrugated Containers

This study assesses corrugated containers featuring a standard container design for each produce type, with the predominant size, style [e.g., regular slotted container (RSC), telescoping] and packing configuration used for each commodity. Containers are presumed to possess adequate strength to hold the specified quantity of produce indicated, however the mass capacity for a particular size fluctuates throughout the industry. Each pallet has 5-10 cases per layer. This study examines the conventional Grocery Manufacturer's Association (GMA) pallet measuring 40”x48”.

While a CC is not reusable for transporting produce, CCs that are recycled instead of landfilled or incinerated may be used as a feedstock for a variety of wood fiber-based products, including corrugated boxes containing recycled materials. It is presumed that no wax or other would-be contaminants or other materials are used during the production or utilization of CCs that might prevent normal recycling.

Figure 2 depicts the life cycle of CCs. The production of virgin fiber encompasses seedling production, reforestation and fertilization, harvesting, sawmill processing, and transport. Containerboard production encompasses the pulping of virgin and recovered fibers and containerboard. Containerboard converting and box assembly are aggregated as conversion in Figure 2. Converting encompasses containerboard corrugation, laying, gluing, and drying. Box assembly encompasses seam construction (folding and gluing) in addition to printing, as described in PE Americas (2009). The use stage encompasses container erection, produce packing, and display of produce at retailer. The end-of-life phase includes collection and waste processing steps including landfill, incineration, and recycling. Transport between processes is incorporated into the life cycle stages as illustrated.

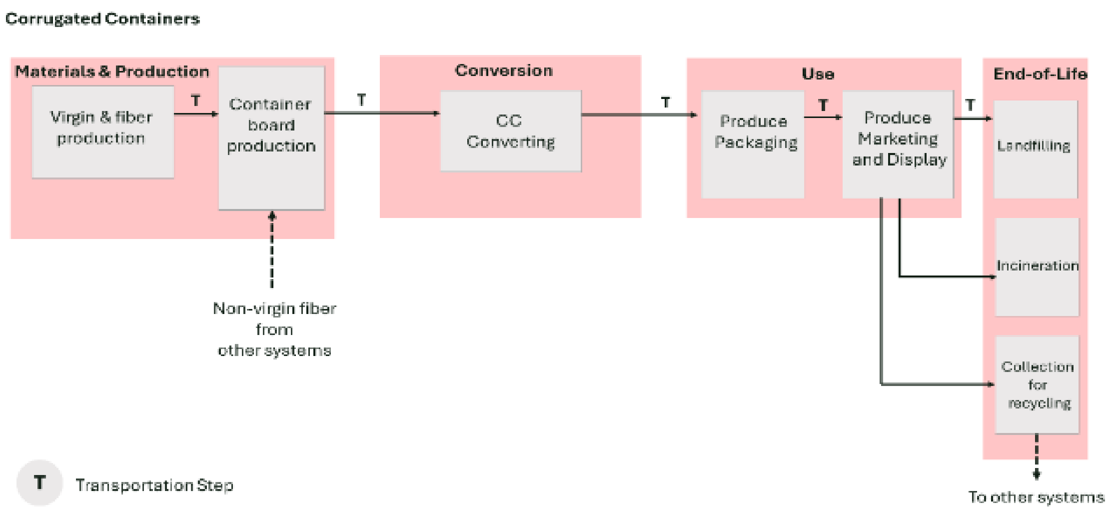

Figure 2: Life cycle stages of corrugated containers (CCs)

2.3.2 Reusable Plastic Containers

This study examines a standard footprint (16” x 24”, 5-containers per layer) RPC that is commonly used in the United States as a packaging solution for produce. Similar to the CC, the RPC is engineered to enhance stacking, loading, and display efficiency, and is transported on standard GMA 40”x48” pallets. RPCs are composed of a mixture of virgin and recycled polypropylene and shaped via injection molding. Following use at the produce retailer, the majority of RPCs are cleaned and reused. The RPCs may be managed by produce growers, retailers, pooling agencies or a consortium of stakeholders. RPCs must be collected for sorting at distribution centers post-market use and subsequently transported for cleaning/sanitation. The containers are subsequently returned to the produce growers for refilling with produce before being dispatched to the market. RPCs that are unfit for reuse can serve as raw materials to produce new RPCs or may be removed from the system as lost or discarded RPCs which are landfilled, incinerated, or recycled.

Reusable containers require a float inventory to address variable demand because of holding points throughout the distribution chain (e.g., on a shelf at a retailer, at a washing facility). Figure 3 depicts the life cycle stages of RPCs. The aggregated materials and production stage encompasses the production of virgin polypropylene (PP), the recycling of PP sourced from products other than RPCs, as well as the recycling and production of RPCs through injection molding. The use stage includes the packaging and display of produce at retail locations. The re-use stage involves the washing, sorting, and temporary storage of RPCs. At end-of-life, RPCs are collected then landfilled, incinerated, or recycled. Transport between processes is incorporated into the life cycle stages as illustrated.

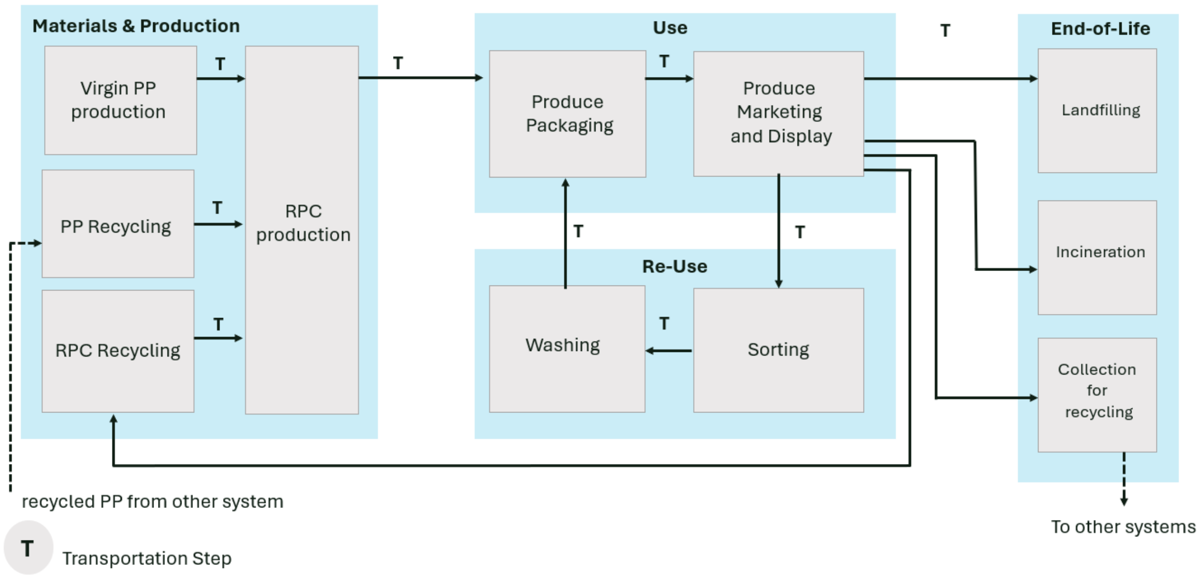

Figure 3: Life cycle stages of reusable plastic containers (RPCs)

2.4 Function, Functional Unit and Reference Flow

LCA relies on a functional unit as the basis for establishing equitable comparisons between multiple product systems.

The functional unit for this study is defined as:

> "The provision of containment during filling, transport, and display of 907,185 kg (1,000 short tons) of grocery market produce in the United States in a manner that maintains the safety of the produce for human consumption and that is consistent with commercial supply chains."

Produce damage or perishability is excluded from the functional unit due to insufficient data regarding loss rates.

While many container types can fulfill the specified functional unit, this study focusses exclusively on CCs and RPCs, which are widely used produce packaging solutions in the U.S. market. This investigation examines container profiles for eight types of produce: apples, carrots, grapes, lettuce (head), oranges, onions, tomatoes and strawberries. These commodities are chosen since they represent the eight highest by volume fresh market produce commodities transported and displayed by both CCs and RPCs (USDA 2017). In 2017, the United States' total utilized production for noncitrus fruits and vegetables was approximately 56.4 million tons. The eight commodities—apples, carrots, grapes, lettuce, oranges, onions, strawberries, and tomatoes—collectively accounted for about 79% of this total production. Table 1, Table 2 and Table 3 provide details about the distinct properties of these containers such as container volume and produce density for the different types of fruits and vegetables transported in these containers. Other produce commodities with comparable pack size and density attributes may be presumed to yield analogous outcomes. Within the LCA model, only what is listed in Table 1, Table 2, and Table 3 varies for the different produce types; the remainder of the model framework remains unchanged.

The outer dimensions of each container are detailed in Table 1 and serve solely as a qualitative description for this study. Table 2 presents the mass and capacity of each container. The values serve as the foundation for determining the quantity of container shipments necessary to meet the functional unit's requirements. All evaluated RPC containers evaluated are shipped as five containers per layer, while CCs are shipped 7-10 containers to a layer, depending on commodity.

Table 3 presents the knock-down ratios for RPCs. Knock down containers are designed to fold flat when not in use, thereby allowing for more containers to be shipped per truck trip between the washing center to the packer and from the retailer back to the washing center.

The RPC data is derived from Franklin Associates (2017)[5], while the CC information is sourced from industry experts.[6] The CC values utilized in this study represent the average of the numbers shared with the CPA. This approach of using averages has been endorsed by all data providers, as it effectively anonymizes specific submissions from individual contributors, ensuring that any individual number provided by a single party are not disclosed. It is important to note that not all parties submitted capacity data. In instances where such data was unavailable, it was estimated by combining with the average mass-to-capacity ratio from data provided by the remaining parties to calculate the capacity. The industry experts consulted for this study are prominent corrugated box manufacturers within the produce sector, who work closely with growers and shippers that also utilize RPCs. These experts are well-positioned to provide reliable insights, given their direct involvement in the supply chain.

The containers provide supplementary functions such as display aesthetics, handling ease and secondary applications. However, for the purpose of this report, these supplementary functions are considered either comparable or irrelevant. As a result, the evaluation is focused exclusively on the primary functional unit outlined above.

Furthermore, the containers must ensure the protection of produce they transport. While this function is not incorporated into the baseline evaluation, a sensitivity analysis is conducted to assess the product's perishability. Specifically, container strength is represented by their capacity. Although performance parameters may vary slightly among manufacturers for specific containers (e.g., RPCs carrying apples), this variation is presumed to remain within a limited range.

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[5] In the present study, RPCs are assumed to have a common footprint of 60cm * 40 cm (23.62in * 15.75in). Data provided by Franklin Associates (2017) agree with these.

[6] It is not clear what resource(s) was used to derive the CC characteristics applied in Franklin Associates (2017); the report simply lists (in Table 1-1) Franklin Associates as the source of the data. The document later mentions CPA (2014) as a source for other information. However, this report does not provide the CC characteristics.

Table 1: CC and RPC outer dimensions for each commodity *

**Values are rounded to an appropriate number of significant figures here for reporting purposes.*

	Length, cm (in)		*Width, cm (in)*		*Height, cm (in)*	
Commodity	*RPC*	*CC*	*RPC*	*CC*	*RPC*	*CC*
Apples	*60 (23.62)*	*49.54 (19.50)*	*40 (15.75)*	*30.75 (12.04)*	*27 (10.60)*	*28.9 (11.4)*
Carrots	*60 (23.62)*	*43.36 (17.07)*	*40 (15.75)*	*30.56 (12.03)*	*19 (7.30)*	*28.2 (11.1)*
Grapes	*60 (23.62)*	*57.47 (22.63)*	*40 (15.75)*	*39.05 (15.37)*	*15 (5.90)*	*11.23 (4.5)*
Lettuce – head	*60 (23.62)*	*59.52 (23.44)*	*40 (15.75)*	*39.20 (15.44)*	*29 (11.5)*	*27.9 (11.0)*
Onions	*60 (23.62)*	*48.80 (19.21)*	*40 (15.75)*	*38.10 (15.00)*	*21 (8.31)*	*23.6 (9.29)*
Oranges	*60 (23.62)*	*43.36 (17.07)*	*40 (15.75)*	*28.68 (11.29)*	*27 (10.60)*	*27.9 (11.0)*
Strawberries	*60 (23.62)*	*49.36 (19.44)*	*40 (15.75)*	*33.20 (15.44)*	*10 (4.1)*	*8.91 (3.51)*
Tomatoes	*60 (23.62)*	*43.36 (17.07)*	*40 (15.75)*	*33.20 (13.07)*	*15 (5.9)*	*17.8 (7.00)*

Table 2: Mass and capacity of each container

	Average weight per empty container, kg (lb)		**Amount of produce per container, kg (lb)**		**Thousand container movements required per FU[1,2]**		**Number of containers in each layer on a pallet**		**Functional unit mass ratio**
	RPC	*CC*	*RPC*	*CC*	*RPC*	*CC*	*RPC*	*CC*	CC: RPC[3]
Apples	2.27 (5.01)	0.82 (1.8)	18.18 (40.08)	18.0 (39.6)	50	50	5	7	0.36
Carrots	1.73 (3.81)	0.71 (1.6)	18.18 (40.08)	19.0 (41.7)	50	48	5	10	0.39
Grapes	1.55 (3.41)	0.69 (1.53)	9.09 (20.04)	9.07 (20)	100	109	5	6	0.45
Lettuce-head	2.38 (5.25)	1.1 (2.4)	22.59 (49.8)	23.6 (51.9)	41	38	5	5	0.44
Onions	1.91 (4.21)	0.89 (2.0)	18.18 (40.08)	16.7 (36.8)	50	54	5	6	0.51
Oranges	2.27 (5.01)	0.90 (2.0)	18.18 (40.08)	20.3 (44.7)	50	45	5	9	0.36
Strawberries	1.27 (2.81)	0.39 (0.86)	4.09 (9.02)	3.78 (8.33)	222	240	5	6	0.33
Tomatoes	1.55 (3.41)	0.60 (1.3)	11.36 (25.05)	13.0 (28.6)	80	70	5	8	0.34

[1]Values are rounded to an appropriate number of significant figures for reporting purposes. The metric "container movement required per FU" refers to how many thousands of containers are needed to fulfill one FU

[2]Functional Unit (FU) = 907,185 kg of produce delivered; [3]Calculated as (CC mass per functional unit) / (RPC mass per functional unit).

Table 3: Knock-down ratios of RPCs

Commodity	Knock-down ratio*
Apples	0.30
Carrots	0.36
Grapes	0.45
Lettuce-head	0.33
Onions	0.38
Oranges	0.38
Strawberries	0.56
Tomatoes	0.64

**Computed as the number of erected containers per pallet divided by the number of knocked-down containers per pallet*

2.5 System Boundaries

The system boundaries define the life cycle phases, processes and flows considered in the LCA, capturing all activities relevant to fulfilling the report's stated objectives and essential for delivering the intended function. This report offers a foundational overview of the system (Figure 2 and Figure 3), outlines its temporal and geographical scope, and identifies any exclusions.

2.5.1 General System Description

This study evaluates the life cycle of CCs and RPCs containers, encompassing every phase from the extraction and processing of raw materials through the end-of-life. Each stage of the LCA meticulously evaluates all identifiable upstream inputs, providing a comprehensive view of the product system. The production chains for all inputs are traced back to their origins in raw material, ensuring a holistic understanding of the entire process. The system boundary for CC and RPC are illustrated in Figure 2 and Figure 3 respectively, detailing the included processes and material flows.

2.5.2 Temporal and geographic boundaries

This LCA aims to provide a comprehensive analysis of the RPC and CC industries along with their related processes in the United States during the 2017-2018 study period. The data and assumptions utilized are intended to reflect the prevailing equipment, methodologies, and market conditions of the time. However, much of the available data-and the majority of temporally relevant information-pertaining to CCs and RPCs originates from earlier periods, reflecting historical industry practices. The RPC focuses on 2003 North American polypropylene resin [USLCI (2010)] and 2007-2008 European injection molding [Plastics Europe (2010)]. The European data has been appropriately adjusted to ensure consistency with the North American context. Additionally, the analysis incorporates 2002 data on North American forestry practices and 2020 U.S. CC industry operations. Additional information regarding the data utilized in this analysis is provided in section 2.6.

This study seeks to offer an analytical overview of typical operations within the U.S industries, concentrating specifically on domestically grown produce. It does not include a detailed analysis of seasonal variations. To estimate transport distances (both to and from growers), a weighted average is used, representing the proportion of produce sourced from different U.S regions in a given year. These transport distances are derived from data provided by the U.S. Census Bureau and U.S. Department of Agriculture (USDA) (U.S. Census Bureau 2012, USDA 2017). Detailed calculations and corresponding transport distances are presented in Appendix A3. The transportation of produce transport is modeled assuming it involves refrigerated vehicles.

The analysis focuses exclusively on containers produced and managed within the U.S. The evaluated RPC system operates as a closed-loop model, with all stages- manufacturing, usage, maintenance and disposal- occurring domestically. In contrast, a portion of the recovered containers within the CC system is transported beyond U.S borders. The domestic supply of recovered materials exceeds local demand, resulting in surplus containers being exported as raw materials inputs for international markets, which are beyond the scope of this study. Broadening the scope to include global markets would require an in-depth examination of the role of CCs in international trade and supply chains.

The foreground processes are designed to align with the North American systems, specifically for electricity grids and transportation, where applicable. Generic datasets used in this report have been adjusted as needed to improve their relevance to the geographical context of these systems. However, the background processes of the model are not tailored to reflect North American electricity grids and transportation, as supply chain products may originate from diverse global locations. This lack of transparency in supply chain dynamics introduces uncertainty about the extent to which the actual electricity sources utilized within these supply chains are accurately represented.

Certain processes within the system(s) boundaries might occur across various locations or timeframes. For instance, the processes related to supply chain management and waste management can occur in North America or in other regions globally. Additionally, specific processes may generate emissions that extend beyond the duration of the reference year. This pertains to landfilling, where emissions such as biogas and leachate are generated over extended periods, often spanning decades centuries, or even millennium. The duration of these emissions depends on factors such as the design and operation parameters of the burial cells and the methodologies used to model environmental emissions. The long-term implications of carbon storage in landfills are further discussed in section 3.1.2.

2.5.3 Treatment of recycled material

The allocation for recycling and reuse is a critical component of analytical assessment. ISO 14044:2006 (ISO 2006), in section 4.3.4.3.2, outlines the significance of sharing the resources and processing loads between the original product and subsequent product cycles. One specific allocation method, referred to as the "the number of uses" is particularly relevant to the recycling of paper products. ISO 14049:2012 (ISO 2012a) illustrates this method through various instances, ranging from comprehensive formulations based on industry data (Galeano et al. 2011) to laboratory-derived usage estimates.

The RPC system operates within a closed-loop framework, ensuring that all recovered material flows are retained within the system. This means that any waste generated at different life cycle stages has its end-of-life impacts accounted for in the EoL stage only, ensuring consistency in how impacts are considered. Although the "number of uses" approach could have been applied, it would have produced mathematically identical outcomes due to the way recycling and reuse are modeled for RPCs. However, the closed-loop nature of the RPC system does not imply that all material is infinitely reused; rather, the amount of recycled material necessary for new RPCs is considered closed-loop, while any surplus recycled material is assumed to be exported (open-loop) and excluded from the system boundary.

Conversely in the CC system, a portion of the model also functions as a closed- loop. However, the treatment of exported, recovered old CCs (OCC)—which are cut off after the point of recovery—may influence the study's findings. Owing to the uncertainty surrounding the end-of-life fate of the exported OCC, a sensitivity analysis was not performed, as it would be infeasible to allocate the impacts of these activities across product systems.

2.5.4 Exclusions and cut-off criteria

Processes may be excluded if they are either (1) identical across systems being compared and/or (2) if they are deemed negligible, defined as contributing less than 1% by mass or energy. It is crucial to acknowledge that excluding processes based on equivalence may affect the calculated relative percentage (%) differences between the products. Mass and/or energy are used as proxies for environmental significance, as assessing such relevance requires prior computation of the LCA results. The following items are excluded from this LCA:

- **The wholesale distribution** of produce has not been analyzed, as neither system incorporates it as an option, and RPCs are entirely absent from the wholesale market. This study focusses exclusively on applications that present a choice between CCs and RPCs.
- **Infrastructure and capital goods** are not included in the analysis, unless such information is provided within aggregated inventory datasets. Notably, the temporary storage of CCs between production and utilization, as well as the storage of RPCs following retail and post-washing stages, is omitted. These storage periods can extend up to one year.
- **The loss of containers** between production and utilization, arising from structural damage incurred during manufacturing, transportation or usage (e.g., manufacturing defects or exposure to, humid environment) is excluded. Such losses are considered negligible, amounting to less than 1% for both types of containers.
- The processes of **container erection and produce packing** at the grower as well as the display of produce at the retailer, are excluded from consideration due to lack of detailed information regarding their infrastructure and energy demands. These activities are presumed to have a minimal impact, likely accounting for less than 1% of the total requirements, as they predominantly rely on manual processes.
- This study does not encompass **secondary packaging**, such as clamshell containers for strawberries. Additionally, the type and quantity of such packaging for each commodity remains consistent between CCs and RPCs.
- **The storage of produce** at the retailer, as well as during transit between the grower and retailer, is excluded from consideration. While this stage seems significant due to the role of refrigeration, it is assumed that the storage operations for both the systems are identical, thereby contributing an equivalent environmental impact to the life cycles of CC and RPC systems.
- The analysis excludes consideration of backhaul. In the context of produce transportation, there is no compelling reason to assume that backhaul arrangements would differ based on the container types. Vehicles typically operate along a fixed route, carrying a predetermined payload from grower to distributor/retailers, and returning regardless of the container used. While variations in backhaul trips may occur between the container systems and produce

type due to differing truck requirements for the functional unit, these differences are expected to have a minimal effect on the overall life cycle impacts.

- The sorting of RPCs during the reuse stage is excluded from the LCA due to insufficient information regarding infrastructure and energy demands. However, these factors are considered negligible, accounting for less than 1% of total requirements.
- In the baseline analysis of RPCs, the float inventory is excluded. To assess its impact on the RPC footprint, a sensitivity analysis is conducted. For further details and clarification, please refer to Appendix B.
- The transportation of RPC collection to PP recycling at the end-of-their life has been excluded from the RPC system; as this step is considered insignificant owing to the negligible quantity of material involved, accounting for less than 1% of total requirements.
- Exported and recovered OCC is excluded from the analysis after the point of recovery because it is not possible to accurately determine their subsequent fate without further investigation (i.e., cut-off). Assuming these materials would be processed in the same manner as OCC retained within the U.S. would result in a misrepresentation of system dynamics. The presumption that excess OCC is directed at municipal solid waste is similarly unrealistic. Reincorporating these materials into the CC production process would require an increase in the average recycled content of CCs, a scenario that conflicts with industry data on recycled content levels. Adopting a cut-off approach for managing the export of recovered OCC ensures that the burdens associated with the CC system remain confined to the current framework. This approach prevents the redistribution of burdens to future product systems, which would occur under a number-of-uses allocation method. As a result, the cut-off method represents a conservative and pragmatic analytical choice. This same consideration applies to RPCs, where increasing the recycled content beyond industry data would misrepresent actual system conditions.
- The baseline assessment excludes produce production due to a lack of sufficient data on produce losses incurred during transit. However, a sensitivity analysis is conducted to evaluate the potential impacts of produce production and the consequences of transit-related damage.
- All produce transportation is modelled as refrigerated; however, due to a lack of adequate data, the report does not account for the thermal properties of the containers. If the container is cooled during transport, fluctuation in the thermal properties of the containers will influence the energy needed to maintain a target temperature. Nevertheless, when analyzed in the context of the total transportation distance, the difference in the impact of initial cooling is considered negligible- contributing less than 1% to the overall energy requirements.
- Land use and land transformation is excluded from the study due to a lack of inventory data. See section 6 for further discussion.
- Toxicity indicators are excluded from the study because data describing toxicity-related emissions are not comparable between the two container systems. Refer to section 6 for further details.
- This report excludes social and economic impacts from its scope. Nonetheless, variations are present in human resource factors (e.g., labor requirements) and cost between the two container systems.

2.6 Data sources and assumptions

The reliability of LCA outcomes is inherently dependent on the quality of data employed during the evaluation. Every effort was made to utilize the most accurate and representative information available. The data collection process was executed through an iterative collaboration between Quantis and CPA. In instances where direct data sources were unavailable, assumptions were guided by professional judgement. To ensure robustness, sensitivity analyses were carried out to evaluate the influence of these parameters on the final outcomes.

The data and assumptions underpinning this report are drawn from prior work, publicly available resources, and expert insights that inform industry practices and provide the metrics required for developing the life cycle inventory of each system. This chapter provides a detailed overview of the data sources and assumptions foundation of the life cycle inventory for each system.

While significant efforts have been undertaken to compile the most accurate information and to evaluate critical factors such as geography, temporal relevance, scientific credibility, and internal report consistency, the findings presented in this report are deemed reliable only within the specified boundaries and limitations outlined. When critical information is unknown, uncertain or exhibits high variability, sensitivity analyses are conducted to assess the potential impacts of the data gap.

This document employs recent life cycle studies on CCs and RPCs as sources of primary data to detail current industry operations.

Table 4 presents a compilation of relevant prior life cycle studies. The original CC model used in previous Quantis study was developed from fiberboard container industry assessment conducted for the CPA and AF&PA, as reported in NCASI (2017). It has since been updated to reflect 2020 industry operations, as reported in NCASI (2023). The RPC system model is constructed using insights from a range of publications that outline the RPC life cycle, with a particular emphasis on U.S. (or North American) data when available (e.g., Franklin Associates 2017). This foundation was further enriched by the input from RPC industry experts[7]. The project team employed an iterative approach, regularly reviewing the framework, underlying assumptions, and data to incorporate improvements as appropriate and practicable. When data quality or relevance was uncertain or inadequate, the combined expertise of Anthesis and the client was leveraged to determine the most reliable and suitable information for inclusion in the report. The assumptions relevant to this section are not reiterated here but can be found in previous sections, particularly in Section 2.5.2, Section 2.5.3 and Section 2.5.4, where key assumptions are detailed.

[7] The names of the consulted parties are not listed in this report to protect their interests. Please inquire for more information.

Table 4: Sample recent life cycle studies on CCs and RPCs

Reference	Description	
Franklin Associates, 2004	Title	*LCI of reusable plastic containers and display-ready corrugated containers used for fresh produce applications*
	Scope and Transparency	Study is a life cycle inventory of containers in U.S. produce market and does not include impact assessment; It is therefore not a life cycle assessment; Systems' primary data and key assumptions are not reported.
Rizo SC, 2005	Title	*A Comparative Study of the Environmental and Economic Characteristics of Corrugated Board Boxes and Reusable Plastic Crates in the Long-distance Transport of Fruit and Vegetables: Executive Summary*.
	Scope and Transparency	Study is an LCA of one type of corrugated box and one type of reusable plastic container for tomatoes exported from Spain and delivered to Germany; Some foreground data reported in Executive summary, and remaining data may be available in the main report.
University of Stuttgart, 2007	Title	*The Sustainability of Packaging Systems for Fruit and Vegetable Transport in Europe based on Life-Cycle-Analysis*
	Scope and Transparency	Study is an LCA of corrugated common footprint containers and reusable plastic containers in Europe; Foreground and background data are comprehensively reported.
PE Americas and Five Winds International, 2009	Title	*LCA of US Industry-average Corrugated Product*
	Scope and Transparency	Study utilizes primary data from fiber and corrugated box industries; Data describes 2006 industry operations
Levi et al., 2011	Title	*A comparative life cycle assessment of disposable and reusable packaging for the distribution of Italian fruit and vegetables*

Reference	Description	
	Scope and Transparency	Study is specific to Italian packaging for distribution; Foreground and background data are comprehensively reported.
Franklin Associates, 2013	Title	*Comparative life cycle assessment of reusable containers and display- and non-display-ready corrugated containers used for fresh produce applications*
	Scope and Transparency	Study is an LCA of corrugated common footprint containers and reusable plastic containers in North America; Foreground and background data are comprehensively reported.
NCASI, 2017	Title	*Life Cycle Assessment of U.S. Average Corrugated Product – Final Report*
	Scope and Transparency	Study utilizes primary data from fiber and corrugated box industries; Data describes 2014 industry operations; Foreground and background data are comprehensively reported.
Franklin Associates, 2017	Title	*Comparative life cycle assessment of reusable containers and display- and non-display-ready corrugated containers used for fresh produce applications*
	Scope and Transparency	Study is an update of Franklin Associates 2013 including more recent data and corrections to prior study.
NCASI, 2023	Title	*Life Cycle Assessment of U.S. Average Corrugated Product – Final Report*
	Scope and Transparency	Study is an update of NCASI 2017 including more recent data. Data describes 2020 industry operations; Foreground and background data are comprehensively reported.

3 Life cycle inventory

This study aims to utilize the most up-to-date and pertinent life cycle inventory (LCI) data that describes the CC and RPC life cycles. Background processes are modelled using ecoinvent v3.10 and SimaPro; no adjustments (to grid mixes or otherwise) are made, unless specified in this report. The data utilized to represent foreground processes for CCs and RPCs is detailed in sections 3.1 and 3.2, respectively.

3.1 CC system model

The life cycle of CC is modelled based on the data and assumptions derived from previous work. The model construction commenced with the NCASI (2023) system model, incorporating additional life cycle stages and modifications to accurately represent the complete CC life cycle. The LCI for fiber production and associated upstream (forest) operations, as referenced in the previous report and this study, is derived from the Consortium for Research on Renewable Industrial Materials (CORRIM). This data reflects practices from 2002 as documented in the USLCI Database (NREL 2014). Data on containerboard production data and CC conversion are sourced from an NCASI survey that examined industry operations in 2020.

3.1.1 Recycled content

A survey conducted by the CPA among its members involved in supplying boxes to the produce industry reveals that the average recycled fiber content in the containerboard is 31.8%. This equates to 0.318 kg/kg containerboard or 0.35 kg/kg of corrugated product. Additionally, the production of 1.1 kg of containerboard is required to produce 1.0 kg of corrugated product.

3.1.2 Biogenic carbon accounting

For products with minimal or no bio-based materials, it is generally assumed that the net flow of biogenic carbon is zero, leading to a negligible impact on assessment results. In contrast, products containing substantial amount of bio-based materials—such as in the case of corrugated board—require careful carbon accounting in order to accurately evaluate the flow of greenhouse gases.

During the production of a forest or agricultural product, such as virgin fiber for CCs, carbon dioxide (CO_2) is removed from the atmosphere and integrated into the material that is harvested from the forest or field. The carbon referred to as "biogenic" is retained within the material throughout the life of the product. Upon utilization as fuel or during the degradation process, carbon is subsequently released into the environment. The emissions are predominantly composed of carbon dioxide (CO_2) and methane (CH_4).

This study employs the net zero biogenic carbon approach to streamline the modeling process. This approach is supported by the claim that if the removed carbon is replenished within a brief period (under 100 years), the overall carbon exchange with the atmosphere is a net zero effect, thereby creating no net impact on climate. Section 6.4.9.2 of ISO 14067 outlines the net zero phenomenon, and, according to PAS 2050 (section 5.1.1), biogenic carbon that is incorporated into human food or animal feed may be excluded, as it typically does not remain for more than 100 years. As they have a lifespan of less than 100 years CCs are similar to food or animal feed in this regard.

In contrast to CO_2, CH_4's presence in the atmosphere is not mitigated during the production processes of forest or agricultural products; thus, there is a net impact related to the emission of biogenic carbon in the form of CH_4. Consequently, biogenic CH_4 is included in this assessment. NCASI (2023) provides a comprehensive overview of the carbon flows within the cradle-to-gate CC production process which was utilized in this analysis.

In the analysis of the gate-to-EOL stages, it is observed that biogenic carbon emissions are generated exclusively at the EOL stage. Emissions can be released soon after the product's life cycle concludes or may remain contained within a landfill for an extended duration, potentially spanning hundreds or thousands of years. An exception to the net zero approach outlined previously occurs in scenarios where carbon is sequestered from the atmosphere for extended durations. It is reasonable to conclude that, over long timeframes (e.g., several decades or centuries), carbon that is stored away from the atmosphere exerts a considerable impact on the environment. The carbon present in the landfill after a century (100 years, the same period used to calculate the global warming potential (GWPs) applied in this study) is accounted for in the inventory as stored carbon. The assumed value for the amount of carbon stored is 55% of the carbon in the CCs (as reported by NCASI 2023 and originally sourced from Wang 2011); there is approximately 0.491 kg carbon per 1 kg containerboard (NCASI 2017).

Table 5 provides a detailed inventory of greenhouse gas (GHG) flows utilized in the assessment, clarifying the treatment of each type of carbon flow. The first column enumerates the potential mechanisms through which greenhouse gases (primarily CO_2 and CH_4) can be absorbed or emitted. The second column provides a variable that denotes the numeric value of the flow, while the third column specifies whether the flow is included in this analysis and if applicable, the direction of the flow. A positive value signifies an emission, whereas a negative value denotes that a GHG is being absorbed (i.e., removed from the atmosphere).

The fourth column indicates the GWP for the specified GHG. The concluding column presents the calculated outcomes within the model, detailing the impact of climate change associated with each GHG flow. The calculation involves multiplying the associated amount of GHG emitted or absorbed (in kg) by the GWP of the respective GHG. The total climate impact attributed to the biogenic carbon flows in the life cycle of a container is derived from the sum of its column. Sensitivity analyses are utilized to explore the influence this methodological decision has on the outcomes of the current study. Please refer to sections 5.5.9 and 5.5.10 or further details.

Table 5: Biogenic carbon accounting approach implemented in this report for each greenhouse gas flow

Type of greenhouse gas flow	Amount	Representation in the life cycle inventory (kg to or from air)	Global warming potential (kg CO2-eq / kg emitted to air)	Result (kg CO2-eq)
Removal of CO_2 from atmosphere by forest or agricultural product, to be stored for less than 100 years	A	-A	0	-A*0
Removal of CO_2 by forest or agricultural product, to be stored for more than 100 years	B	-B	1	-B*1
Uptake or release of CO_2 by forest soils	C	Not included	N/A	N/A
Other indirect uptake or release of CO_2 by forestry and land use	D	Not included	N/A	N/A
Emission of CO_2 from fossil sources (e.g., oil combustion) pre 100-year threshold	E	E	1	E*1
Emission of methane from fossil sources (e.g., oil combustion) pre 100 year threshold	F	F	30[1]	F*30
Emission of CO_2 from biotic sources (e.g., biomass combustion) pre 100 year threshold	G	G	0	G*0
Emission of methane from biotic sources (e.g., biomass combustion) pre 100 year threshold	H	H	28[1]	H*28
Emission of GHG beyond threshold of 100 years	I	Not included	N/A	N/A

[1]The global warming potential for CH4 used by TRACI 2.1 is based on IPCC (2007). This value was manually updated to reflect the latest IPCC (2013) recommendations. It does not include the impact of CO2 produced by the degradation of CH4 because, as described in (IPCC 2007) section 2.10.3 by Solomon et al. (2007), the degradation product is included in national carbon inventories and would result in double counting should the characterization factor also include it. Since this study is using LCIs, rather than national inventories, to compute climate change, additional impact is included here. It is included only for *fossil* methane as biotic CO2 is ignored in this study.

3.1.3 End-of-Life

After their use, CCs are sent to the end-of-life. NCASI reports that the average percentage of corrugated containers recovered for recycling is 90.5%. Within industry, this percentage is regarded as relatively low because recycling provides economic advantages to produce retailers by enabling them to avoid conventional waste management fees (such as trash disposal) and by presenting a potential revenue stream in markets with high demand for container board. The recycling rates used in this study reflect corrugated containers recovered within the U.S. produce supply chain, rather than national averages that include imported boxes. Recent reports indicate lower national recycling rates; however, these figures account for all corrugated boxes, including imports, which are not relevant to U.S. produce transportation. No open-top corrugated containers or corrugated containerboard fiber containers are imported for produce movement.

Franklin Associates (2004), Franklin Associates (2013), and Franklin Associates (2017) assume a recovery rate of 95%. According to EPA data for corrugated containers within the municipal solid waste stream (U.S. EPA 2018), approximately 80% of corrugated containers are directed to landfills, while the rest (20%) is subjected to incineration. The split of CCs between landfill and incineration for the baseline in this report utilizes a value of 90.5%, and a sensitivity analysis is performed to assess a value of 80.5% (refer to section 5.5.7). The remaining material is assumed to be either landfilled or incinerated.

3.1.4 Transportation

Transportation data for the first two phases of the CC system—raw materials & production and conversion—are sourced from NCASI (2023). The data presented, including the End-of-life transportation data, are derived from the 2017 Commodity Flow Survey from the U.S. Dept. of Commerce. Section 3.3 provides a detailed description of the use of stage data. Appendix A3 presents the transport modes, distances and data sources utilized for each transport step outlined in Figure 2. Additionally, it includes utilization rates and sample calculations.

3.2 RPC system model

The life cycle model of RPCs is designed to represent the U.S. RPC market within the produce industry, analogous to the CC model. The system relies significantly on data pertaining to IFCO RPCs, as provided by Franklin Associates (2017)[8], due to the insufficient availability of publicly accessible information. This document encompasses recycled content pertaining to new RPCs, specifications regarding RPC dimensions and weights, as well as comprehensive details on the RPC production and washing processes. The data utilized for the baseline analysis are deemed applicable within the U.S. context, however the study conducted by Franklin Associates (2017) also considers the North American RPC market. Supplementary information, when accessible, is incorporated to enhance representation of the industry at large and is detailed in the following sections of this report. Sensitivity analyses were conducted to enhance the understanding of the significance of these parameters on study outcomes. Refer to section 4.2 for comprehensive information. The unit process LCIs are detailed in Appendix A2.

[8] The IFCO data are considered representative of a large portion of RPC production in the U.S. given IFCO's relatively large market share in North America. IFCO's 2010 Annual Report states that it constitutes "an estimated 75% market share in the United States" based on total number of RPC trips per annum and "...the produce market has been, historically, the [primary] focus of IFCO's RPC Management Services segment" (IFCO 2010)

3.2.1 Number of uses, loss rate, and breakage rate

The number of uses, commonly known in the RPC industry as the number of cycles or turns, represents the number of times a container may be utilized for produce containment and protection prior to its removal from service due to sufficient wear. RPC may also be removed from use if it is broken or lost. The frequency of RPC usage can exhibit significant variability.

According to Franklin Associates (2017), there are an estimated 39.3 uses with a break and loss rate of 1.78%. A European LCA of RPCs (University of Stuttgart 2007), establishes 50 cycles as the baseline scenario and evaluates up to 100 cycles in a sensitivity analysis. The report indicates a breakage rate of 0.4%. The turn values are classified as relatively high, while the break and loss rates are deemed low within the U.S. context.

The baseline evaluation presented in this study is predicated on 24 uses, with an aggregate break and loss rate of 5%. The values presented are derived from inputs provided by experts[9] in the RPC industry. These industry experts indicated that RPCs have a turnover period of 3-4 months and a lifespan of 5-6 years. Assuming a conservative rate of four (4) cycles annually (once every 3 months) and a lifespan of six (6) years, the calculation yields a total of 24 uses (4 x 6). The assumptions presented are specific to the U.S. context and may vary significantly from the logistics observed in other markets. Sensitivity tests were performed to analyze the impact of these parameters on the conclusions of the study.

The reference flow quantities for the use stage are calculated using these values. For the purpose of this computation, it is crucial to note that the reference flow quantity, defined as the mass of RPCs associated with the functional unit, is designated as X for a specific commodity. The flow from Materials and Production into the Use stage, as illustrated in Figure 3, is represented by the equation (5% + 1/24) X. The identical equation is applicable to the transition from the Use phase into the End-of-life stage. The flow into and out of the Re-use stage is as follows: (100%-5%-1/24) X. The value of 5% indicates the flow out of the Use/Re-use loop with every cycle due to break and loss. Fraction 1/24 represents the average quantity of RPC material exiting this loop every turn.

3.2.2 Recycled content

The estimated baseline recycled content for RPC is 25%, based on information obtained from RPC experts.[10] The study conducted by Franklin Associates (2017) assigns a value of 50% for comparison purposes. A sensitivity analysis, as detailed in section 5.5.3 was performed to evaluate the effects of varying (higher and lower) amounts of recycled content, thereby elucidating the significance of this variable on the outcomes of the study.

3.2.3 Cleaning process

It is assumed that all reused RPCs undergo a washing and sanitization process, achieving a 100% compliance rate. The inputs of detergent, water and electricity utilized in the cleaning process are represented through a composite inventory, drawing on data sourced from the University of Stuttgart (2007) and Franklin Associates (2017). The information supplied by the Franklin Associates (2017) delineates the cleaning and sanitizing procedures specifically

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[9] Please inquire with CPA if you are interested in the names of the parties consulted.

[10] Please inquire with CPA if you are interested in the names of the parties consulted.

employed by IFCO, serving as a representative sample for all of their service centers in 2016.

The cleaning chemicals indicate consumption data from one facility for the year 2015. IFCO is one of the leading RPC manufacturers and distributors in the U.S. The information provided reflects a cleaning process that is applicable to a significant number of RPCs in circulation today. An inventory detailing less efficient technology, as indicated from the University of Stuttgart (2007), is utilized in the model to illustrate the residual segment of the industry. The composite dataset is derived by applying a weight of 70% to the data from Franklin Associates (2013), reflecting the estimated market share[11] of IFCO and a weight of 30% to the data from the University of Stuttgart (2007). This composite inventory aims to accurately represent the "average" cleaning process within the U.S. RPC market, under the assumption that the rest of the industry employs older technology compared to that utilized by IFCO facilities. All other inputs and outputs are sourced from Franklin Associates (2017). The data can be found in Appendix A3.

A sensitivity test was conducted using only the data from Franklin Associates (2017) to understand the potential results should the entire U.S. RPC industry implement the new cleaning technology (see section 5.5.4).

3.2.4 End-of-life

Considering the economic value of RPCs, it is presumed that the vast majority of these containers are retrieved by RPC providers and subsequently processed for re-grinding to facilitate the production of new RPCs. A segment of the discarded RPCs that enter the municipal solid waste stream is highly probable to be recycled, with the PP being directed to the recycled materials market. The total amount of RPCs recovered for recycling is defined as the product of (1) the mass of RPCs used, (2) the percent recycled content of an RPC and (3) the sum of the break and loss rate and the inverse of the number of uses. The model is designed as a closed loop for the integrated PP sourced from the recycled materials market and PP from spent RPCs. The recycling process demonstrates 98% efficiency, applicable to both recycling processes, according to Franklin (2017). Reference flows are depicted in Appendix A1.

The RPCs that are not recycled are directed to end-of-life. The distribution of RPCs at their end-of- life is based on U.S. EPA municipal waste figures (U.S. EPA 2018). Of all municipal solid waste which is discarded and not recycled, 19.6% is combusted for energy recovery; the remaining 80.4% is landfilled.

3.2.5 Transportation

Transportation during the RPC life cycle is modeled using data from multiple sources, including the U.S. Department of Transportation and U.S. Department of Commerce as well as Franklin Associates (2017). Appendix A3 comprises the transportation modes, distances and data sources utilized for each transport step identified in Figure 3, along with truck utilization rates and sample calculations. The transportation during the utilization and repurposing phases is elaborated in section 3.3.

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[11] IFCO's 2010 Annual Report estimates the company holds 75% of the RPC market across all industries in the U.S. (IFCO 2010). A value of 70% of the market share in the produce industry is applied for the current study based on insight from RPC industry experts.

3.3 Transportation from grower to retailer

The two container systems utilize a shared transportation phase between the produce grower and the retailer. The distances are contingent upon the type of commodity and may fluctuate seasonally as certain locations become suitable for commodity production.

The baseline analysis computes a composite transportation profile utilizing data from the Economic Research Service, U.S. Census Bureau and USDA National Agricultural Statistics Service. Seasonal fluctuations are compiled as a weighted average according to the portion of produce obtained from each agriculture center throughout the year, when applicable. The calculations and corresponding distances derived from this data are shown in Appendix A3. The transportation of produce is modeled as refrigerated transport.

This study assumes, for simplification, that just a single item is being transported, despite the practical capability of pallets and trucks to carry mixed loads of various commodities simultaneously.

Transportation of full containers designed for the retailers is modeled as either volume-limited or mass-limited, contingent upon the commodity. The majority of container and commodity combinations surpass the truck's payload capacity, estimated at around 18,143 kg (40,000 lb), indicating that most commodities are transported by truck in a mass-limited situation. Trailers are presumed to measure 16 m (53 ft) in length and accommodate a maximum of 24 pallets. The model excludes backhaul, as described in section 2.5.3. Additional details, including truck utilization rates and sample calculations, are provided in Appendix A5.

3.4 Electricity Grid Mix

The electricity grid mix used for CC production was modeled using data from NCASI (2023), incorporating region-specific grid factors for facilities involved in containerboard production. The average grid mix was applied exclusively for CCs production, using facility-level electricity data to determine regional electricity consumption based on production volumes. This approach ensures a representative allocation of electricity sources in line with industry data.

The U.S. average grid mix for CC production was created using regional electricity consumption patterns, where most electricity consumption occurs in the East region (75.3%), with smaller contributions from the West (19.7%) and Texas (5.0%). The U.S. average electricity grid mix were modeled using ecoinvent background processes for East, West and Texas, ensuring consistency with LCA modeling practices. Additionally, for converting mills, a default U.S. grid mix from ecoinvent was used as a proxy due to lower representativeness of regional data and the dispersed nature of these facilities.

For RPC production, due to the unavailability of location- or facility-specific grid data, the default U.S. grid mix from ecoinvent was used as a proxy, following the methodology outlined in Franklin Associates (2017). This represents a conservative assumption, as substituting the default grid with facility-specific electricity sources could improve accuracy and potentially lower the environmental impact of RPCs by reflecting actual energy procurement strategies. This limitation is acknowledged as an area where future refinements could enhance precision, particularly if facility-level grid mixes become available for RPC manufacturers.

3.5 Product end-of-life

When a material is shared across multiple product systems, a question emerges concerning how the impact of producing, recycling and managing this material over its life cycle should be shared among those multiple product systems. The necessity to address the issue of sharing resources and associated burdens in the original product with subsequent uses has been addressed by ISO LCA standards since 2000 in ISO 14041 and more recently is described in ISO 14044:2006 (ISO 2006b), section 4.3.4.3.2. Furthermore, ISO 14049:2012 provides examples in estimating the number of uses as well as the allocation of burdens between the original product and subsequent uses, which are well suited for products such as paper where the reclaimed material retains the essential properties of the original product.

Numerous strategies for addressing this allocation problem have been proposed in academia (literature) and beyond. While not all methods adhere to ISO standards, these methods offer several alternatives from both a computational perspective and for the criteria established for allocating effect across product systems. The allocation approaches used for recycling in this study are presented and discussed further in section 2.5.3 and Appendix B.

CCs and RPCs that are not recycled are either landfilled or incinerated. In waste-to-energy conversion, energy flows from the CC or RPC life cycle to a subsequent (receiving) life cycle, which may pertain to various industrial processes. Between the emitting and receiving product systems, the energy distribution must be apportioned. Each system's fluxes will be modeled using the system expansion approach. The specifics of this methodology are explained in Table 6. This is depicted as the net values of the inventory flows linked to the treatment (i.e., landfill or incineration) process and credited (negative) inventory flows related to the generation of conventionally produced energy (heat and electricity). The identical methodology is utilized to methane captured from landfills, with the collected methane presumed to be combusted for heat generation at the landfill. The aforementioned procedures transpire within the end-of-life boxes depicted in Figure 2 and Figure 3. This model is derived from the updated study (NCASI 2023) which utilizes industry data that characterizes operations from 2020.

Table 6: Summary of end-of-life modelling for CCs and RPCs sent to incineration or landfill

	CC		RPC	
	Impact	*Credit*	*Impact*	*Credit*
Incineration (with energy recovery)	Corrugated board incineration process	Heat & electricity generation	Polypropylene incineration process	Heat & electricity generation
Landfill	Corrugated board landfill process (including methane flaring as well as fugitive emissions)	Heat generation from captured methane combustion	Polypropylene landfill process	(none)

4 Life cycle impact assessment

TRACI 2.1 (Bare 2012) has been used as the principal impact assessment methodology for this investigation. TRACI 2.1 is a peer reviewed, globally acknowledged life cycle impact assessment (LCIA) methodology. An exception to the use of the TRACI pertains to the non-renewable energy indicator. TRACI's assessment of this impact—referred to as fossil fuel use—forecasts the future energy requirements for the extraction of non-renewable energy resources. This surplus energy represents the difference between the energy presently required to extract a certain resource (e.g., coal) and the energy anticipated to be necessary for extracting the same quantity of that resource in the future. Future extraction is projected to be increasingly energy-intensive owing to the diminishing supply of resources throughout time. This LCA report instead uses the non-renewable energy use indicator offered by "Cumulative Energy Demand (v1.12)" as it measures the primary energy (energy content) of the resources consumed. This is an immediate evaluation of energy use and does not need forecasts regarding the future state of resource availability and consumption. Additionally, water consumption impacts have been evaluated using ReCiPe 2016 Midpoint H to account for direct and indirect freshwater use in the lifecycle, enhancing the comprehensiveness of the analysis. As required by ISO 14044, there is international acceptance for the category indictors selected for use in this report.

The following are the indicators (potential impacts) that are evaluated in this report. These are as provided by TRACI 2.1, unless otherwise noted.

- Acidification (to air and water, kg SO_2-eq)
- Global warming (kg CO_2-eq)[12]
- Non-renewable energy (Cumulative Energy Demand V1.12) (MJ primary)
- Eutrophication (to air and water, kg N-eq)
- Smog formation (kg O_3-eq)
- Respiratory effects (kg $PM_{2.5}$-eq)
- Ozone depletion (kg CFC-11-eq)
- Water Consumption (ReCiPe Midpoint H, m^3)

All of these metrics are midpoint indicators, which means that they each characterize a physicochemical process that takes place in the environment as a result of a release of a substance into the environment. A second category of indicator is known as endpoint or damage categories. Examples include measures of ecosystem quality, human health and resource depletion. This study does not evaluate endpoints as they are not available in the TRACI methodology.

A sensitivity analysis was performed utilizing the ReCiPe 2016 (hierarchist approach) impact assessment technique to enhance the evaluation accomplished using TRACI. Additional details regarding this analysis can be found in section 4.4. Results are NOT normalized, weighted, or grouped into endpoint indicators. However, in some cases, outcomes are presented on a relative basis (%) and are compared to the reference for each system.

[12] The global warming potential for CH4 used by TRACI 2.1 is based on IPCC (2007). This value was manually updated to reflect the latest IPCC (2013) recommendations

4.1 Calculation tools and model

SimaPro is utilized as the LCA modeling tool by connecting reference flows with the life cycle inventory database and calculating the comprehensive life cycle inventory for each product system. The final life cycle inventory result is derived by integrating foreground data, which includes intermediate products and elementary flows, with generic datasets that supply cradle-to-gate background elementary flows. This process generates a comprehensive inventory of the two systems. Simapro is utilized to implement the impact assessment method and calculate the results of the analysis. The data is subsequently exported to Microsoft Excel® where it is organized in tables and utilized to generate the graphs included in this report.

4.2 Sensitivity analyses

The parameters, methodological choices and assumptions employed in modeling the systems exhibit a specific level of uncertainty and variability. Evaluating the influence of parameter selection, methodological approaches and underlying assumptions on the conclusions of the report is crucial. It is also necessary to determine the extent to which the findings are contingent upon specific sets of conditions. A series of sensitivity analyses was conducted to assess the impact of the potential variability in modeling assumptions and data on the results and conclusions, thus evaluating their robustness. Sensitivity analyses have been conducted on a restricted set of commodities. The selection of strawberry, apple and grape systems is based on their relative functional unit mass ratios. The mass ratios of the apple system functional unit are closest to the average within the range of commodity functional unit mass ratios. Strawberries exhibit the lowest ratios, while grapes demonstrate the highest ratios, respectively.

A summary of the sensitivity analyses parameters, along with the baseline values, are provided in Table 7.

Table 7: Parameter values used in the baseline and sensitivity tests for this study.

Sensitivity test	CC system			RPC system		
	Worst case	Baseline	Best case	Worst case	Baseline	Best case
Container mass	110% of Baseline	Average mass of CC for each commodity	90% of Baseline	----------(Not applicable)----------		
Recovery rate (OCC)	80.5%	90.5%	(Not evaluated)	----------(Not applicable)----------		
Number of uses	1	1	1	7	24	40
Break and loss rates	----------(Not applicable)----------			8%	5%	2%
Recycled content	(Not applicable)	31.80%	52%	0%	25%	42% (Based on IFCO ESG Report 2024) 50% (Best case)
Cleaning process	----------(Not applicable)----------			(Not evaluated)	Composite technology (weighted average)	IFCO technology (Franklin Associates, 2017)
Transportation	Max distance from grower to retailer	Average distance from grower to retailer	Min distance from grower to retailer	Max distances from grower to distributor/ retailer to servicing/ distributor and back to the grower	Average distances from grower to distributor/ retailer to servicing/ distributor and back to the grower	Min distances from grower to distributor/ retailer to servicing/ distributor and back to the grower

4.2.1 CC system model

The available evidence on the CC system suggests that extensive sensitivity analysis may not be required. Nevertheless, it remains critical to assess specific parameters to determine their influence on study outcomes. For instance, a sensitivity analysis focusing on biogenic carbon is undertaken to assess the significance of the proportion of storage. These comprehensive evaluations are provided in the following sections.

4.2.1.1 CC unit mass

An evaluation of the container weight is conducted by varying it between 90% and 110% of the baseline value. This analysis accounts for potential variations in container dimensions, which can result from manufacturer variability or seasonal fluctuations in produce size over the course of a year.

4.2.1.2 OCC recovery rate

The recovery rate sensitivity presented in this report is based on an average recovery rate of OCC produced in the U.S. of 80.5% (EPA 2011). The outcomes are evaluated against the baseline assumption of 90.5% (see section 3.1.3).

4.2.1.3 CC Recycled content

The sensitivity regarding recycled content was determined by the average recycled content for container board that is produced and utilized in the U.S., which is 52% according to NCASI (2023). This is in comparison to a baseline assumption of 31.8% which represents the average recycled content specific to containerboard utilized in the production of containers.

4.2.1.4 Biogenic carbon accounting

This study utilizes the conventional method approach for counting biogenic carbon, commonly known as the flows approach, as employed in LCA. This technique involves monitoring the exchanges of carbon between the atmosphere and other systems as they take place. An alternative methodology commonly utilized in national inventories of carbon is known as stock change accounting. This method involves quantifying biogenic carbon as alterations in carbon stocks take place. Stock change accounting is utilized in a sensitivity analysis.

Carbon stocks are present in forests, products and landfills, and consequently, the flux of carbon to and from these entities is what is measured. According to NCASI (2023), it is assumed here that harvesting wood for containerboard production does not result in a change in forest carbon stocks. It is also assumed that there will be no increase in product carbon stocks, as CCs are not designed to persist for an extended duration (e.g., greater than 100 years). The disposal of CCs in this manner results in an increase in landfill carbon stocks. This study quantifies the fraction of CC carbon that does not degrade in a landfill in a century, categorizing it as an augmentation of carbon stocks. NCASI (2023) provides further clarification on stock change accounting.

4.2.1.5 *Biogenic carbon stored in landfill*[13]

Any approach to biogenic carbon accounting requires an underlying assumption about the time frame during which carbon sequestration from the atmosphere is considered significant. Several methodologies have been developed to measure carbon storage within products over the course of their functional lifespan. Moreover, distinct approaches have been developed to evaluate carbon storage in products disposed of in landfills, where the release of carbon may occur gradually over centuries or even thousands of years.

4.2.2 RPC system model

The RPC system model is built upon key assumptions regarding number of uses, filling rate, washing and transportation; the baseline assumptions are described in section 3.2. Prior studies (Franklin Associates 2004, Franklin Associates 2013, Franklin Associates 2017) highlight significant variability in these factors and their potential to influence the system's environmental performance of the RPC system. To evaluate the impact of each parameter, adjustments are made independently to the number of fillings (or uses) of the RPC, recycled content and transportation distances. These parameters are modeled to operate independently while maintaining compliance with the necessary constraints of system mass balance. All values assessed fall within a reasonable and realistic range for the U.S. market.

4.2.2.1 *Number of uses*

In this sensitivity analysis, the number of uses is modified from the 24 cycles expected in the baseline assessment to 7 and 40. The selected values are informed by insights from RPC industry professionals regarding their practical usage, in addition to the baseline value of 40 established by the Franklin Associates (2017).

4.2.2.2 *Break and loss rates*

The extent of RPC breakage and loss is varied to assess the impact of this parameter on study results. A minimal value of 2% and a maximal value of 8% are utilized in the sensitivity analysis. The figures are derived from feedback from RPC industry experts regarding their actual breakage rate.

4.2.2.3 *Recycled content*

The assumed average recycled content of an RPC is 25%. To assess the significance of this parameter, a sensitivity analysis explores a worst-case scenario of 0% recycled content and best-case of 50%. All recycled content values are based on data provided by RPC experts[14]. The methodology used to account for recycled materials in the study's model is outlined in detail in Appendix B.

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[13] The carbon contained in the RPC is assumed to be from fossil sources and so there is no need to consider the effect of carbon taken from the atmosphere being stored during its use or disposal. The discussion of carbon storage is therefore presented only in regard to the CC system.

[14] Please inquire with CPA if you are interested in the names of the parties consulted.

4.2.2.4 Cleaning process

The RPC cleaning process can leverage various technologies, each characterized by unique operational parameters and levels of effectiveness. The baseline analysis utilizes a composite cleaning approach, incorporating inputs from technologies of different efficiencies based on their anticipated market penetration, as described in section 3.2.3. To evaluate the implications of alternative scenarios, a sensitivity analysis is performed to understand the effect of the entire U.S. RPC industry adopting the IFCO-applied technology. This technology is less intensive than the composite values used in the baseline analysis, influencing the study outcomes. Detailed datasets for the cleaning process are provided in Appendix A3.

4.2.2.5 Transportation

Transportation distances between growers, retailers and cleaning facilities vary depending on the type of produce and the population center. Studies by the University of Stuttgart (2007) and Levi et al. (2011) highlight that these logistical stages can contribute significantly, exceeding 30% in the 2007 study, to the total life cycle impact of RPCs. This underscores the significance of transportation as a critical factor within the system, potentially affecting the comparisons between RPCs and CCs. While Franklin Associates (2017) describe transportation from retailer to service center as having a moderate influence on the overall study outcomes, their earlier analysis though Franklin Associates (2013) suggests that the impact is inconsequential. Thus, a thorough evaluation of transportation's role is warranted.

This sensitivity analysis examines the minimum and maximum transport distances for both the use stage (from grower to retailer) and reuse stages (from retailer to sorting and cleaning and back to produce grower). Details of the transport steps, along with their respective minimum and maximum values, are provided in Appendix A5. The distances between retail locations, servicing facilities, and growers were calculated using data from the U.S. Department of Agriculture (USDA 2017) and U.S. Census bureau (2012) data. These distances were selected to align with published data and to ensure consistency with the principle that inbound transport distances (from grower to retailer) must not exceed outbound distances (from retailer to servicing and back to the grower), in accordance with insights from industry experts.

The transportation phase during the utilization period (between produce grower and retailer) does not require sensitivity analysis, as it exhibits consistent variations for both RPCs and CCs. This phase comprehensively documents each produce type based on data from the U.S. Department of Agriculture (USDA 2017) and the U.S. Census Bureau (2012). However, transportation is included in this analysis due to its connection to the return leg distance; when the return leg reaches its minimum or maximum, the inbound distance similarly achieves its corresponding limit. Since the inbound distance remains unchanged regardless of the container type, adjustments are made to the CC transport distances to reflect this consistency.

4.3 Global parameters and assumptions

By examining the parameters and assumptions shared across all systems under evaluation, it becomes possible to assess whether the outcomes are influenced by the chosen reporting methodology. This analysis focuses on two global components of the LCA: the inclusion of produce and its associated produce loss due to perishability and the selection of impact assessment method. The approach to model allocation is excluded from this analysis, as alternative methods are anticipated to yield equivalent outcomes. For further details, refer to section 2.5.

4.4 Impact assessment methodology choice

TRACI 2.1 was employed for the baseline analysis, while the sensitivity analysis utilized the hierarchist approach of ReCiPe 2016 (Goedkoop et al. 2008). Like TRACI, ReCiPe is a widely recognized methodology for environmental impact assessment. Section 5.6 provides a comparison of results derived from the TRACI and ReCiPe indicators. Notably, ReCiPe offers several indicators absent from TRACI, such as Ionizing radiation, impacts related to land use and transformation, as well as damage categories (endpoints). However, findings related to these additional indicators are excluded due to the lack of corresponding TRACI indicators for comparison. Land use is identified as a critical factor influencing the production of CC or RPC. Nonetheless, land use inventory data is frequently missing from key datasets used in this analysis, particularly within the forestry sector. Reporting results for this indicator without comprehensive data would risk presenting a misleading narrative. For a more detailed discussion on this limitation, refer to section 6.

4.5 Data quality assessment

The reliability of the results and conclusions derived from a LCA depends fundamentally on the quality of the data employed in the analysis. Ensuring that the data is adequate to meet the objective of the report is paramount. According to ISO 14044, data sources are assessed based on several criteria, including temporal, geographical, and technological coverage, precision, completeness, representativeness, consistency, reproducibility, source description and the degree of uncertainty associated with the information.

The methodology for the completeness and consistency check, contribution analysis and uncertainty analysis for this report are described in the following paragraphs.

4.5.1 Completeness and consistency check

The completeness check verifies that data utilized are relevant and adequately comprehensive to fulfill the objectives of the goal and scope. The consistency check verifies that assumptions, methods and data align with the report's goal and scope of the report.

All data utilized are (1) verified for their temporal, geographical and technological representativeness, (2) gathered at the highest level of detail possible, and (3) documented in accordance with established best practices. Notable differences exist in the quality of data across each system.

4.5.2 Uncertainty analysis

To ensure the robustness and reliability of the life cycle assessment results, an uncertainty analysis was performed using the Monte Carlo simulation method in SimaPro. This approach evaluates the variability and confidence levels of the comparative environmental impacts between the systems, accounting for uncertainties in input data, emission factors, and key model parameters. By running 1,000 iterations, the analysis provides probabilistic distributions for each impact category, enabling a clearer understanding of the statistical significance of the observed results. Results of the uncertainty assessment are presented in section 5.5.

4.5.3 Interpretation and requirements for comparative assertion

The conclusions of this study will integrate insights from the baseline analysis, sensitivity analysis, study limitations, data quality and the outcomes of the uncertainty assessment. In accordance with ISO 14044 (clause 5.3), any comparative assertions must ensure equivalency in scope and comparable quality and resolution of data across the systems being analyzed. Furthermore, the conclusions, limitations and recommendations must remain consistent with the defined scope of the report. To meet these requirements, consistency check, completeness check, contribution analysis and uncertainty analysis have been conducted. As stipulated by ISO 14044 for comparative assertions, a critical review is also undertaken, as detailed in the following section.

4.6 Critical review

A panel of independent experts conducted a critical review of this LCA. This process guarantees adherence to the requirements established by the ISO 14040 and 14044 standards (ISO 2006a, b).

For this study, the panel consists of three qualified individuals considered experts in their fields.

The critical review process is carried out in several steps.

1. Report review by all panelists;
2. Clarification of and response to points raised by the reviewers; and
3. Review of responses and final comments by all panelists.

The external critical review reports, practitioner comments and practitioner responses to the review comments are available in Appendix E.

5 Results

This section provides results for the baseline analysis, sensitivity analyses and data quality assessments as described in the previous sections of this document.

5.1 Baseline results

The first two sections include a comprehensive review of all eight produce types across all assessed indicators. Results are presented in two formats: a market-weighted average across all commodities and by individual commodity—providing interpretations that cater to diverse audiences. The market-weighted average view aggregates findings for all commodities by utilizing the share each commodity holds of the produce market, based on USDA data. This perspective on the results aims to satisfy the requirements of container buyers who utilize only one container type, such as produce retailers. The commodity-specific perspective of the study outcomes is beneficial for entities that acquire containers for a specific product, or those who may procure many containers for different commodities, such as produce growers.

Appendix A summarizes the major reference flows in the modeling, while section 4 details the impact assessment method applied in this study.

5.2 Market-weighted average results

Table 8 presents the weights of produce-market items, derived from the eight leading commodities (by production) that are typically transported and displayed in both RPCs and CCs. Section 5.2 illustrates the market-weighted average results. The apple and onion systems exert significant influence on the average results, each accounting for approximately 20% of fresh market production. The remaining commodities account for a share ranging from 7% to 15% each.

The market-weighted average outcomes indicate the directional trends noted at the commodity level. Similar to the commodity-specific results, the three (3) indicators that favor RPC in every commodity—acidification, ozone depletion, and water consumption—show an advantage over the CC system in the market-average results (relative to the CC system results). Global warming, non-renewable energy use, respiratory effects, and eutrophication, which show an advantage for the CC system in each commodity, show an advantage of 57%-110% over the RPC system when applying market weights.

When applying commodity specific uncertainty results, smog formation is the only indicator where the results for the container systems overlap within their range of uncertainty. Thus, no conclusion can be drawn about the relative performance in smog formation. See section 5.9 for more information.

The market-weighted average outcomes are contingent upon the market shares of each commodity at a specific point in time. If apples and/or onions represent a significantly reduced share of the market, the results of the market-weighted average may change, affecting both the extent of the disparity in environmental performance between the container systems and the overall trends observed. Nonetheless, when an indicator demonstrates a consistent advantage for one system across all commodities, the directional outcomes cannot change for that indicator even if the market share across commodities shifts.

Table 8: Commodity market shares used to calculate the market-weighted average results

Commodity	Market share*
Apples	23%
Carrots	7%
Grapes	7%
Lettuce – head	15%
Onions	19%
Oranges	11%
Strawberries	8%
Tomatoes	10%

*Based on top eight commodities (by fresh market production) commonly transported and displayed in both RPCs and CCs (USDA 2017).

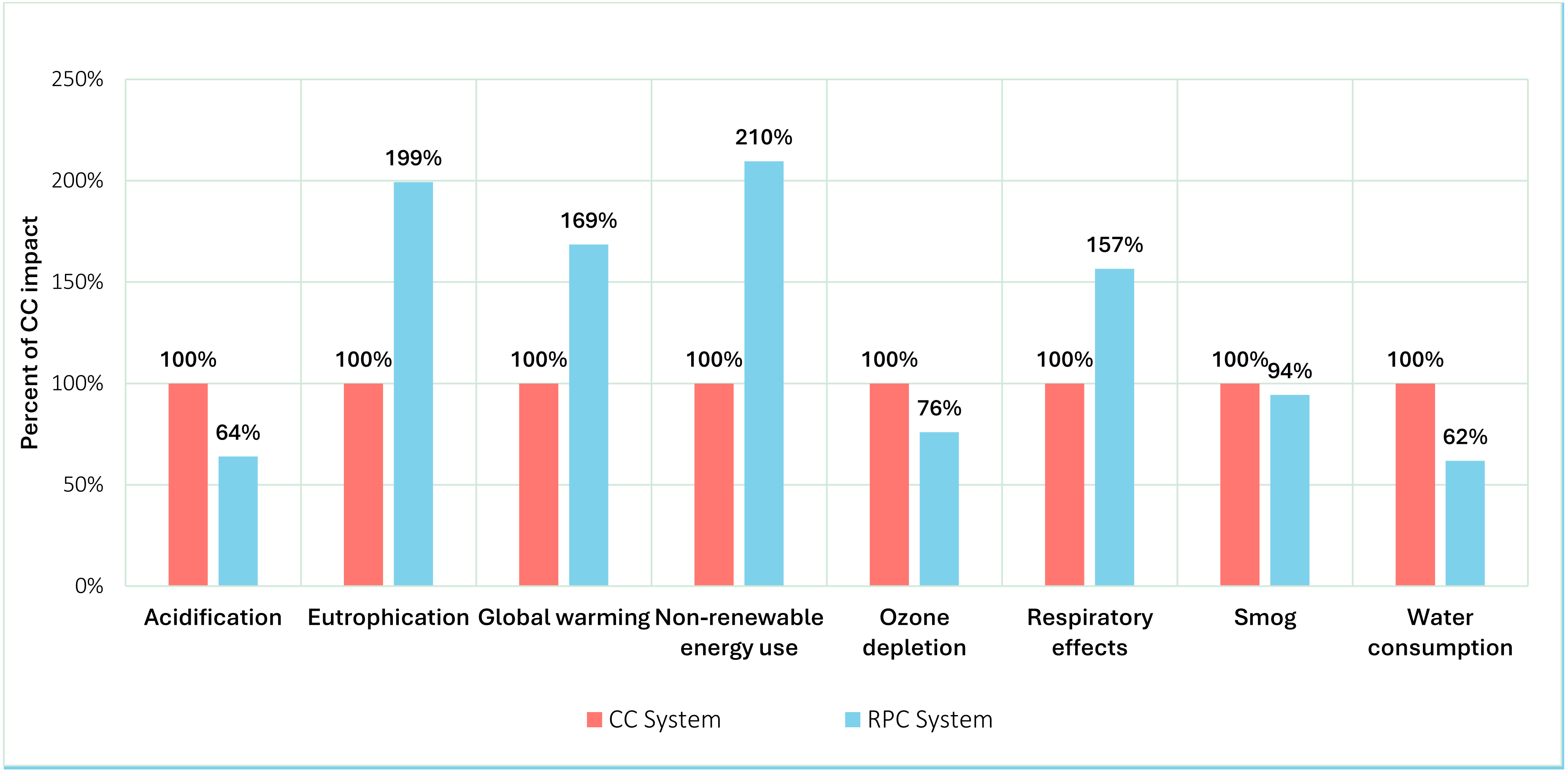


Figure 4: Market weighed average results for the baseline analysis.

5.3 Commodity-specific results

Figure 5 and Table 9 present a comprehensive overview of the baseline results for all commodities and environmental indicators assessed. Each commodity exhibits trade-offs in types of environmental impact; neither CCs nor RPCs consistently have a lower impact across all evaluated indicators.

Three indicators show an environmental advantage for RPCs regardless of commodity: acidification, ozone depletion, and water consumption. In these indicators, the RPC system demonstrates less impact than the CC system.

Four (4) indicators, eutrophication, global warming, non-renewable energy use, and respiratory effects show an environmental advantage for CCs regardless of the commodity.

The final indicator, smog formation, is favorable for CCs in 3 (strawberries, tomatoes, and oranges) out of the 8 commodities. However, for apples, no difference in the results is observed. Additionally, smog formation is favorable for RPCs in 4 (carrot, lettuce, onions, and grapes) out of the 8 commodities.

It is not possible to conclude that either system is clearly a superior overall environmental performer as the number of categories supporting a particular container system is not a good measure of environmental superiority. Counting the number of midpoint categories to determine relative environmental performance requires the assumption that each category of impact is equally important. Evaluating the relative importance of these categories requires not only an evaluation of the contribution each has in affecting the things we are concerned about (often assumed within an LCA to be protection of human health, ecosystem quality and resource availability), but also the relative importance of these concerns (e.g., what amount of human health should be equivalent to what amount of ecosystem quality). While it is possible to have views or values that define a position on such matters, it is not possible for the authors to defend these values as more correct than the values that might lead another party to a different decision. It is therefore not possible here to draw a definitive conclusion of environmental superiority in cases where there are conflicting indicators that require a trade-off that is primarily value-based. In such cases, including the current one, the only overall conclusion that can be drawn is that trade-offs exist between the systems. Users of this study may apply values systems to arrive at conclusions that may assist in making selections between the container systems under different market conditions.

The observation that the directional results (i.e., whether CCs or RPCs are preferable) are not the same across impact categories indicates that there are different processes in the life cycles of each container type that are the primary drivers of impact among different indicators. In other words, it is not a common process between the systems that is the primary cause of environmental impact. This is explored in the section 5.5.

Three variables principally affect the trends between the different commodity profiles: mass-to-capacity ratio, the functional unit mass ratio and grower-to-retailer transport distances.

Regarding the first, each commodity requires a different mass of containers (for a given container type) to fulfill the functional unit. These quantities are listed in Table 10 and are calculated based on the data presented in Table 2. The total mass affects the scale of the impact for each system, as the total mass increases, the magnitude of impacts increases. For instance, the strawberry container requires the greatest amount of container weight as compared to any other commodity. This is true for both the CC and RPC systems.

Consequentially, the absolute results for this system are higher than for other commodities. A similar observation can be made for the carrots system: for both containers, carrots require the least amount of container mass to fulfill the functional unit and therefore show the lowest impact for every indicator compared to other commodities.

The mass of the functional unit is determined by the ratio of container mass to produce mass for each container of a specific commodity. The “mass-to-capacity ratios” serve as a basis for determining the total mass necessary to meet the functional unit for each container system. Consequently, one can forecast the relative significance of impact for each commodity system within a specific container system by utilizing the mass-to-capacity ratios. The mass-to-capacity ratio emerges as the crucial variable influencing the comparative outcomes across various commodities within a specific container system.

The second variable influencing trends among commodity profiles is the ratio of these container masses, termed as the “functional unit container mass ratio” as illustrated in Figure 6. The ratio affects the comparative outcomes for each commodity. In other words, comparing the mass required by CCs to that required by RPCs for a given commodity offers insight into the comparative environmental efficiency of the two container systems[15]. A high CC/RPC functional unit mass ratio favors the RPC system, while a low ratio favors the CC system. For instance, the containers transporting strawberries exhibit a lower CC/RPC mass ratio compared to all other commodities. The CC system demonstrates a more significant environmental advantage in global warming and non-renewable energy use and a lower degree of environmental advantage for the RPC system in the remaining indicators.

The analysis of one indicator (smog formation), reveals that the variations in functional unit mass ratios among different produce types are significant enough to lead certain commodities to prefer one container system, while others exhibit no discernible difference between the two systems. Specifically, smog formation demonstrates an environmental advantage for RPCs for most commodities. However, as the functional unit mass ratio of the commodity rises, the disparity between the container systems increases. Upon examining the uncertainty, it becomes evident that neither container demonstrates a distinctive advantage.

The significant reliance on functional unit mass ratio suggests that one can anticipate the comparative outcomes for commodities not assessed in this study with a reasonable degree of precision. The findings of this study could potentially extend to other types of produce, provided they are packaged, transported, and displayed in CCs and RPCs in a manner akin to the procedures outlined in this study.

The third variable contributing to the differences in environmental performances of commodity profiles is the grower-to-retailer transport distance, which varies across commodities. Similar to the container mass required per functional unit, the transport distance influences the magnitude of impact associated with a specific commodity. Nevertheless, given that these distances exhibit less variation across commodities compared to the mass-to-capacity ratios,

[15] Note that it is generally not possible to predict the relative environmental performance of two different materials (e.g., containerboard and polypropylene) or the products in which they are used by considering—with no other information—the masses of the two materials. One product may have a higher impact despite a lower mass to fulfill the functional unit. The ability to use the functional unit mass ratio as an indication of relative environmental performance is a phenomenon of the results of this study.

they play a less significant part in the discrepancies observed in the magnitude of results among different commodities. Transport distances are listed in Appendix A3.

Impact category	Unit	System	Onions	Grapes	Lettuce	Carrot	Apple	Oranges	Tomatoes	Strawberries
Acidification	(kg SO2 eq)	CC	4.9E+02	7.1E+02	4.3E+02	3.5E+02	4.2E+02	4.1E+02	4.3E+02	9.8E+02
		RPC	2.3E+02	4.0E+02	2.4E+02	2.2E+02	2.9E+02	2.9E+02	3.3E+02	7.9E+02
Eutrophication	(kg N eq)	CC	8.4E+01	1.2E+02	7.3E+01	5.9E+01	7.1E+01	7.0E+01	7.3E+01	1.7E+02
		RPC	1.2E+02	2.1E+02	1.3E+02	1.2E+02	1.5E+02	1.5E+02	1.7E+02	4.2E+02
Global warming	(kg CO2 eq)	CC	7.7E+04	1.1E+05	6.7E+04	5.4E+04	6.5E+04	6.5E+04	6.7E+04	1.6E+05
		RPC	9.4E+04	1.6E+05	1.0E+05	9.3E+04	1.2E+05	1.2E+05	1.3E+05	3.3E+05
Non-renewable energy use	(MJ)	CC	1.2E+06	1.7E+06	1.0E+06	8.2E+05	9.8E+05	9.7E+05	1.0E+06	2.4E+06
		RPC	1.8E+06	3.1E+06	1.9E+06	1.7E+06	2.2E+06	2.3E+06	2.5E+06	6.1E+06
Ozone depletion	(kg CFC-11 eq)	CC	3.8E-03	5.5E-03	3.4E-03	2.7E-03	3.3E-03	3.2E-03	3.3E-03	7.7E-03
		RPC	2.1E-03	3.7E-03	2.3E-03	2.1E-03	2.7E-03	2.7E-03	3.0E-03	7.2E-03
Respiratory effects	(kg PM2.5 eq)	CC	4.8E+01	6.9E+01	4.2E+01	3.4E+01	4.1E+01	4.0E+01	4.2E+01	9.8E+01
		RPC	5.5E+01	9.5E+01	5.8E+01	5.4E+01	6.8E+01	6.9E+01	7.8E+01	1.9E+02
Smog	(kg O3 eq)	CC	4.8E+03	6.9E+03	4.2E+03	3.4E+03	4.1E+03	4.0E+03	4.2E+03	9.7E+03
		RPC	3.3E+03	5.7E+03	3.5E+03	3.2E+03	4.1E+03	4.2E+03	4.7E+03	1.1E+04
Water consumption	(m3)	CC	8.5E+02	1.2E+03	7.4E+02	6.0E+02	7.3E+02	7.1E+02	7.4E+02	1.7E+03
		RPC	3.9E+02	6.7E+02	4.0E+02	3.7E+02	4.7E+02	4.8E+02	5.4E+02	1.3E+03

Figure 5: Baseline results (impact per functional unit) for the 8 commodities evaluated in this study. Commodities are ordered from greatest to least functional unit mass ratio. Each bar is shown relative to the system of greatest impact for that impact category.

Table 9: Baseline results (impact per functional unit) for the 8 commodities evaluated in this study.

	System	Strawberries	Tomatoes	Oranges	Apples	Carrots	Lettuce – head	Grapes	Onions
Functional unit mass ratios		0.33	0.34	0.36	0.36	0.39	0.44	0.45	0.51
Acidification (kg SO2 eq)	CC	978	427	410	420	346	431	708	492
	RPC	786	325	289	285	224	242	399	228
Eutrophication (kg N eq)	CC	171	73	70	71	59	73	121	84
	RPC	416	173	153	152	119	128	214	125
Global warming (kg CO2 eq)	CC	162,390	67,113	64,538	65,234	54,340	67,494	111,360	76,702
	RPC	326,192	134,917	121,546	119,458	93,329	101,809	164,774	93,903
Non-renewable energy use (MJ)	CC	2,440,141	1,010,276	971,501	982,362	818,018	1,016,139	1,676,337	1,154,924
	RPC	6,058,332	2,525,618	2,266,450	2,236,152	1,745,976	1,900,082	3,098,251	1,786,437
Ozone depletion (kg CFC-11 eq)	CC	0.008	0.003	0.003	0.003	0.003	0.003	0.006	0.004
	RPC	0.007	0.003	0.003	0.003	0.002	0.002	0.004	0.002
Respiratory effects (kg PM2.5 eq)	CC	98	42	40	41	34	42	69	48
	RPC	187	78	69	68	54	58	95	55
Smog (kg O3 eq)	CC	9,666	4,163	4,002	4,081	3,372	4,197	6,906	4,785
	RPC	11,212	4,668	4,200	4,143	3,229	3,522	5,707	3,268
Water consumption (m3)	CC	1,671	737	708	726	597	744	1,223	850
	RPC	1,304	544	477	473	374	399	672	391

Table 10: Key container mass ratios for CCs and RPCs.

Commodity	Container mass required to fulfill the functional unit, kg[1]		Container mass-to-capacity ratio[2]	
	RPC	CC	RPC	CC
Apples	113,275	41,328	0.12	0.05
Carrots	86,329	33,900	0.10	0.04
Grapes	154,692	69,400	0.17	0.08
Lettuce – head	95,578	42,285	0.11	0.05
Onions	95,311	48,347	0.11	0.05
Oranges	113,275	40,220	0.12	0.04
Strawberries	281,694	93,599	0.31	0.10
Tomatoes	123,780	41,870	0.14	0.05

[1]Calculated as [907,185 kg produce) *(container mass, kg)]/(produce mass per container, kg). Values have been rounded to two significant figures. Does not subtract the amount of RPCs reused; [2]Calculated as (Container mass, kg)/ (Produce mass per container, kg)

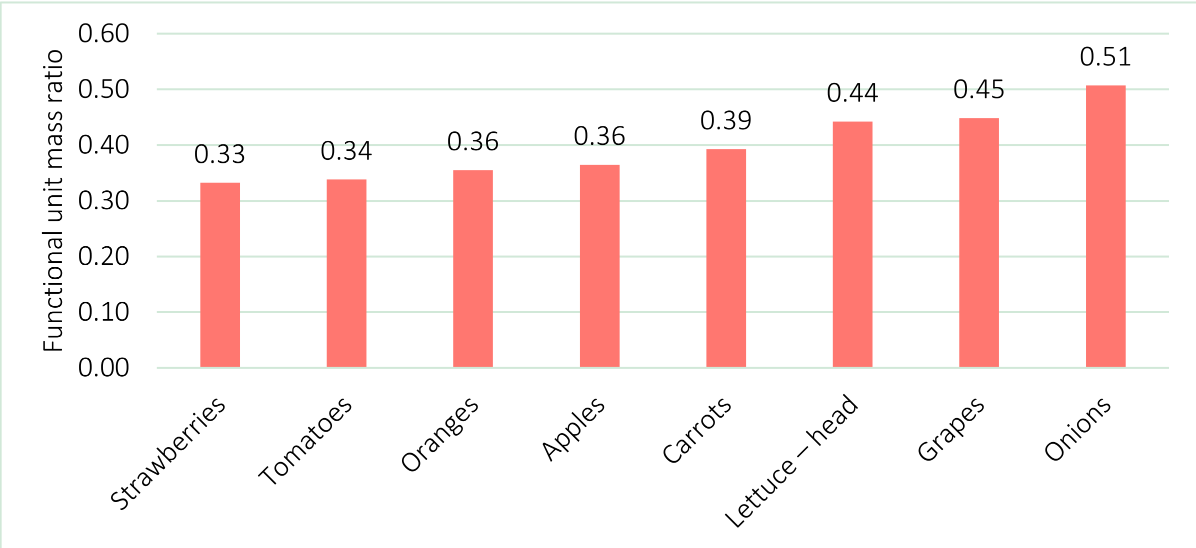


Figure 6:Functional unit container mass ratios (CC mass per functional unit/RPC mass per functional unit).

5.4 Life cycle stage contribution

This section presents the impact of each container system categorized by life cycle stage. The scope of each life cycle stage is outlined in section 2.3. To maintain conciseness, only the apple scenario is presented here as the overall trends for this commodity are consistent for all other commodities. Appendix C contains a comprehensive table of results for strawberries and grapes system.

Figure 7 presents the baseline outcomes by life cycle stage for the CC associated with apples. The diagram illustrates that raw materials and production significantly influence each indicator's result. The conversion and/or use stages represent the second-largest contributors to all indicators. The contribution from the end-of-life stage is relatively minor for most indicators, and in most cases, it is negligible when compared to other life cycle stages. This encompasses the credit attributed to CCs directed towards the municipal solid waste stream that undergoes disposal through waste-to-energy (WTE) incineration and methane capture at landfills. The primary factor contributing to solid waste is the end-of-life phase, particularly due to the disposal of CCs, which represents the greatest flow of solid waste from the system.

The trend observed in Appendix C exhibits a comparable pattern for the strawberries and grapes system. The contribution of each stage varies slightly among different produce types, mainly because of the differences in the container mass-to-capacity ratio, although transportation distances play a minor role.

Figure 8 presents the RPC baseline results by life cycle stage for the apple system. The diagram illustrates that the reuse stage significantly influences most indicators, except for eutrophication & water consumption. The raw materials and RPC production stage represent the most significant contribution to these indicators.

The second most significant factor influencing all indicators is the raw materials and production stage or reuse stage. The impact from the end-of-life stage is generally minimal for most indicators. The credit attributed to RPCs for disposal via waste-to-energy (WTE) incineration plays a significant role in diminishing the overall burden linked to these processes.

The end-of-life stage has a negligible impact on all environmental indicators, as shown in Figure 8. This stage accounts for all RPCs that reach disposal, including those lost or damaged during reuse. However, even when considering these losses, the end-of-life stage remains an insignificant contributor to overall impacts across the life cycle.

As shown in Appendix C, these trends are similar for the strawberries and grapes system. The exact contribution of each stage is slightly different across produce types mainly due to differences in the container mass-to-capacity ratio, although transportation distance between the grower and retailer also causes some (slight) differences.

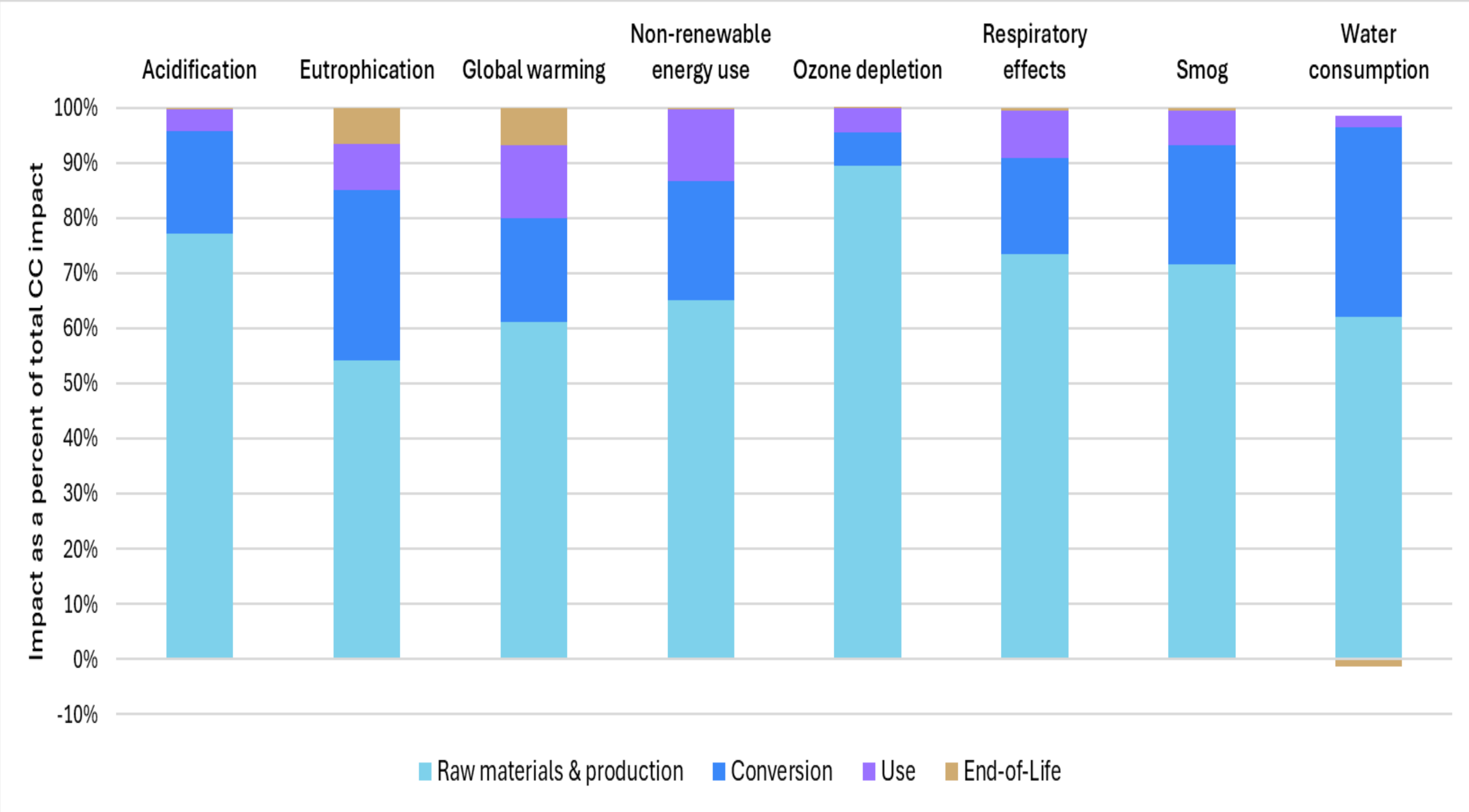


Figure 7:Baseline results by life cycle stage for CCs containing apples.

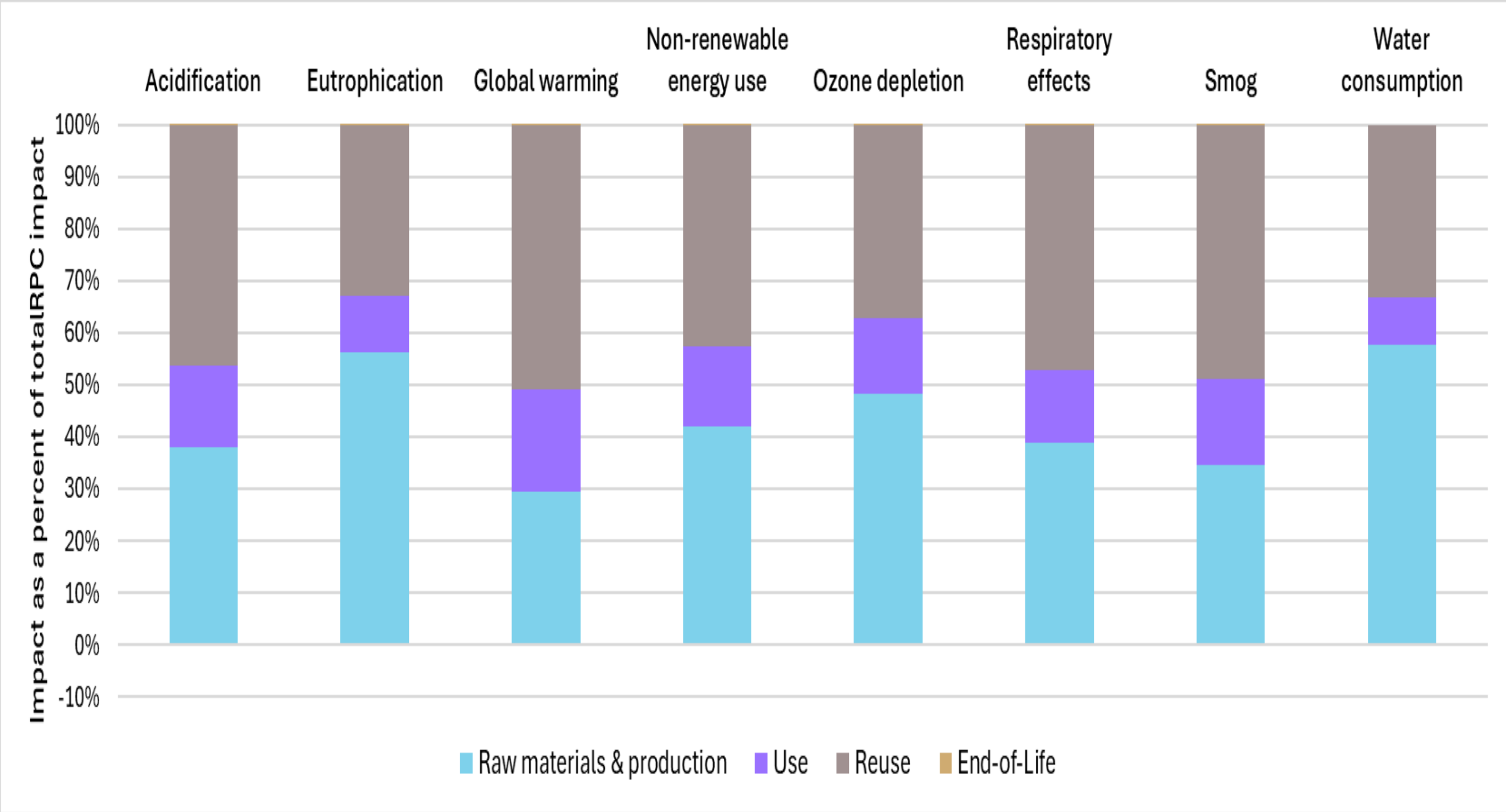


Figure 8:Baseline results by life cycle stage for RPCs containing apples.

5.5 Sensitivity analyses

This section presents the results for each sensitivity analysis. The parameter values evaluated are presented in Table 7. For brevity, only the apple scenario is depicted here as the overall trends for this commodity are consistent for all other commodities. Complete results for two exemplary commodities' (i.e., strawberries and grapes) sensitivity analyses are available in Appendix C.

The figures throughout this section illustrate results relative to the baseline system for each comparison. For the RPC sensitivity analysis, the CC system is set at 100%, while for the CC sensitivity analysis, the RPC system is set at 100%. Results are displayed as a percentage of the baseline, making it clear whether impacts increase or decrease relative to the reference system. Positive values (>100%) indicate higher impacts for the tested system compared to the baseline, while negative values (<100%) indicate lower impacts. This approach to displaying results provides clarity and aligns with the objective of assessing whether the study conclusions change under the different parameter values tested.

A key concept explored in this sensitivity analysis is the break-even point, which refers to the threshold at which the environmental impact of RPCs equals that of CCs for a specific impact category. Beyond this point, RPCs exhibit a higher impact than CCs, whereas below it, RPCs maintain a lower impact. This is particularly relevant in the sensitivity analysis of RPC with parameters such as number of uses, break and loss rates, and recycled content, as it helps identify the conditions under which RPCs cease to provide an environmental advantage over CCs, as calculated by simple linear extrapolation of the results depicted. Understanding the break-even point allows for a clearer evaluation of the factors influencing RPC sustainability and provides critical insight into their long-term environmental performance.

5.5.1 RPC number of uses

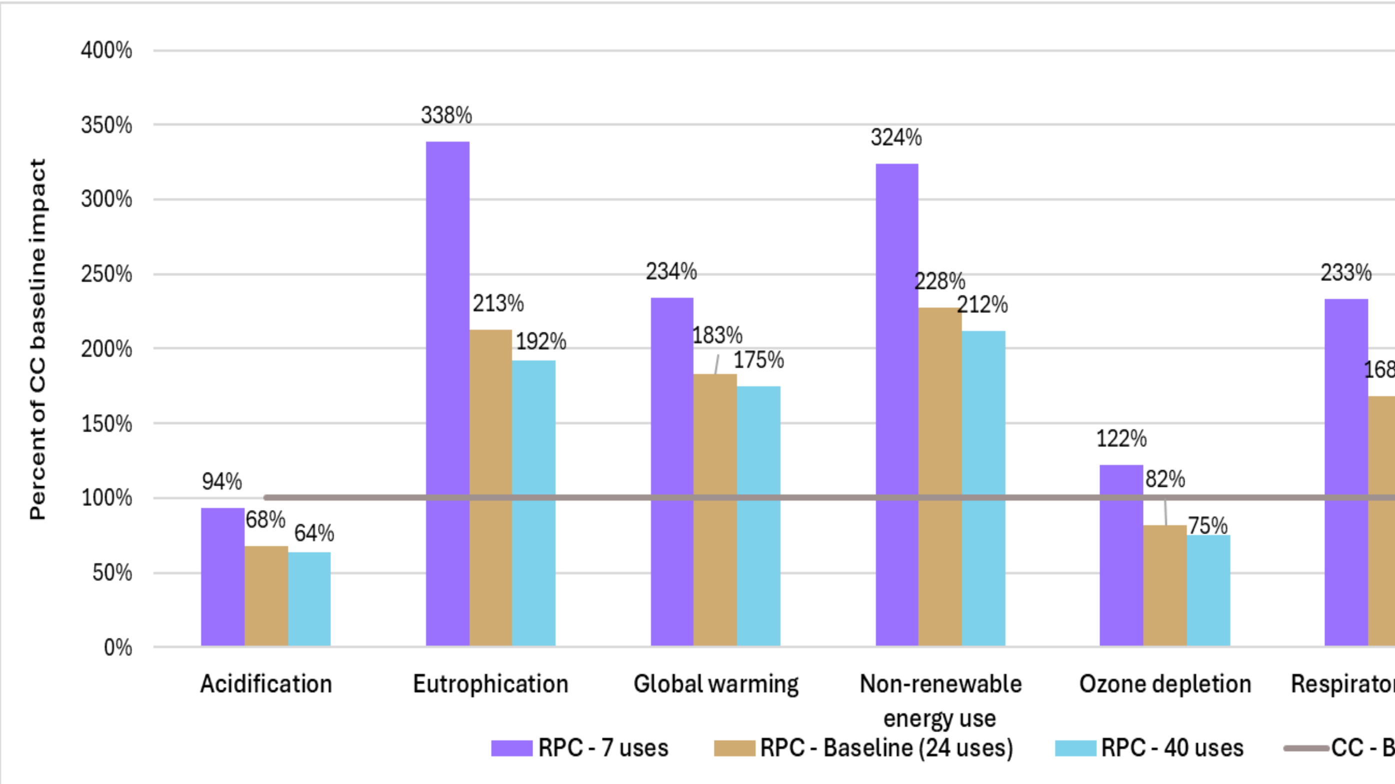


Figure 9 illustrates the sensitivity of the RPC system to the number of times an RPC is used. Every impact category demonstrates a measurable reduction in total impact as the utilization of the RPC increases. The increase in usage leads to a reduction in number of new RPCs that need to be manufactured and disposed of, thereby mitigating certain life cycle impacts during these stages. However, since the use and reuse stages contribute less significantly to most indicators than the manufacturing stage, the frequency of RPC use has minimal impact on the RPC system across the modeled datasets.

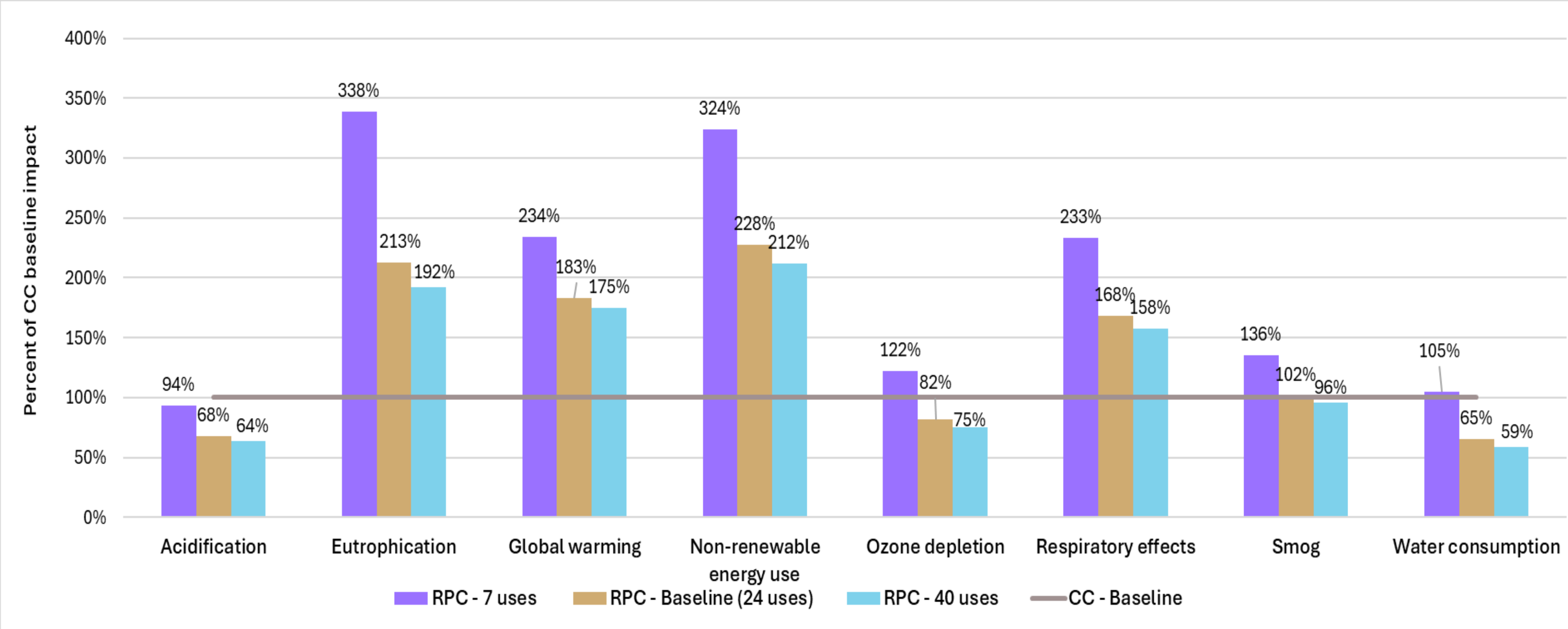


Figure 9: Sensitivity of RPC results to number of uses for RPCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

Appendix C illustrates that the grape and strawberry systems exhibit comparable sensitivity to this parameter, and the general trend of decreasing RPC impact with increasing number of uses remains consistent. The variations in trends among the commodities indicate disparities in container mass-to-capacity ratios and—to a minor degree—transport distances from the grower to the retailer for the various commodities, as explained in section 5.3 and detailed in Appendix A3. To demonstrate the significant reliance on the functional unit mass ratio, one can consider the trends associated with global warming. The number of uses break-even point for the systems decreases with an increasing functional unit mass ratio. The grape, apple, and strawberry systems have functional unit mass ratios of 0.45, 0.36, and 0.33 respectively. Mathematically speaking, the break-even points for these commodities are approximately 94, 111, and 126 uses, respectively.

5.5.2 RPC break and loss rates

Figure 10 illustrates the impact of break and loss rates. The rise in RPC breakage and loss leads to the production of additional RPCs and the additional spent RPCs to be sent to end- of-life, consequently amplifying the total impact on the RPC system. The extent of this alteration in environmental impact is determined by the reliance of an indicator on these life cycle stages (i.e., raw materials and production and end-of-life). Indicators to which these stages contribute only minor portions of total life cycle impact, such as global warming and non-renewable energy use, are not as affected as those in which these stages play important roles, such as ozone depletion.

The results indicate that for the apple system baseline (considering 5% BR), smog formation impacts remain relatively close to CC system. However, an 8% breakage and loss rate has more profound impact on the smog formation, while at 2% breakage and loss rate, the impact is lower than that of the CC system. Mathematically speaking, the break-even point for this indicator is approximately 4.5%. For ozone depletion, the highest combined break and loss rate shows a negligible difference between RPCs and CCs. Mathematically the break-even point is 7%.

The strawberry system demonstrates a change in directional trends from the baseline commodity in two indicators: ozone depletion and smog formation. For ozone depletion, RPCs are favorable at both the baseline (5%) and 2% break and loss rates, but this trend reverses at the 8% rate. In contrast, for smog formation, corrugated containers (CCs) consistently perform better than RPCs across all three break and loss rate scenarios.

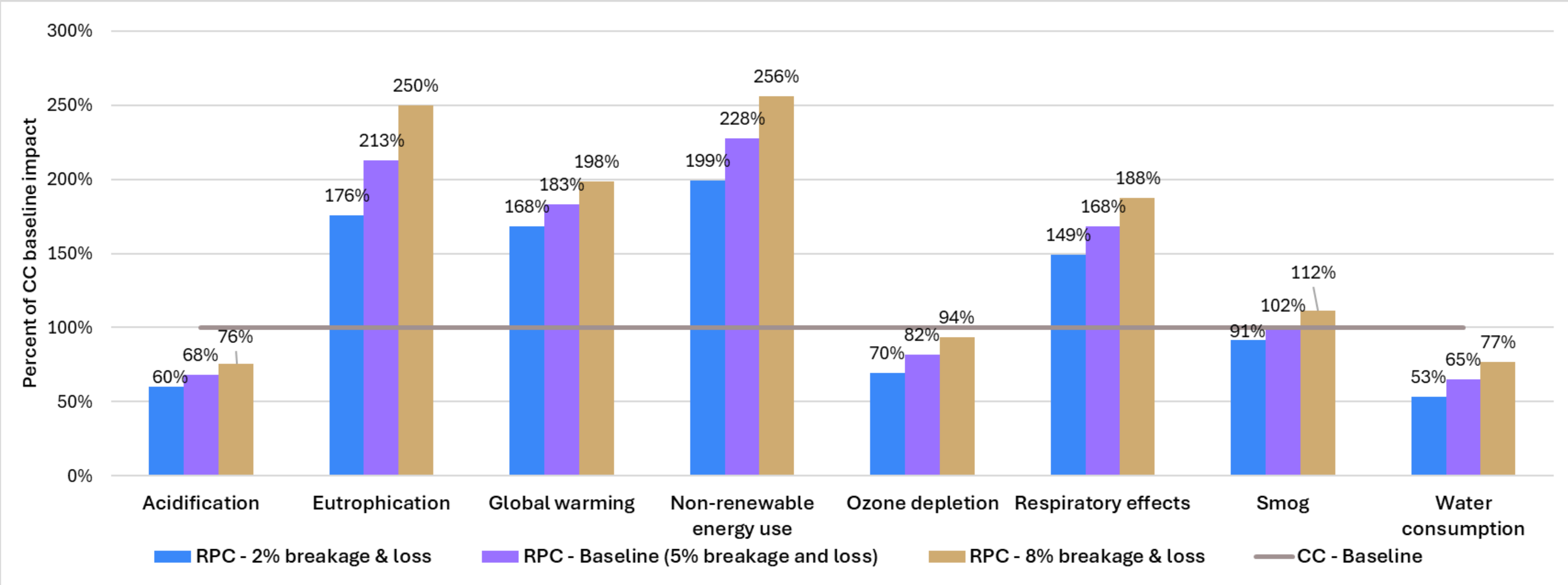


Figure 10: Sensitivity of RPC results for break and loss rate for RPCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

5.5.3 RPC recycled content

Figure 11 illustrates the impact of varying the recycled content in the range of 25% (baseline)-50% including 42% following the IFCO ESG report (2024). As the recycled content of the RPCs increases from 25%, there is a corresponding decrease in the utilization of virgin polypropylene. Consequently, a pattern of diminished impact is observed with the rise in recycled content. Furthermore, given that virgin PP production significantly influences the raw materials and production phase, for indicators where a considerable share of impact originates from the raw materials and production stage, the comparative results show a more substantial shift in favor of the RPC system.

In the apple system, the use of RPC is advantageous when 25%, 42% or 50% recycled content is used in the case of ozone depletion, which has a breakeven point of 15%. The data presented in Appendix C indicate that the strawberry and grape systems show similar sensitivity to this parameter. For the strawberry system, ozone depletion impact is lower for CCs when RPCs contain 25%, 42%, or 50% recycled content. However, when RPCs have 0% recycled content, their ozone depletion impact becomes higher than that of CCs. For the grapes system, CCs demonstrate a clear advantage in terms of eutrophication at all recycled content scenarios analyzed, including 0%, 25%, 42%, and 50%.

5.5.4 RPC cleaning process

Figure 12 illustrates the impact of the cleaning process on study outcomes. The findings from the apple system suggest that the quantities of detergent, electricity and water utilized in the cleaning process do not significantly affect the comparative outcomes of the study. Implementing a more efficient cleaning process provides certain environmental benefits for the RPC system; however, this process does not significantly influence the overall environmental impact. Additionally, the modifications made to the process do not enhance environmental performance to a degree that would change the directional outcomes.

The data pertaining to the cleaning process presented here exclude emissions commonly associated with wastewater generated by industrial operations utilizing detergents and chloro-sanitizers. The presence of these substances can have significantly influenced the quality of receiving water bodies or the nature of air emissions. Incorporating these emissions into the study would likely lead to a heightened impact on the RPC system; however, the significance of these impacts in relation to other life cycle components of RPCs remain uncertain. Results for the strawberry and grape systems show the same outcome. The baseline relative results are unaffected by an improvement in cleaning efficiency.

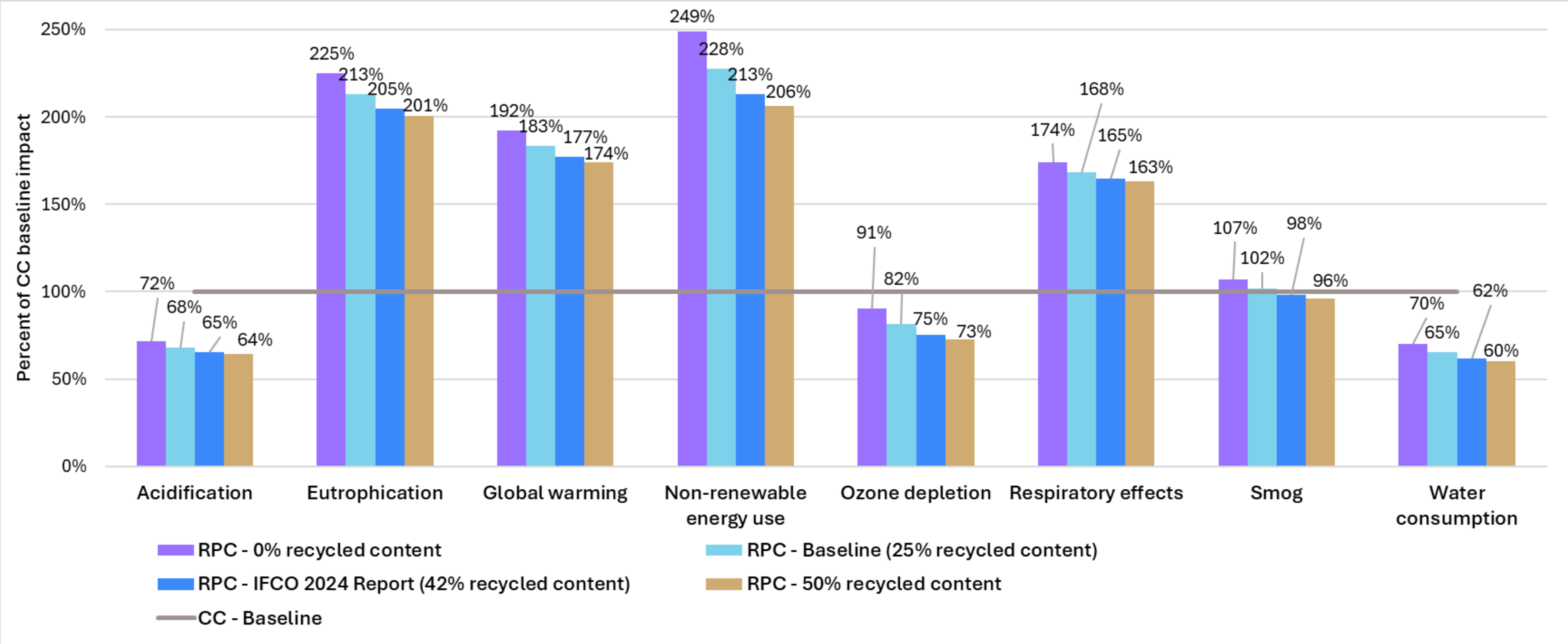


Figure 11: Sensitivity of RPC results to recycled content for RPCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

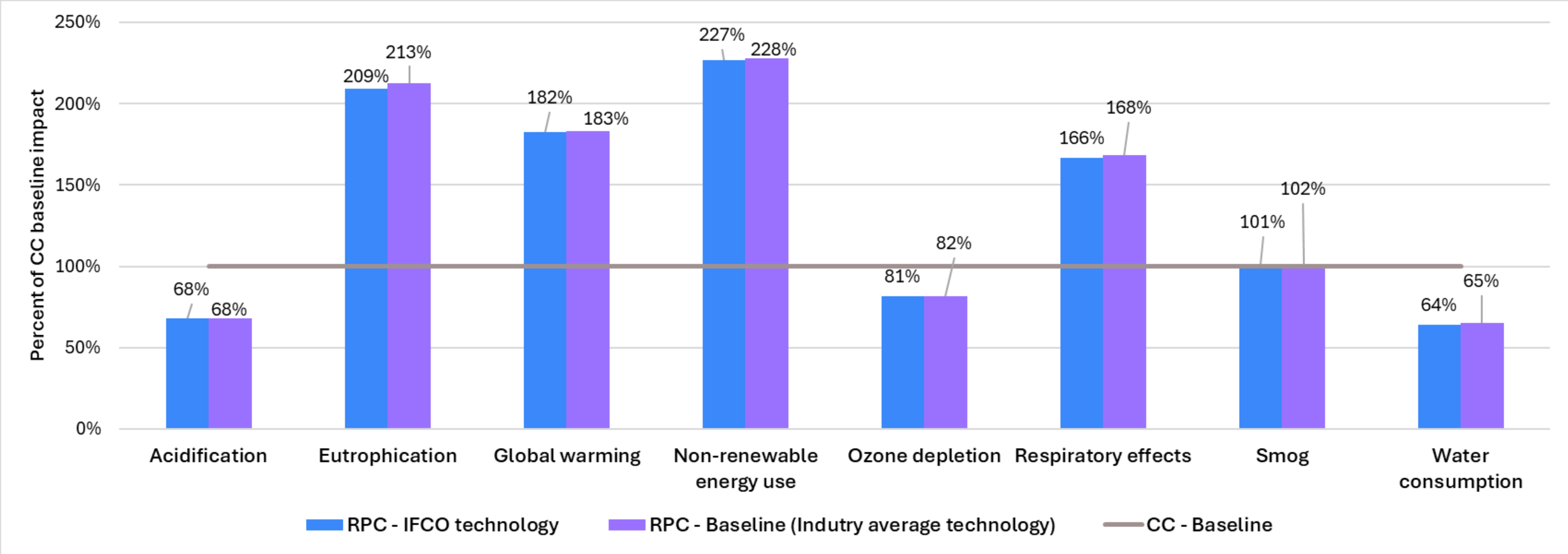


Figure 12: Sensitivity of RPC results to the RPC cleaning process for RPCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

5.5.5 RPC transport

Figure 13 presents the outcomes of the sensitivity analysis around RPC transportation distances during the use and reuse stages (from growers to retailer, from retailer to sorting and cleaning, and from cleaning to growers) for the apple system. The distances established are as follows: from growers to retailers, the minimum, baseline and maximum distances applied are 1,420 km, 2,498 km and 3,408 km for CCs and RPCs, 1,345 km, 2,472 km, and 3,766 km from the retailer to servicing, and 405 km, 1,121 km and 1,833 km from servicing to growers. See Appendix A5 for further details regarding transportation assumptions and distances.

The findings for apple system suggest that transportation significantly influences the comparative results of global warming, respiratory effects, eutrophication and non-renewable energy use but does not affect the directional outcomes of any indicator. In scenarios involving the shortest transport distances, the CC system retains its environmental advantage. However further reductions could eliminate this benefit in the case of global warming and—with additional reduction—respiratory effects, eutrophication, and non-renewable energy use. However, increasing the distances offers an opportunity for CCs to multiply its advantage.

Results can vary significantly, particularly due to the critical role of transportation during the use and reuse phases. The magnitude of the shifts in results within each indicator is evident; particularly where transportation serves as the key contributor, revealing a more pronounced difference in results between the three scenarios (i.e., transport distances). Figure 8 illustrates that this is applicable to the majority of the assessed indicators, particularly global warming and non-renewable energy use which predominantly source from these two stages. In contrast, eutrophication and water consumption are more influenced by the raw materials and production stage, as shown in section 5.4, and are comparatively less sensitive to transportation distances. In all indicators, the RPC system's environmental performance improves as the distances that RPCs are transported from the grower to the retailer to the cleaning facility and back to the grower are reduced.

Appendix C demonstrates that the strawberry and grape systems exhibit similar sensitivity to this parameter. For the grape system, the range of transportation distances evaluated is adequate to alter the directional results of the study in global warming and eutrophication. For global warming, the minimal transport scenario results in an advantage for the RPC system, while the baseline and the maximal transport scenario results in an advantage for the CC system. A similar trend is observed for respiratory effects, where RPCs perform better than CCs in the minimal transport scenario, but CCs show lower impacts in both the baseline and maximal scenarios. For the strawberry system, the minimum transport scenario results in an advantage for RPCs in the smog formation indicator, while both the baseline and maximal scenarios show an advantage for CCs. The environmental benefit of RPCs diminishes with increased transport distances. The transportation of RPCs inside the RPC system is a significant component influencing global warming results.

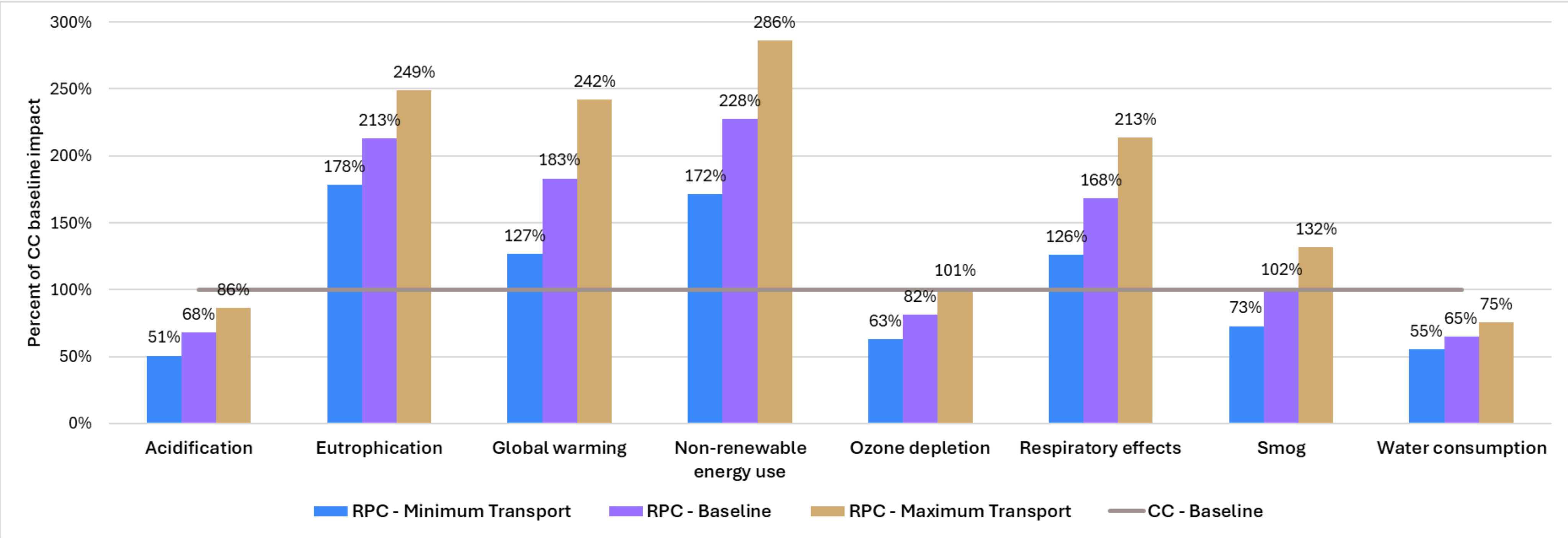


Figure 13: Sensitivity of RPC results to transport distances during use and reuse for RPCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

5.5.6 CC container weight

Figure 14 presents the results of modifying the CC weight by plus and minus ten percent (+/-10%). Since this adjustment to the model directly manipulates the amount of container required for the functional unit, total impact of the CC system simply changes by a magnitude of ten percent (10%) for each indicator. Note that Figure 14 depicts the relative results, which do not necessarily shift to the same degree. For apples a directional change occurs in the case of smog, showing a negligible difference in the 10% decrease in CC weight for smog formation.

The strawberry and grape systems show a similar trend of reduced environmental impact with reduced container weight for the CC system, as presented in Appendix C. While overall patterns are consistent, directional differences are observed in the smog formation indicator: in the grape system, RPCs perform better than CCs across all container weight scenarios, whereas in the strawberry system, CCs consistently outperform RPCs in all scenarios.

5.5.7 OCC recovery rate

Figure 15 illustrates that, the directional outcomes exhibit minimal sensitivity to the quantity of CC recovered after use within the evaluated range of values. The recovery rate is a critical metric that indicates the volume of material being disposed, whether through landfill or incineration), as well as the quantity of material that is exported. The outcomes of altering the recovery process represent a trade-off between the heightened effects of supplementary waste treatment methods, such as landfilling and incineration, and the credits accrued from the energy produced through these waste management strategies. The impact surpasses the benefits, as demonstrated by the positive values observed for each indicator.

The amount of virgin materials required for the production of CC is potentially influenced by the recovery rate. However, since the quantity of recycled fiber in CCs is maintained at a constant level to represent the average recycled content for produce containers, the amount of recovered containerboard does not impact the amount of virgin fiber utilized in the production of CCs. The recovery of additional CCs leads to a reduced environmental impact, with the extent of the savings being contingent upon the significance of the end-of-life stage in relation to the overall CC system results as well as the variance between the CC system and RPC system. In the analysis of all indicators, end-of-life is minimal or insignificant. Consequently, the influence of recovery on overall impact appears to be minimal or insignificant.

The grape and strawberry systems exhibit a consistent trend of reduced environmental impact. While directional results remain consistent across all indicators for the strawberry system, the grape system shows a directional shift in the smog formation indicator, where RPCs perform better than CCs across all recovery rate scenarios.

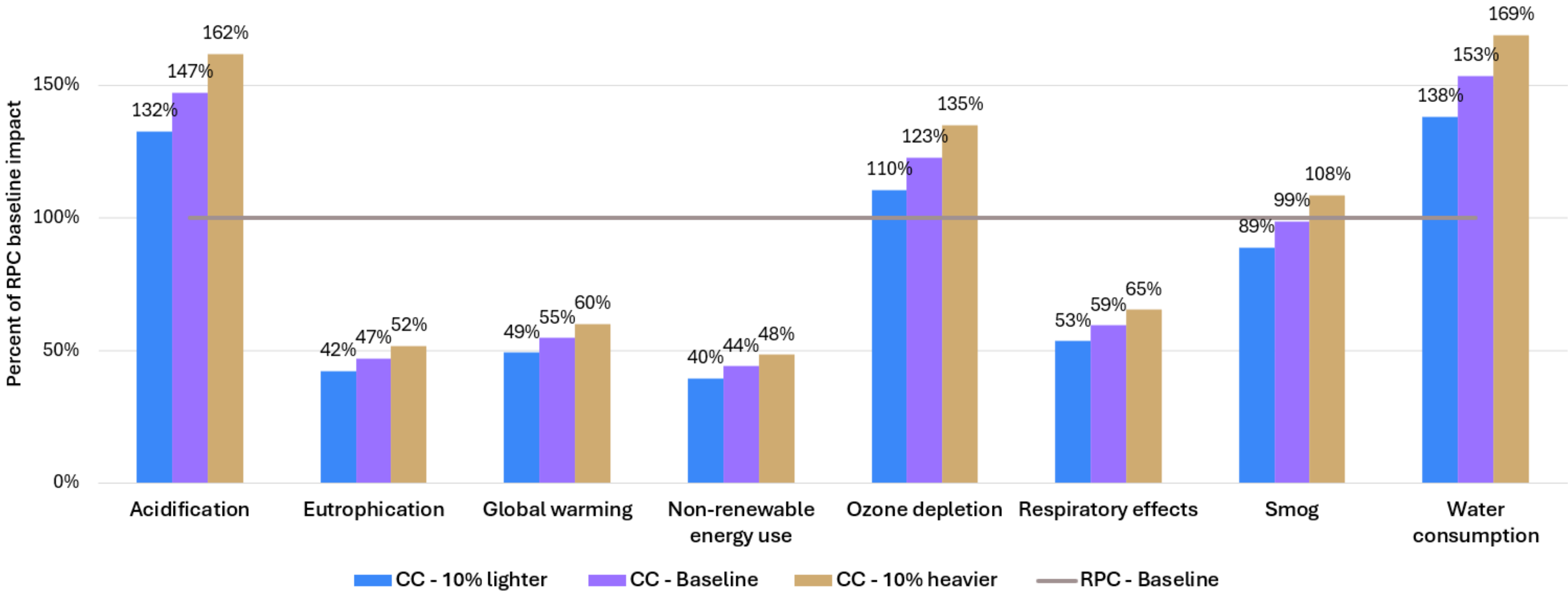


Figure 14: Sensitivity of CC results to container weight for CCs containing apples. For each indicator, a score higher than 100% indicates a greater impact than the RPC baseline results.

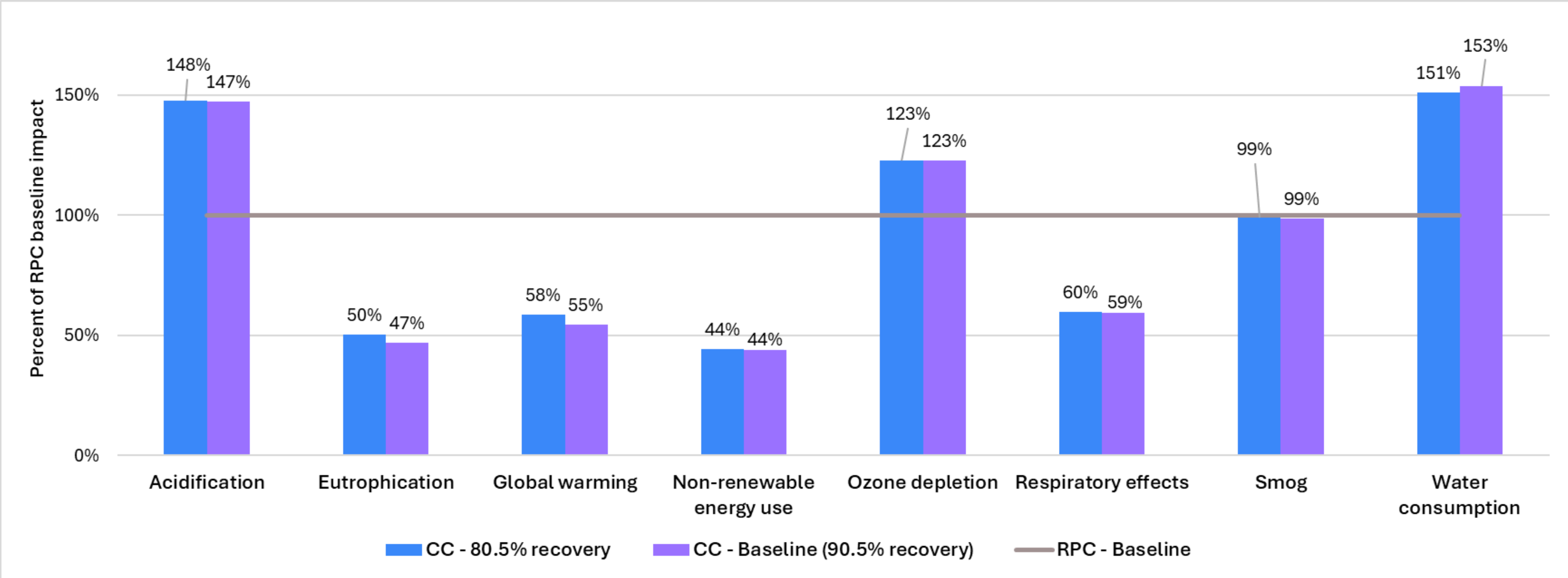


Figure 15: Sensitivity of CC results to recovery rate for CCs containing apples. For each indicator, a score higher than 100% indicates a greater impact than the RPC baseline results.

5.5.8 CC Recycled content

Figure 16 illustrates the outcomes of the sensitivity analysis regarding CC recycled content for the apple system. The directional results remain consistent across the evaluated recycled content; however, the findings indicate that tradeoffs arise among indicators when the recycled content is increased. Interestingly, an increase in the amount of recycled content reverses the impact trend for Ozone Depletion, as higher recycled content reduces the need for virgin pulp production, which is a major contributor to Ozone Depletion due to emissions from fuel combustion at pulp and paper mills. As a result, the Ozone Depletion impact for CCs becomes lower than that of RPCs at higher recycled content levels. The remaining indicators, on the other hand, show an advantage when augmenting the recycled content, but this improvement is not significant enough to reverse the overall trend. They are comparatively less affected by fuel consumption emissions within the raw material life cycle stage. [See NCASI (2023) for specifics].

5.5.9 Biogenic carbon accounting

Figure 17 illustrates the comparative outcomes derived from the flows approach (baseline analysis) and stock change accounting. The selection of biogenic carbon accounting does influence the outcomes for the CC system; however, it does not alter the comparative results. The reason for this is that the Global Warming impact of CCs remain lower than that of the RPCs when applying the flows accounting method (excluding biogenic carbon), and this impact is further reduced under the stocks accounting method. The RPC system exhibits minimal biogenic carbon flows and is consequently only marginally affected by alterations in biogenic carbon accounting. Please consult to Appendix B3 for further details.

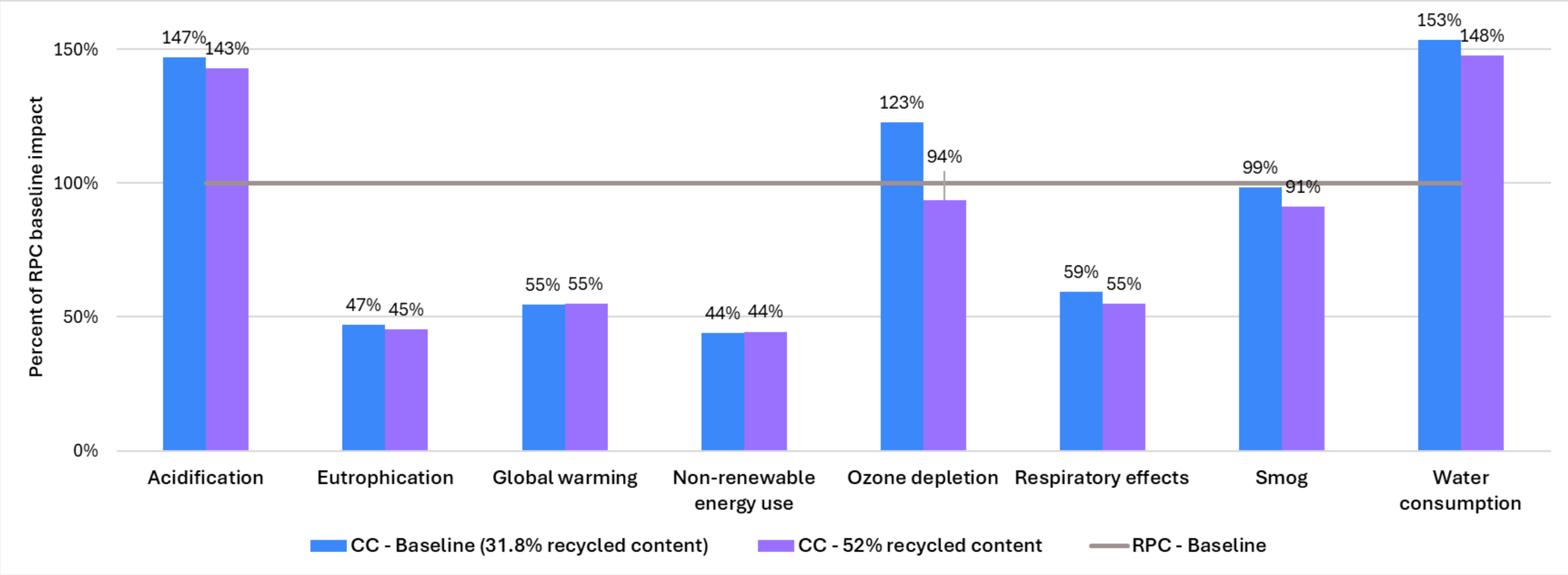


Figure 16: Sensitivity of CC results to recycled content for CCs containing apples. For each indicator, a score higher than 100% indicates a greater impact than the RPC baseline results.

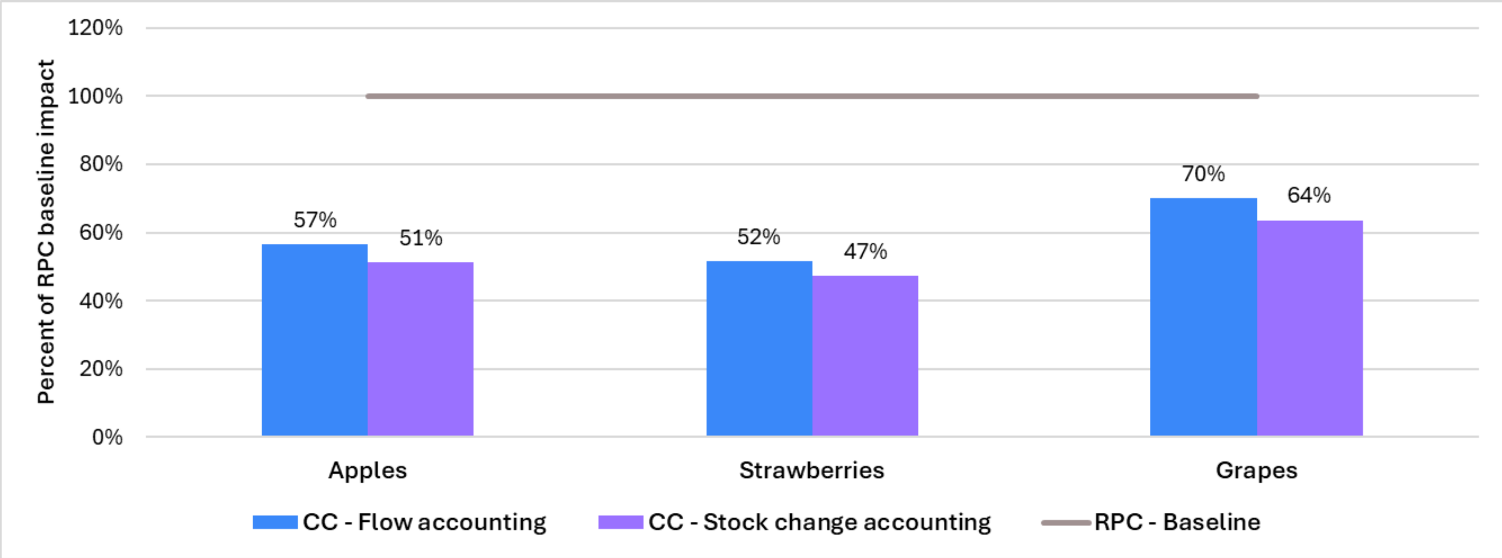


Figure 17: Sensitivity of CC global warming results in biogenic carbon accounting method for CCs containing apples. For each commodity, a score higher than 100% indicates a greater impact than the RPC baseline results.

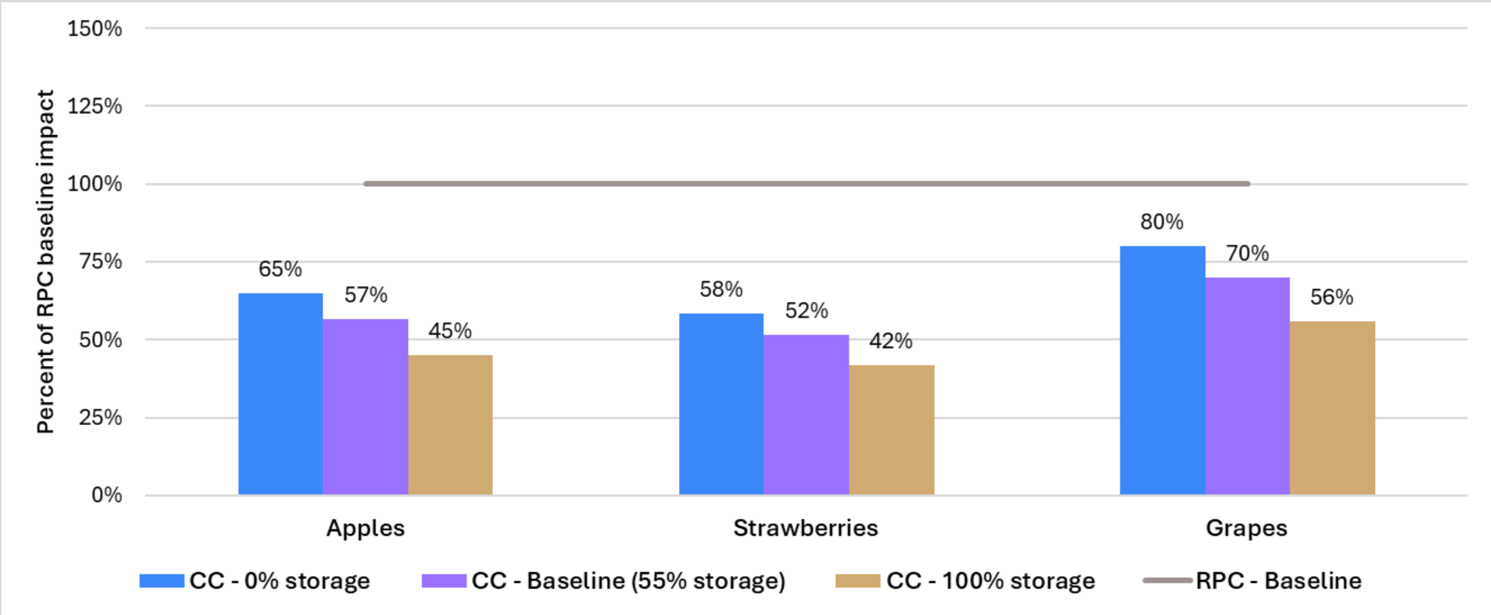
5.5.10 Biogenic carbon stored in landfill

Section 4.2.1.4 outlines the rationale and methodologies for evaluating the quantity and timing of biologically fixed carbon being stored away from the atmosphere. Figure 18 illustrates the outcomes related to the sensitivity of this parameter, specifically examining the extreme scenarios of considering no storage or complete storage of carbon in landfills is tested. The global warming indicator is shown as it is the sole indicator affected by carbon storage.

For all three commodities assessed, enhancing the amount of carbon stored leads to improved environmental performance of the CC system. The reason for this is that that the storage of sequestered carbon prevents emissions to the atmosphere, thus mitigating environmental impact. In no commodity system does carbon storage influence the directional results of the analysis.

The extent of variation in the relative results (i.e., transitioning from 55% storage to either 0% or 100%) escalates as the functional unit mass ratio diminishes. In other words, strawberry system exhibits highest sensitivity to changes in carbon storage, followed by apples, while grapes show the lowest sensitivity. However, in the absolute terms, grape system demonstrates the broadest range of variation, whereas the strawberry system has the narrowest range. The pattern occurs because

as the functional unit mass ratio increases, the impact differences between the container systems



become less pronounced.

Figure 18: Sensitivity of CC global warming results to biogenic carbon storage for CCs. For each commodity, a score higher than 100% indicates a greater impact than the RPC baseline results.

5.5.11 Best- and worst-case scenarios

In addition to the sensitivity analyses in section 5.5, best- and worst-case scenarios are evaluated for both systems. These scenarios implement the most favorable (best) and least favorable (worst) values from each sensitivity analysis. The only exception is the CC recycled content, which was not varied for the best- and worst-case scenarios since the sensitivity test revealed that trade-offs exist between indicators depending on the recycled content value used. Parameter values are summarized in Table 7.

The best-case scenario for the RPC system includes the highest reuse rate, lowest break/loss rate, greatest amount of recycled content, shortest transport distances (from growers to retailers, retailers to servicing and servicing back to growers) and state-of-the-art cleaning technology. The worst case for RPCs applies the opposite ends of these values (e.g., lowest reuse rate), except for the cleaning technology, for which the baseline assumption (composite technology) is used. This is a conservative (favorable) assumption for RPCs.

The best case for the CC system includes the least container weight, highest recovery rate and shortest transport distances (from growers to retailers); the worst case evaluates the heaviest container, least amount of recovery and longest transport distances (from growers to retailers). The biogenic carbon accounting scheme and the biogenic carbon storage parameter are excluded from the best- and worst-case scenarios because the purpose of the test is to understand the relative results of RPCs and CCs under varying industry conditions, and the biogenic carbon topics are methodological choices, rather than industry variables.

The results offer a sense for the range of results that could be obtained under various combinations of the different assumptions. One system's worst-case scenario doesn't necessarily have to be preferable to the others' best-case scenario for conclusions to be drawn. The best- and worst-case scenarios are presented here for the apple system in Figure 19.

It should be noted that there is no basis for assuming that the best or worst parameter values will exist in tandem. The analysis is theoretical and offers a sense for the potential range of results.

As shown by the spread of results for each indicator in Figure 19, the RPC system results show wider variability in most indicators compared to the CC system for the best- and worst-case scenarios. This span can be attributed to the relatively wide range of parameter values as well as their influence on the system comparison. The different ranges of RPC results for each indicator (in terms of percentage points) indicates that parameters affect indicators in different ways, and some impact categories are affected by the parameters to a greater extent than are others. In order of most to least influenced, non-renewable energy use, eutrophication, global warming, and respiratory effects are more sensitive to the RPC parameter values than acidification, ozone depletion, water consumption, and smog formation. The parameters that are varied affect the number of RPCs produced, the distances RPCs travel, the servicing process inputs, as well as the amount of RPC sent to end-of-life. This implies that indicators most sensitive to changes in these parameters are materially contributed to by one or more of these processes.

Overlap between the ranges of results for the two container systems carrying apples exists in all indicators, except non-renewable energy use. However, if we consider that a higher CC recycled content would push the worst case higher, it is likely there would be overlap. This means that within the range of industry variability captured by the sensitivity analyses, the directional conclusions can change for all indicators.

The trends illustrated in this sensitivity test indicate that the functional unit mass ratio can be used to predict the degree of overlap between results of the two container systems. For commodities with lower ratios, more indicators will favor CCs, while for commodities with higher ratios, more indicators will favor RPCs, but across the board there will always be trade-offs. The functional unit mass ratio in combination with parameter values plays a defining role in the directional outcomes between the systems.

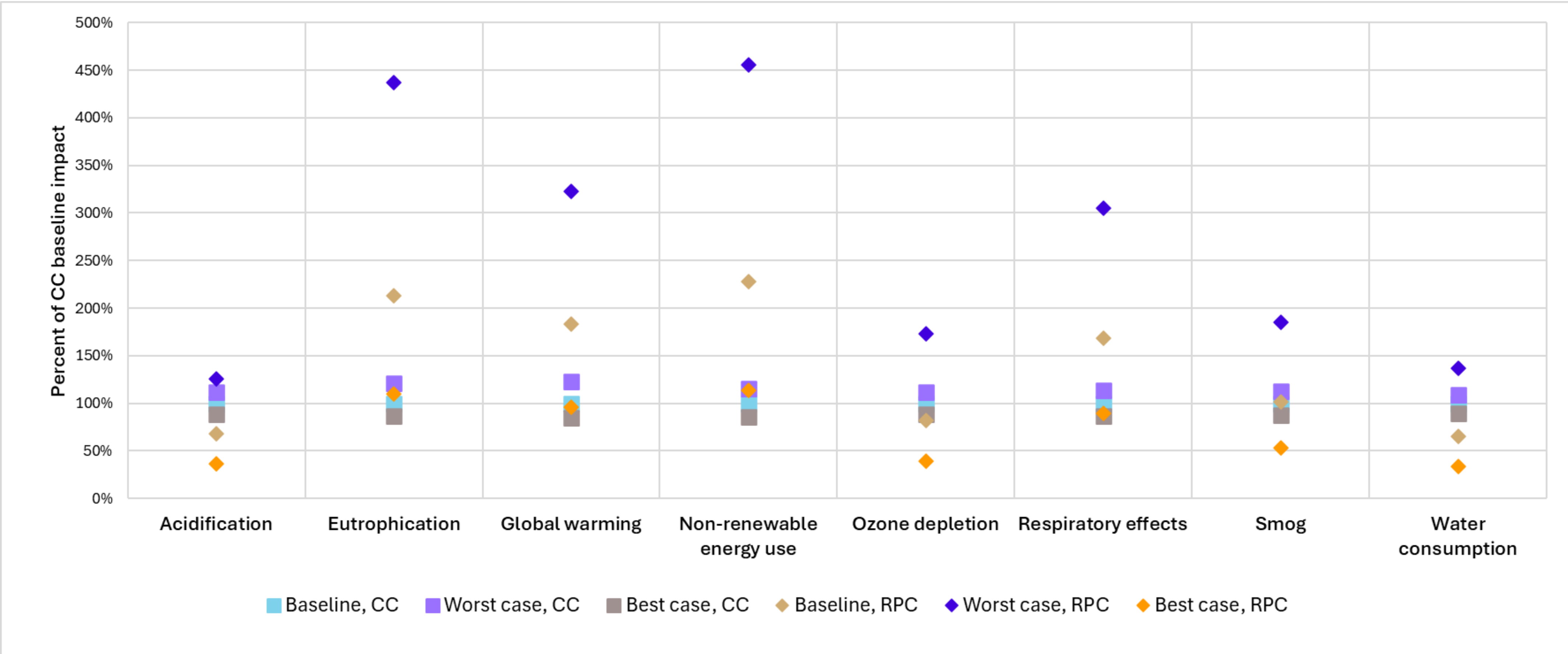


Figure 19: Baseline, best- and worst-case scenarios for RPCs and CCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

5.6 Impact assessment methodology choice

This section presents the results of the primary and secondary impact assessment methods for the apple system, comparing outcomes generated using the TRACI 2.1 and ReCiPe methodologies. Figure 20 provides a detailed comparison of the results as a percent of the CC baseline across key impact categories. The results for other systems are not shown here but follow similar patterns and trends.

Across the impact categories, the directional results between TRACI and ReCiPe are largely consistent, indicating that the overall conclusions remain robust regardless of the chosen impact assessment method. However, notable differences are observed in the relative magnitudes of certain indicators, particularly Ozone Depletion.

The primary difference for ozone impacts arises from the treatment of nitrous oxide (N_2O), which is excluded in TRACI but included in ReCiPe, leading to significantly higher ozone depletion impacts under ReCiPe. Additionally, a review of the characterization factors within SimaPro reveals that ReCiPe includes a more comprehensive list of substances contributing to ozone depletion, and even when both methods consider the same substances, the characterization factors differ by up to a factor of 10.

For resource-related category, ReCiPe reports result for Fossil Resource Scarcity, while TRACI 2.1 assesses Non-renewable Energy Use based on Cumulative Energy Demand (CED). Although these indicators are not directly comparable, Fossil Resource Scarcity focuses on the depletion of fossil resources, while Non-renewable Energy Use measures total energy consumption from non-renewable sources—the trends between the two methods remain consistent. Both indicators highlight similar directional results, showing higher impacts for the RPC system compared to the CC baseline. This alignment reinforces the robustness of the conclusions, despite differences in the scope and interpretation of resource-related indicators.

Overall, the agreement in directional results across the two methods ensures that the conclusions for the apple system are robust. However, the observed differences in relative magnitudes, particularly for Ozone Depletion, highlight the importance of understanding methodological assumptions, such as the treatment of N_2O and variations in characterization factors, when interpreting life cycle assessment results.

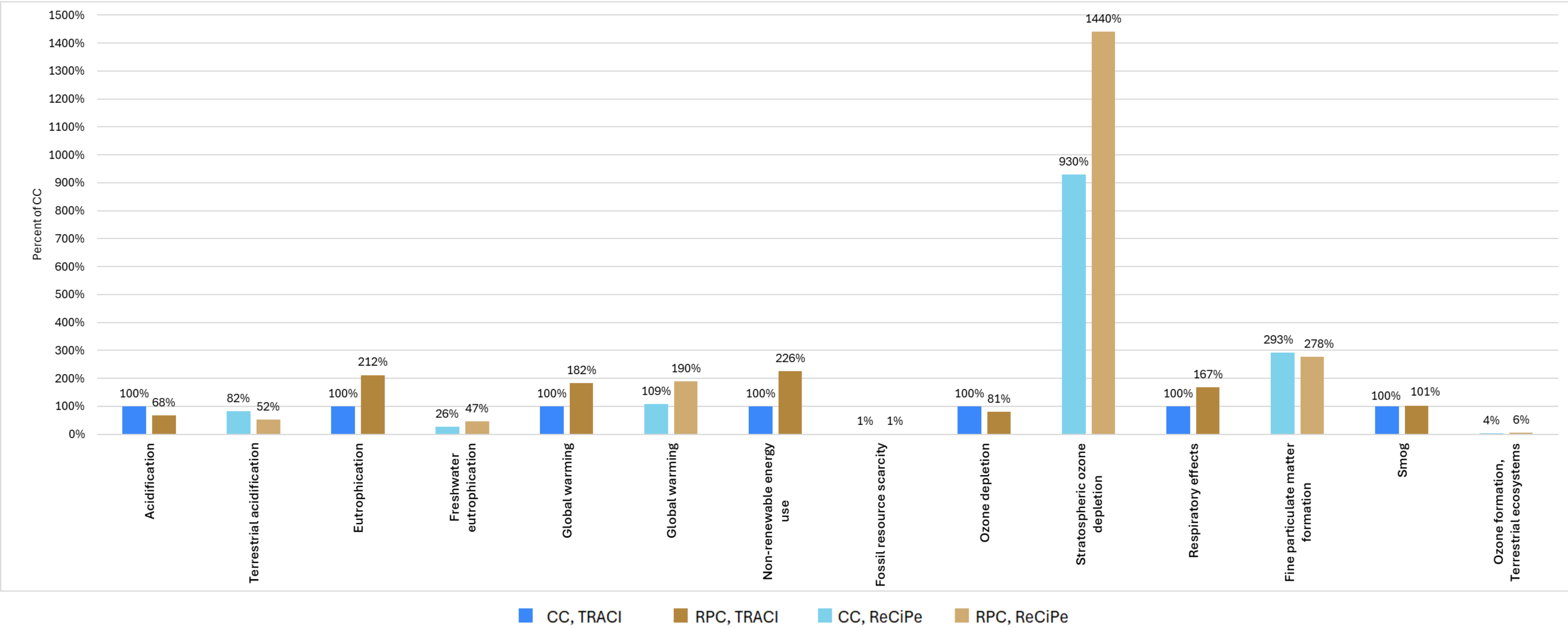


Figure 20: Baseline results using TRACI and ReCiPe for RPCs and CCs containing apples. Results are shown as a percent of CC impact for each indicator.

5.7 Data quality assessment

The main limitations of the data for this study comes from the fact that:

- The RPC modeling data used in this study are based on assumptions from the past Quantis (2019), as no new primary data were collected for RPCs; and
- The CC model has been updated to reflect the latest data and assumptions from the NCASI (2023), ensuring alignment with current industry practices.

Within the RPC system, transportation distance assumptions were identified as the most sensitive and influential parameter. To address this limitation, sensitivity analyses were conducted to test the impact of variations in transport distance, along with other parameters as reuse rate, washing practices, and recycled content. The recycled content from the IFCO ESG Report 2024 was tested in the sensitivity analysis, though the baseline remains consistent with the earlier Quantis (2019) assumptions for comparability.

For the CC system, modeling was updated using 2020 industry average data as reported in NCASI (2023). Transportation is a sensitive and influential parameter for CCs as well, though the sensitivity analysis shows that changes in transportation assumptions do not significantly alter the relative performance of CC compared to RPCs in most impact categories.

Overall, while the RPC model is reliant on older data, the use of comprehensive sensitivity testing ensures that key uncertainties are addressed. In categories where the CC system shows better performance—such as global warming, eutrophication, and respiratory effects—these findings remain robust even when varying transportation distances and other key parameters in the RPC model. The results of this study are therefore considered valid within the data quality bounds described in Table 11.

This approach aligns with the requirements of ISO 14044, which calls for a transparent assessment of data quality, but which does not require the use of formal Data Quality Indicators (DQIs).

Table 11: Data Quality Assessment

Aspect	Requirement in this study	RPC system	CC system
Time-related coverage	General data represent the most current conditions as close to the study date as possible.	Based on legacy data from the Quantis (2019) study. Recycled content was updated and tested with a sensitivity analysis based on the IFCO ESG Report 2024.	The CC model has been updated to reflect the latest 2020 industry data and assumptions as reported in NCASI (2023).
Geographical coverage	Data are representative of the specified regions for the study.	The data are intended to provide the best possible representation of operations in the U.S.	The data represent typical U.S. operations using the best available and most relevant information.
Technology coverage	Data reflect the technology used in the specified systems.	The RPC model relies on legacy assumptions but includes updated recycled content for polypropylene (PP) which was tested in sensitivity analysis based on the IFCO ESG Report 2024.	The CC model reflects current technologies and processes based on NCASI data, ensuring an accurate representation of 2020 industry practices.
Consistency	Consistent assumptions and methodological choices are applied across all systems (e.g., allocation methods, boundaries).	Consistent assumptions and modeling approaches were applied across all product systems. Where database differences arose, conservative assumptions were made, and consistent allocation approaches were ensured across all processes for comparability.	Consistent assumptions and modeling approaches were applied across all product systems. Where database differences arose, conservative assumptions were made, and consistent allocation approaches were ensured across all processes for comparability.

Aspect	Requirement in this study	RPC system	CC system
Completeness	Simple validation checks (e.g., mass and energy balances) are performed to confirm completeness.	Based on previously validated assumptions, with critical parameters-such as transportation distances, material usage, number of uses, are thoroughly analyzed in sensitivity analysis to ensure comprehensive coverage.	Mass and energy balances were conducted to validate the completeness of the system boundaries. All critical flows, including recycled content, transportation distances, and recovery rate are tested in sensitivity analysis.
Representativeness	The data fulfill time-related, geographical, and technological scope requirements.	Based on historical data from prior LCA studies, primarily Franklin Associates (2017), supported by expert input, and U.S.-specific assumptions where available. Robustness was improved through scenario and sensitivity analyses.	Reflects updated 2020 industry operations as documented in NCASI (2023), ensuring strong alignment with current U.S. practices in terms of geography, time, and technology.
Precision	Data that are representative and reliable are used; a sensitivity analysis evaluates variability of key parameters.	Data were assessed for reliability and supplemented with expert judgment about where gaps existed. Sensitivity analyses were conducted to test variability in key assumptions and parameters as detailed in section 5.5.	Data are representative of 2020 industry operations and were validated through iterative expert review. Sensitivity analysis was performed to understand the influence of key parameters as detailed in section 5.5.
Reproducibility	Information about the methods and data sources is provided for transparency.	Adequate transparency of data sources, and inventory data is provided to ensure reproducibility. Inventory data for RPCs, including inputs, outputs, and transport data, is presented in Appendix A.	Full inventory details for CCs along with specific datasets used in the modeling and transport data are documented in Appendix A. This level of disclosure supports reproducibility

Aspect	Requirement in this study	RPC system	CC system
Sources of the data	Data originate from credible sources with references provided.	Drawn from previously published LCA reports, industry data, and expert consultations, particularly Franklin Associates (2017), complemented by iterative validation with stakeholders.	Sourced from peer-reviewed literature, the NCASI (2023), with data validated through collaboration between Quantis, CPA, and industry experts.
Uncertainty of the information	A sensitivity and uncertainty analysis are conducted to evaluate the robustness of results.	Semi-quantitative uncertainty assessment conducted; recycled content and reuse rates were tested via scenario analysis as detailed in section 5.5.	Semi-quantitative uncertainty assessed through Monte Carlo simulation and sensitivity testing as reported in section 5.5.

5.8 Completeness and consistency check

This report contains the information utilized for the construction of the CC system and RPC system models. The data utilized for both models is regarded as high quality; however, further examination is necessary to assess their completeness and consistency.

The modelled container systems are adequately comparable to facilitate comparative conclusions across the indicators evaluated. The data utilized for the RPC system description is predominantly obtained from a singular RPC provider (IFCO)[16]. In contrast the CC system model primarily derives its information from studies that examine the broader U.S. containerboard industry. However, given that IFCO supplies the majority of RPCs available in the market and that the data has been adjusted to include practices from other potential RPC providers' practices (as outlined in section 3.2), it is reasonable to conclude that the data utilized here effectively represents a typical RPC life cycle in the U.S. market. Information and data at the industry level regarding additional participants and/or data describing the U.S. RPC market would facilitate validation of this assumption.

5.9 Uncertainty Analysis

To assess the robustness of the comparative results between the corrugated product (CC) system (A) and the reusable plastic container (RPC) system (B), an uncertainty analysis was conducted using a Monte Carlo simulation in SimaPro software. This analysis accounts for variability in data input and model parameters by randomly sampling values from assigned probability distributions over multiple iterations. The number of iterations was set at 1,000 runs to ensure statistical significance and stable output distributions. For each environmental impact category, standard deviations were calculated based on the resulting distribution of values from the Monte Carlo runs.

The results are visualized in Figure 21, which presents the net differences across key environmental impact categories. The graph compares the impacts for apple system, where the results are expressed as the difference of CC to RPC (A minus B). In the graph, light blue bars represent categories where the corrugated product system has a lower environmental impact (A < B), while dark blue bars indicate categories where the corrugated product has an equal or higher impact relative to the RPC system (A ≥ B). The horizontal scale quantifies the magnitude of the difference, with negative values (extending left) favoring the corrugated product and positive values (extending right) favoring the RPC system.

The uncertainty assessment highlights key trends and trade-offs:

- Global Warming, Eutrophication and Respiratory Effects show a clear advantage for the corrugated product, indicated by the substantial light blue bars extending to the left.

[16] The RPC modeled in this study does not intend to represent an RPC provided by IFCO. The LCI for RPC production and cleaning, as well as some transport steps, are sourced from a publication [Franklin Associates (2017)] describing the IFCO RPC system due to a lack of available data describing the greater U.S. RPC industry. The model is developed in the present study with the objective of reflecting this broader context.

This suggests lower greenhouse gas emissions and nutrient-related impacts for the corrugated system.

- Non-renewable Energy Use also favors the corrugated product, with minimal differences indicating near-parity between the two systems.
- Acidification shows a clear advantage for the RPC system, reflected by the prominent dark blue bars extending rightward.
- Ozone Depletion favors RPCs, but the difference is minimal, suggesting that while RPCs perform better, the advantage is not substantial.
- Smog Formation and Water Consumption show moderate advantages for the RPC system, with impacts approximately 40-50% lower. However, the results suggest that the differences may not be definitive enough to predict a clear preference between the two systems.

The uncertainty analysis confirms that the observed trends are consistent and reliable within the bounds of variability in input data. The results provide confidence that the key trade-offs between the two systems remain robust and highlight the importance of considering multiple impact categories when evaluating overall environmental performance.

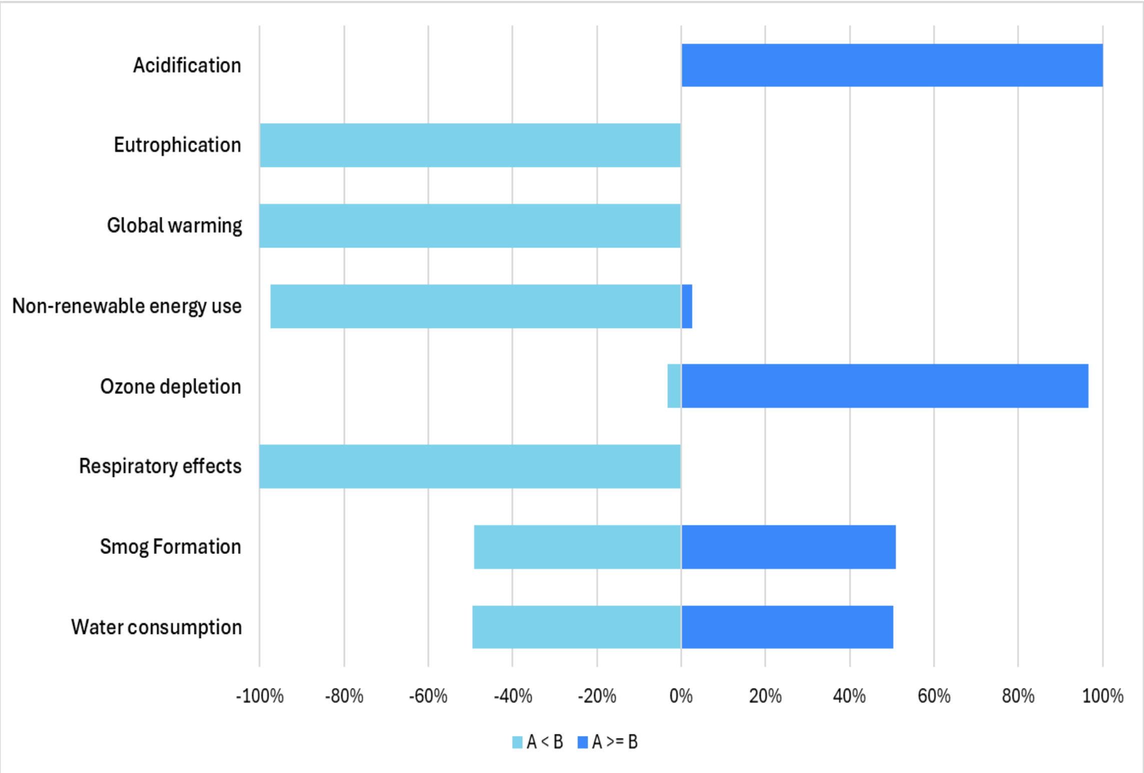


Figure 21: Uncertainty analysis for apple containers showing indicator standard deviation as error bars for each system.

6 Limitations

The present study has certain limitations that must be considered when interpreting its results. These include limitations intrinsic to LCA, as well as those arising from the existing state of science, and the methodological approaches employed in this research. It is essential to consider the following limitations in conjunction with the context outlined in previous sections of this report when analyzing the information provided herein.

- LCIA results indicate relative and potential environmental impacts rather than the measured ones. These are relative expressions concerning the functional unit, which are not suitable for predicting specific instances of adverse impacts or risks, nor for determining whether standards or safety margins are exceeded. LCIA models typically aim to depict the most likely scenario, rather than accounting for worst-case situations, safety margin or other conservative strategies commonly employed in regulatory framework. The categories assessed in this analysis do not encompass all environmental impacts linked to human activities. For instance, factors such as noise, odors, electromagnetic fields and others are excluded from the current assessment. The methodological advancements concerning these impacts are inadequate for their consideration.
- LCIA methodologies are unable to fully characterize the complete range of emissions released into soil, air and water from various processes. They characterize the most recognized pollutants and, in doing so, offer the most accurate estimate for assessing environmental impact.
- Unlike CC systems, the RPC systems are mainly defined by data that pertains to the operations of a single company, attributed to a scarcity of information. Therefore, the quality of data utilized for modeling the two container types is not inherently equivalent. Multiple sensitivity analyses—especially concerning parameters identified in prior life cycle studies as significant impact drivers, were conducted to assess the implications of choosing specific values within the practical range for the U.S. market, along with the combined effects of altering several parameters simultaneously.
- The available data on water emissions from the RPC cleaning process is constrained, as it excludes emissions commonly present in wastewater generated by industrial processes that utilize detergents and chloro-sanitizers. These substances can significantly affect receiving water bodies or air emissions. The significance of these impacts in relation to other components of the life cycle of RPCs remains unclear.
- While the sensitivity analysis accounts for produce production and associated losses, the baseline assessment does not address the disparity in losses between CCs and RPCs. For most indicators, the environmental impacts of produce production far outweigh those of container life cycle processes. Even marginal differences-such as a few percentage points in produce loss between container types-can substantially influence the relative environmental performance of these indicators. However, this study found no evidence to suggest any variation in produce loss rates between the two systems under evaluation.
- The assessment does not incorporate environmental indicators for land use and land transformation owing to the unavailability of the relevant datasets that are central to the assessment. These issues (land use and transformation) are inherently complex, often marked by competing perspectives. Key factors in evaluating impacts may include the

economics of forestry, competing land-use demands, and the ecosystem services provided by forest land, among others. Existing impact assessment methodologies are insufficient to address these challenges and fail to distinguish between the effects of conventional and sustainable forestry practices. Even if data on land use and transformation had been available, conducting a thorough analysis of these issues would have exceeded the scope of the LCA.

- The study excludes environmental indicators related to ecotoxicity and human health, including carcinogens and non-carcinogens, due to discrepancies in the inclusion of these flows within the LCIs utilized for modeling polypropylene and containerboard. Toxicity flows are excluded from the polypropylene production inventory data (as provided by the USLCI database), while the NCASI containerboard production data includes details on toxicity flows. The authors lack confidence in the comparability of the data for this metric across systems.
- This report excludes social and economic impacts from its scope. Assessing these impacts is essential for a comprehensive assessment of system sustainability.

7 Conclusions

This comparative LCA examines the performance of CCs and RPCs in transportation and display of eight produce types. The analysis reveals that neither container system consistently outperforms the other across all indicators or produce categories, whether considering market-weighted or commodity-specific outcomes. When accounting for uncertainty, RPCs show advantages in one (1) impact category (Acidification), moderate advantages to two (2) impact categories (Smog Formation and Water Consumption), and three (3) impact categories show an advantage for CCs (Global Warming, Eutrophication and Respiratory Effects)). While CCs show an advantage in Non-renewable Energy Use and RPCs in Ozone Depletion, neither category demonstrates a complete advantage for one system, as some level of overlap exists. This suggests that the differences, while present, are not absolute. However, as discussed further in section 5.2, the number of categories that support a container system is not a reliable indicator of environmental superiority. The assessment indicates that it is not possible to determine a definitive environmental advantage of either system over the other under the baseline US market conditions presented. Further refinements in data or methodology may not yield a fully consistent directional finding.

The subsequent paragraphs of this section discuss secondary findings derived from a thorough analysis of the outcomes. Their variation under the scenarios examined are discussed in the remaining paragraphs of this section.

Neither container system demonstrates a definitive environmental advantage across most indicators under various conditions for different commodities. It is essential to acknowledge that the authors cannot conclusively determine the superiority of one system over the other purely from an environmental perspective. Such a conclusion assumes that all impact categories are equally significant. Evaluating the relative significance of these categories requires an analysis of their individual contributions to the issues at hand, which are typically framed in an LCA around the protection of human health, ecosystem quality and resource availability. Furthermore, it involves considering the relative weighting of these concerns, such as assessing the trade-offs between human health and ecosystem quality.

While individuals may possess personal views or values that shape their position on these matters, the authors cannot claim that one set of values holds greater validity than another, which might lead a different party to an alternative decision. As a result, reaching an objective, and definitive conclusion about environmental superiority becomes impractical when conflicting indicators demand a trade-off rooted in subjective values. In such cases, including the current one, the only overarching insight is that trade-offs exist between the systems. This study provides a framework for users to apply weighting schemes, enabling the derivation of conclusions aligned with their own value systems.

The analysis of variability and sensitivity in the results indicates that comparative performance is likely context- dependent. The combination of factors, including the type of produce transported, the RPC transport distances, and the weight of CCs, among others, influences the outcomes. Altering these assumptions with a reasonable range typically influences the outcomes toward one system or the other, though it seldom reverses the directional outcomes. In most instances, altering these assumptions does not sufficiently shift the directional findings such that a significant outcome for one system transforms into a significant outcome for the other.

The analysis of both “best case” and “worst case” scenarios for each container system indicates that specific indicators and commodity systems may experience directional changes in outcomes depending on certain market conditions. It can be concluded that a clear and definitive advantage is unlikely to exist for either system across all scenarios or conditions.

The environmental trade-offs of container systems can be assessed by analyzing the ratio of the mass needed to fulfill the functional unit for each container system. The indicators demonstrating advantages for each container system, as well as the magnitude of differences between the systems for each indicator, are directly correlated with the variations in container masses required to ship a specified quantity of produce.

The findings highlight potential avenues for both systems to minimize their environmental impact. The CC system focuses on optimizing recovery processes while reducing container weight, ensuring that such measures do not comprise the integrity of the produce. Similarly, the RPC system can improve the environmental performance by prioritizing reuse, which entails increasing the number of usage cycles, minimizing damage and loss rate, integrating recycled materials, along with optimization of logistics (i.e., transport distances).

While this study did not evaluate differences in produce damage rates between the systems, the existence of such a difference could influence the overall advantage. Even minor variations, such as a few percentage points in produce loss, could yield a significant benefit for the system with reduced damage.

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Appendices

A1. Reference flow quantities

The main reference flow quantities for container material in the CC and RPC systems are listed in Table A-1 and Table A-2 along with the calculation of these quantities.

Table A- 1: Summary of key reference flows for the RPC system

From	To	Equation*	Calculation example: Apples
RPC production	Use	(B+1/N)X	(0.05+1/24)(110,000 kg RPC) = 10,083 kg RPC
Use	End-of-life	(B+1/N)X	(0.05+1/24)(110,000 kg) = 10,083 kg RPC
Use	Re-Use	[1-(B+1/N)]X	[1-(0.05+1/24)](110,000 kg) = 99,917 kg RPC
Re-Use	Use	[1-(B+1/N)]X	[1-(0.05+1/24)](110,000 kg) = 99,917 kg RPC
End-of-life	RPC production	(1/E)(B+1/N)XR	(1/0.98)(0.05+1/24)(110,000 kg)(0.25) =2,572.3 kg RPC

*B = Break and loss rate, N = Number of uses, X = Mass of containers per FU, E = Efficiency of recycling process, R = Recycled content

Table A- 2: Summary of key reference flows for the CC system

From	To	Equation*	Calculation example: Apples
Materials & production	Conversion	CX	(1.1 kg containerboard / kg CC) * (42,000 kg CC) = 46,200 kg containerboard
Conversion	Use	X	42,000 kg CC
Use	End-of-life	X	42,000 kg OCC
End-of-life	Materials & production	RX	(0.905) * (42,000 kg OCC) = 38,010 kg OCC

* X = Mass of containers per FU, C = Mass of containerboard per mass of CC, R = Recovery rate

A2. RPC production process

The RPC production process is taken from Franklin Associates (2017) and describes production of IFCO RPCs. As IFCO is one of the major RPC manufacturers in North America (and elsewhere), the data is considered to represent a large portion of RPCs currently in use in the U.S.

Table A- 3: Life cycle inventory for RPC production (per 1,000 lbs RPCs manufactured) (Franklin Associates 2017)

INPUTS		
Materials	***Quantity***	***Units***
Cleaning solvent	0.025 (0.011)	lb (kg)
Colorant	17.9 (8.12)	lb (kg)
LLDPE stretch film	0.71 (0.32)	lb (kg)
Lubricant	0.047 (0.021)	lb (kg)
Polypropylene resin[1]	984 (446)	lb (kg)
Energy	***Quantity***	***Units***
Electricity (grid)	390 (4,013)	kWh (1,000 BTU)
LPG	0.15 (1.25)	gal (L)
Transportation (of material inputs)[2]	***Quantity***	***Units***
Combination truck	525 (1,863)	ton-mile (tonne-km)
Diesel	5.51 (46)	gal(L)
OUTPUTS		
Materials	***Quantity***	***Units***
RPCs, for use	1,000 (453.6)	lb (kg)
Solid waste, landfilled	2.98 (1.35)	lb (kg)
Solid waste, waste-to-energy	0.75 (0.34)	lb (kg)

[1]As per Franklin Associates (2017), this can be any ratio of virgin and recycled PP.

[2]As per Franklin Associates (2017), this transportation is mainly for delivery of PP resin to the manufacturing facility and is therefore used to model this transport step in the present study, as noted in Table A-7.

A3. RPC cleaning process

The baseline RPC cleaning process is a composite dataset based on information provided in University of Stuttgart (2007) and Franklin Associates (2017). The dataset weights the inputs for detergent, electricity, and water by the portion of the market estimated to be applying the new or older technology. The University of Stuttgart (2007) data were chosen to represent 30% of the total composite dataset. All other inputs were characterized by the values provided in Franklin Associates (2017) and described in Table A-5.

As the data provided by Franklin Associates (2017) represents all of IFCO's cleaning facilities, and as IFCO represents approximately 70%[17] of RPCs currently used in the U.S. produce industry, the Franklin Associates (2017) data was weighted at 70%. A sensitivity test assessed the effect of implementing the IFCO technology (i.e., Franklin Associates 2017 data) across the entire RPC industry in the U.S.

Table A- 4: Calculation of detergent, electricity and water inputs for the life cycle inventory describing RPC cleaning used in the baseline analysis, weighting Franklin Associates (2017) data at 70% and University of Stuttgart (2007) data at 30%

Item	Franklin Associates (2017)	University of Stuttgart (2007)	Value for composite cleaning process
Detergent (kg/RPC)	3.99E-03	8.88E-04	3.06E-03
Electricity (MJ/RPC)	1.86E-01	0.492	0.278
Water (kg/RPC)	7.21E-02	0.413	0.174

[17] See section 3.2.2.

Table A- 5: Life cycle inventory for RPC cleaning (per 1,000 washed & sanitized RPCs) provided by Franklin Associates (2017)

INPUTS		
Materials	*Quantity*	*Units*
RPCs, used (to be cleaned)	1,024	pieces
Chloro-sanitizer	0.54 (1.2)	kg (lb)
HDPE pallet cap	0.84 (1.86)	kg (lb)
Industrial detergent[1]	3.99 (8.80)	kg (lb)
LLDPE stretch film	9.79 (21.6)	kg (lb)
Water (consumed)[1]	72.1 (19)	L (gal)
Wood pallets	1.32 (2.90)	kg (lb)
Energy	*Quantity*	*Units*
Electricity (grid)[1]	51.7 (532)	kWh (1,000 BTU)
Natural gas	7.98 (282)	m^3 (ft^3)
LPG	1.8 (0.47)	L (gal)
Diesel	0.33 (0.086)	L (gal)
Transportation (of material inputs)[2]	*Quantity*	*Units*
Combination truck	16.3 (10.1)	tonne-km (ton-mi)
Diesel	0.40 (0.11)	L (gal)
OUTPUTS		
Materials	*Quantity*	*Units*
RPCs, cleaned & sanitized	1,000	pieces
Damaged RPCs[3]	24	pieces
LLDPE stretch film	9.79 (21.6)	kg (lb)
HDPE pallet cap	0.84 (1.86)	kg (lb)
Emissions	Quantity	Units
Chlorine, emission to air	1.6E-03 (3.6E-03)	kg (lb)
COD, emission to water	0.055 (0.12)	kg (lb)
Solid waste, landfilled	0.0031 (0.0069)	kg (lb)
TSS, emission to water	0.021 (0.045)	kg (lb)

[1]Input changed for the baseline analysis; [2]As per Franklin Associates (2017), this transportation is primarily for materials used during the washing process. RPC transport is modeled with the information provided in Table A-9 and 10. [3]As per Franklin Associates (2017), this includes units that are repaired, and returned to service, as well as units scrapped for recycling.

A4. Datasets utilized for CC system

Table A- 6: The generic dataset used in the corrugated system model as per NCASI 2023

FIBER			
Fiber name	**Database**	**Specific dataset**	**Comment**
Logs, Northern Hardwood	U.S. LCI	Pulpwood, hardwood, average, at forest road, NE- NC/RNA	
Logs, Southern Hardwood	U.S. LCI	Pulpwood, hardwood, average, at forest road, NE- NC/RNA	No data available for southern hardwood pulpwood, northern used as a proxy
Logs, Southern Softwood	U.S. LCI	Softwood logs with bark, harvested at average intensity site, at mill, US SE/US	Without transportation
Chips, Northern Hardwood	U.S. LCI	Wood chips, hardwood, green, at sawmill, NE- NC/kg/RNA	
Chips, Southern Hardwood	U.S. LCI	Wood chips, hardwood, green, at sawmill, NE- NC/kg/RNA	No data available for southern hardwood chips, northern used as a proxy
Chips, Northern Softwood	U.S. LCI	Wood chips, softwood, green, at sawmill NE- NC/kg/RNA	
Chips, Southern Softwood	U.S. LCI	Pulp chips, at sawmill, US SE/kg/US	
Recovered Paper, Mixed	N/A	Transportation only	
Recovered Paper, Corrugated	N/A	Transportation only	
Recovered Paper, Pulp Substitutes	N/A	Transportation only	
Recovered Paper, High-grade Deinking	N/A	Transportation only	
Purchased BKMP	NCASI	NCASI 2006/2007 bleached kraft market pulp dataset	
Purchased UBKMP	EI	Sulphate pulp, unbleached, at plant/RER	
Purchased RNDI	EI	Paper, recycling, no deinking, at plant/RER	No data for pulp, paper used as a proxy

CHEMICALS			
Chemical name	**Database**	**Specific dataset**	**Comment**
Aluminium chloride	EI	Chemicals inorganic, at plant/GLO	
Aluminum sulfate	EI	Aluminum sulphate, powder/RoW	
Coatings	EI	Coating powder, at plant/RER	
Dispersant	EI	Pitch dispersants, in paper production, at plant/RER	
Fillers	EI	Calcium carbonate, precipitated/RoW	
Quicklime	EI	Quicklime, milled loose/RoW	
Soda	EI	Soda ash, light/RER	Includes soda powder, soda ash and sodium carbonate
Sodium hydroxide	EI	Sodium hydroxide, without water in solution state/RER	
Starch	EI	Maize starch/RoW	
Strength agents	EI	Polyacrylamide/GLO	Polyacrylamide is one type of strength agent, used as a proxy for all
Sulfuric acid	EI	Sulfuric acid/RER	
FUELS			
Fuel name	**Database**	**Specific dataset**	**Comment**
Purchased Hogged Fuel, Logging Residues	U.S. LCI/US, NCASI	Forest residue, processed and loaded, at landing system/RNA, NCASI combustion emissions	
FUELS			
Fuel name	**Database**	**Specific dataset**	**Comment**
Purchased Hogged Fuel, Manufacturing Residues	U.S. LCI/US, NCASI	Bark, at sawmill, US SE/kg US, NCASI combustion emissions	
Self-Generated Hogged Fuel, Logging Residues	U.S. LCI/US, NCASI	Forest residue, processed and loaded, at landing system/RNA, NCASI combustion emissions	
Self-Generated Hogged Fuel, Manufacturing Residues	NCASI	NCASI combustion emissions	
Spent Liquor Solids	NCASI	NCASI combustion emissions	
Self-Gen Hydroelectricity	EI	Electricity, hydropower, at run-of-river power plant/RER	
Non-Recyclable	EI	Disposal, paper, 11.2% water, to municipal incineration/CH	

Paper			
Other biomass	U.S. LCI/US, NCASI	Bark, at sawmill, US SE/kg/US, NCASI combustion emissions	
Sludge	NCASI	NCASI combustion emissions	
Coal	U.S. LCI	Bituminous coal, combusted in industrial boiler /US	
Distillate Fuel Oil (#2)	U.S. LCI	Diesel, combusted in industrial boiler/US	Diesel combustion used as a proxy for DFO combustion
Gasoline	U.S. LCI	Gasoline, combusted in equipment/US	
Kerosene	U.S. LCI	Diesel, combusted in industrial boiler/US	Diesel combustion used as a proxy for kerosene combustion
Liquid Propane Gas	U.S. LCI	Liquefied petroleum gas, combusted in industrial boiler/US	
CHEMICALS			
FUELS			
Fuel name	**Database**	**Specific dataset**	**Comment**
Natural Gas	U.S. LCI	Natural gas, combusted in industrial boiler/m3/RNA	
Other Fuel/Other Fuel 1	U.S. LCI	Diesel, combusted in industrial boiler/US	Diesel combustion used as a proxy for other fuels
Petcoke	U.S. LCI/U.S. EPA	Bituminous coal, combusted in industrial boiler/US,	With coal replaced by petcoke and GHG emissions modeled after U.S. EPA (2010)
Residual Fuel Oil (#5,6)	U.S. LCI	Residual fuel oil, combusted in industrial boiler/US	
Rubber Tire Chips	Literature (U.S. EPA 1997)		
Purchased electricity	EI	Electricity, medium voltage	Custom mix obtained from the mills
Purchased steam	U.S. LCI	N/A	Steam mix obtained from the mills purchasing steam (mostly coal)
WASTE MANAGEMENT			
Name	**Database**	**Specific dataset**	**Comment**
Residuals, landfilled	NCASI	N/A	
Residuals, land applied	NCASI	N/A	
Residuals, burned	NCASI	N/A	Assumed to be included in combustion emissions
Sludge, ash, other waste, other beneficial	N/A	N/A	Ignored
Effluent to river	NCASI	N/A	

TRANSPORT			
Name	**Database**	**Specific dataset**	**Comment**
Truck, non-refrigerated	EI	Transport, freight, lorry 16-32 metric ton, EURO 6/RoW	
Train	EI	Transport, freight train/US	
Boat, river	EI	Transport, freight, inland waterways barge/GLO	
Boat ocean	EI	Transport, freight sea, container ship/GLO	
Pipeline	EI	Transport, natural gas, pipeline, long distance/RER Transport, crude oil pipeline, onshore/RER	
END-OF-LIFE			
Name	**Database**	**Specific dataset**	**Comment**
Landfill of corrugated packaging	EI	Waste paperboard, sanitary landfill/RoW	Carbon modeled using methods described in section 4.2.1.4
Incineration of corrugated packaging	EI	Waste paperboard, municipal incineration/GLO	Carbon modeled based on U.S. conditions

A5. Transport models

A full load is assumed for all container transportation from manufacturing to grower, from grower to retailer, and, for the RPC system, from retailer to servicing and then back to the grower. Determination of volume-limited or weight-limited the truck's mass- based utilization rate is based on (1) a truck payload capacity of 18,143 kg (40,000 lb), (2) the assumption that a maximum of 24 102-cm by 122-cm (40-in by 48-in) pallets each weighing 23 kg (50 lb) fit on a truck, and (3) a typical number of containers carried on a pallet.

For full containers traveling to the retailer, the total payload (i.e., weight of the containers, their produce and the pallets) exceeds the truck capacity for all commodities carried by CCs and RPCs, except strawberries carried by CCs and RPCs, and is modeled as mass-limited transport. The one exception noted is modeled as volume-limited transport.

The methodology for computing the utilization rate (UR) of trucks hauling empty containers is consistent between the two container types but considers key differences in their handling. For RPCs, the utilization rate of trucks carrying empty RPCs is performed with the same approach as for full RPCs, however, the number of containers per pallet is different (as described in Table A-7), where the distinction between erected and collapsed RPCs is accounted for. The produce mass is set to zero (0) for empty RPC and CC shipments. For CCs, it is assumed that manufacturers send collapsed CCs to growers in consolidated stacks or bales. The utility rate of the trucks is based on a typical CC baling density of 535 kg/m^3 (900 lb/yd^3) (U.S. EPA 1993). The CC baling density is applied to a bale volume of 1.42 m^3 (50 ft^3) per bale (60 in x 30 in x 48 in). It is assumed that each pallet carries one bale.

The following equation is applied to determine the utilization rate of truck transport for CCs and RPCs regardless of commodity, transport step (i.e., to/from grower) or format (i.e., erected or knocked down). The exception is for empty CCs moving from the manufacturer to the grower, the calculation for which is provided directly following this first set of sample computations.

<u>Utilization rate for transport of containers, except for transport of CCs from the manufacturer to the grower.</u>

$$Utilization\ rate = \frac{Npa * [Nc(Mc + Mpr) + Mpa]}{Ct}$$

Where,

N_{pa} = $Number\ of\ pallets\ per\ truck$

N_c = $Number\ of\ containers\ per\ pallet$

M_c = $Mass\ of\ one\ container, kg$

M_{pr} = $Mass\ of\ produce\ per\ container, kg$

M_{pa} = $Mass\ of\ one\ pallet, kg$

C_t = $Mass\ capacity\ of\ truck, kg$

Sample calculations, Apple system:

$Utilization\ rate, from\ grower\ to\ retailer, CCs$

Sample calculations, Apple system:

$$Utilization\ rate, from\ grower\ to\ retailer, CCs = \frac{\left(24\frac{pallets}{truck}\right)\left[\left(49\frac{containers}{pallet}\right)\left(0.82\frac{kg}{container} + 18.0\frac{kg}{container}\right) + 23\frac{kg}{pallet}\right]}{18{,}144 kg/truck} > 100\% \therefore 100\%$$

$$Utilization\ rate, from\ grower\ to\ retailer, RPCs = \frac{\left(24\frac{pallets}{truck}\right)\left[\left(50\frac{containers}{pallet}\right)\left(2.27\frac{kg}{container} + 18.18\frac{kg}{container}\right) + 23\frac{kg}{pallet}\right]}{18{,}144 kg/truck} > 100\% \therefore 100\%$$

Utilization rate for transport of CCs from the manufacturer to the grower

$$Utilization\ rate, from\ manufacturer\ to\ grower, CCs = \frac{N_{pa}N_bV_b\rho_b}{C_t}$$

Where,

N_{pa} = $Number\ of\ pallets\ per\ truck$

N_b = $Number\ of\ CC\ bales\ per\ pallet$

V_b = $Volume\ of\ one\ CC\ bale, m^3$

ρ_b = $Density\ of\ one\ CC\ bale, kg/m^3$

C_t = $Mass\ capacity\ of\ truck, kg$

Sample calculation, Apple system:

$$Utilization\ rate, from\ manufacturer\ to\ grower, CCs = \frac{\left(24\frac{pallets}{truck}\right)\left(1\frac{bale}{pallet}\right)\left(1.43\frac{m^3}{bale}\right)\left(535\frac{kg}{m^3}\right)}{18{,}144 kg/truck} > 100\% \therefore 100\%$$

Table A- 7: Pallet loads and truck utilization rates for container transport in the CC and RPC systems

Container type	Produce type	Pallet load		Truck utilization rate (mass basis)	
		Number of containers when erected	*Number of bales/ containers when collapsed/knocked-down*	*Full containers*	*Empty containers*
CC	Apples	49	1 bale per pallet	100%	100%
CC	Carrots	60	1 bale per pallet	100%	100%
CC	Grapes	108	1 bale per pallet	100%	100%
CC	Head Lettuce	40	1 bale per pallet	100%	100%
CC	Onions	48	1 bale per pallet	100%	100%
CC	Oranges	63	1 bale per pallet	100%	100%
CC	Strawberries	108	1 bale per pallet	63%	100%
CC	Tomatoes	80	1 bale per pallet	100%	100%
RPC	Apples	50	165	100%	53%
RPC	Carrots	60	165	100%	41%
RPC	Grapes	75	165	100%	37%
RPC	Head Lettuce	35	105	100%	36%
RPC	Onions	40	105	100%	30%
RPC	Oranges	40	105	100%	35%
RPC	Strawberries	110	195	81%	36%
RPC	Tomatoes	105	165	100%	37%

Table A- 8: Transport distances used in the baseline analysis for the CC system

	Wood logs to pulp and paper mills[1] (km)		Wood chips to pulp and paper mills[1] (km)		Recovered fiber to pulp and paper mills[1] (km)			Chemicals[1] (km)				Purchased hogged fuel, other biomass[1] (km)	All other fuels[1] (km)
Commodity	*Truck*	*Train*	*Truck*	*Train*	*Truck*	*Train*	*Boat, barge*	*Truck*	*Train*	*Boat, barge*	*Boat, ocean*	*Truck*	*All*
Apples	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	See U.S. LCI database (NREL 2012)
Carrots	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	
Grapes	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	
Lettuce	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	
Onions	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	
Oranges	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	
Strawberries	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	
Tomatoes	159	1,580	299	1,670	241	505	82 2	217	1,300	674	2,990	145	

	Containerboard to converting[1] (km)		Corrugated sheets[1] (km)		Manufacturers to growers[1] (km)		Growers to retailers[2] (km)	Retailers to end-of-life[1] (km)		
Commodity	*Truck*	*Train*	*Truck*	*Train*	*Truck*	*Train*	*Truck*	*Truck*	*Train*	*Boat, barge*
Apples	262	1,510	283	2,450	283	2,446	2,498	241	505	2,256
Carrots	262	1,510	283	2,450	283	2,446	2,806	241	505	2,256
Grapes	262	1,510	283	2,450	283	2,446	2,827	241	505	2,256
Lettuce	262	1,510	283	2,450	283	2,446	2,721	241	505	2,256
Onions	262	1,510	283	2,450	283	2,446	2,599	241	505	2,256
Oranges	262	1,510	283	2,450	283	2,446	2,827	241	505	2,256
Strawberries	262	1,510	283	2,450	238	1,849	2,827	241	505	2,256
Tomatoes	262	1,510	283	2,450	238	1,849	2,827	241	505	2,256

[1]Sourced from NCASI (2017); Original source is USDOT and USDOC 2010.

[2]Calculated based on USDA 2017 and U.S. Census Bureau 2012.

Table A- 9: Transport distances used in the minimum and maximum transport sensitivity analysis for the CC system

	Growers to retailers[1] (km)	
Commodity	*Minimum*	*Maximum*
Apples	1,420	3,408
Carrots	589	4,435
Grapes	349	4,689
Lettuce	479	4,439
Onions	874	4,190
Oranges	349	4,689
Strawberries	349	4,689
Tomatoes	349	4,689

[1]Calculated based on USDA 2017 and U.S. Census Bureau 2012.

Table A- 10: Transport distances used in the baseline analysis for the RPC system

	PP Resin to RPC production (tkm per 1 kg RPC)		RPC production to growers[1] (km)		Growers to (distributors and) retailer (km)		Collection (Retailer/Retailer & Distributor) to Washing center (km)		Washing Center to Growers (km)		Retailer to end-of-life (km)			
Commodity	***Truck***	***Source***	***Truck***	***Source***	***Truck***	***Source***	***Truck***	***Source***	***Truck***	***Source***	***Truck***	***Train***	***Boat, barge***	***Source***
Apples	1.863	FA (2017)	1,115	FA (2017)	2,498	multiple[2]	2,472	estimate[3]	1,121	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Carrots	1.863	FA (2017)	1,115	FA (2017)	2,806	multiple[2]	2,562	estimate[3]	505	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Grapes	1.863	FA (2017)	1,115	FA (2017)	2,827	multiple[2]	2,554	estimate[3]	187	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Lettuce	1.863	FA (2017)	1,115	FA (2017)	2,721	multiple[2]	2,554	estimate[3]	513	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Onions	1.863	FA (2017)	1,115	FA (2017)	2,599	multiple[2]	2,001	estimate[3]	544	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Oranges	1.863	FA (2017)	1,115	FA (2017)	2,827	multiple[2]	2,554	estimate[3]	468	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Strawberries	1.863	FA (2017)	1,115	FA (2017)	2,827	multiple[2]	2,554	estimate[3]	468	estimate[3]	241	505	2,256	USDOT & USDOC 2010
Tomatoes	1.863	FA (2017)	1,115	FA (2017)	2,827	multiple[2]	2,554	estimate[3]	468	estimate[3]	241	505	2,256	USDOT & USDOC 2010

[1]Plastics and rubber manufacturing data used as a proxy; [2]Calculated based on USDA 2017 and U.S. Census Bureau 2012; [3]Estimated based on Franklin Associates, "FA" (2017) and consultation with RPC industry experts.

Table A- 11: Transport distances used in the minimum distance sensitivity analysis for the RPC system

	PP resin to RPC (km)		RPC production to growers[1] (km)		Growers to retailers (km)		Collection (Retailer/Retailer & Distributor) to washing center (km)		Washing Center to Growers (km)		Retailer to end-of-life[3] (km) production[1]			
Commodity	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Train*	*Boat, barge*	*Source*
Apples	1.863	FA (2017)	1,115	USDOT & USDOC 2010	1,420	multiple[2]	1,345	estimate[4]	405	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Carrots	1.863	FA (2017)	1,115	USDOT & USDOC 2010	589	multiple[2]	972	estimate[4]	274	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Grapes	1.863	FA (2017)	1,115	USDOT & USDOC 2010	349	multiple[2]	1,036	estimate[4]	37	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Lettuce	1.863	FA (2017)	1,115	USDOT & USDOC 2010	479	multiple[2]	1,036	estimate[4]	350	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Onions	1.863	FA (2017)	1,115	USDOT & USDOC 2010	874	multiple[2]	1,473	estimate[4]	484	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Oranges	1.863	FA (2017)	1,115	USDOT & USDOC 2010	349	multiple[2]	1,036	estimate[4]	37	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Strawberries	1.863	FA (2017)	1,115	USDOT & USDOC 2010	349	multiple[2]	1,036	estimate[4]	37	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Tomatoes	1.863	FA (2017)	1,115	USDOT & USDOC 2010	349	multiple[2]	1,036	estimate[4]	37	estimate[4]	241	505	2,256	USDOT & USDOC 2010

[1]Plastics and rubber manufacturing data used as a proxy; [2]Calculated based on USDA 2017 and U.S. Census Bureau 2012; [3]Waste and scrap data used as a proxy; [4]Estimated based on consultation with industry experts.

Table A- 12: Transport distances used in the maximum distance sensitivity analysis for the RPC system

	PP resin to RPC production[1] (km)		RPC production to growers[1] (km)		Growers to retailers (km)		Collection (Retailer/Retailer & Distributor) to washing center (km)		Washing Center to growers (km)		Retailer to end-of-life[3] (km)			
Commodity	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Train*	*Boat, barge*	*Source*
Apples	1.863	FA (2017)	1,115	USDOT & USDOC 2010	3,408	multiple[2]	3,766	estimate[4]	1,833	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Carrots	1.863	FA (2017)	1,115	USDOT & USDOC 2010	4,435	multiple[2]	4,244	estimate[4]	2,526	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Grapes	1.863	FA (2017)	1,093	USDOT & USDOC 2010	4,689	multiple[2]	4,174	estimate[4]	1,244	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Lettuce	1.863	FA (2017)	1,115	USDOT & USDOC 2010	4,439	multiple[2]	4,174	estimate[4]	2,253	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Onions	1.863	FA (2017)	1,115	USDOT & USDOC 2010	4,190	multiple[2]	3,518	estimate[4]	2,568	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Oranges	1.863	FA (2017)	1,115	USDOT & USDOC 2010	4,689	multiple[2]	4,174	estimate[4]	2,526	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Strawberries	1.863	FA (2017)	1,115	USDOT & USDOC 2010	4,689	multiple[2]	4,174	estimate[4]	2,526	estimate[4]	241	505	2,256	USDOT & USDOC 2010
Tomatoes	1.863	FA (2017)	1,115	USDOT & USDOC 2010	4,689	multiple[2]	4,174	estimate[4]	2,526	estimate[4]	241	505	2,256	USDOT & USDOC 2010

[1]Plastics and rubber manufacturing data used as a proxy; [2]Calculated based on USDA 2017 and U.S. Census Bureau 2012; [3]Waste and scrap data used as a proxy; [4]Estimated based on consultation with industry experts.

Appendix B: Model approach and assumptions

B1. RPC float

Float refers to the quantity of excess RPCs that exist in the total system. These excess RPCs are required to assure flexibility to respond to surges in system demand or extended time in the return loop. Float can be considered as a type of infrastructure that needs to be constructed to enable the system to function. It can be thought of as what is needed to "prime" the system, like how a pipe system is primed. Take, for example, a toilet. The bowl contains the water that is used to carry out the system's function, while the tank contains the water that facilitates the function. When the toilet is first installed, both the bowl and the tank must be filled. The tank then replenishes the bowl over time. The bowl is analogous to the in-use RPCs, while the tank represents the float. The float must be produced only once, and new RPCs enter and leave the system as containers are worn out, broken or lost. Over time, as more containers are put through the system, the significance of providing that initial excess capacity or "float" diminishes with regard to the total impact of all containers that have been put through the system.

As indicated by publications describing the container industry as well as other industries where float is required (e.g., the refillable bottle industry), float is indeed a non-negligible percentage of all containers within the system at any given time (Saphire 1994, Pira and ECOLAS 2004). However, it is important to remember that while the initial float is established at the onset of the industry to enable its operation, some level of replenishment occurs over time due to breakage, loss, and recycling. This replacement process maintains the float rather than constituting a continuous expansion of it. Therefore, the relevant ratio to consider is not float to current in-use containers but rather float to the entire container inventory over the lifetime of the RPC industry. Assuming that the industry will exist for many years, the mass of RPCs needed for replenishment remains small in comparison to the total mass of all containers ever manufactured.

Since the size of float within the industry is not well documented and the total number of RPCs to be manufactured is unknowable, it is not possible to include the float component in the system or to conduct a scenario analysis around its inclusion based on reliable information. In the present study, it is assumed that the float required for the RPC system is less than one percent (1%) of all RPCs and therefore can be excluded. However, because the float is so poorly understood, it is important to explore a less conservative scenario to assess whether the float could have an important effect on the outcomes of this study.

Consider a hypothetical scenario in which for every RPC in use, one is in float (Figure B-1). (This assumption is likely a worst-case approach, but no resources could be identified by the authors with which any assumption can be made.) This means that to fulfill the functional unit, two RPCs must be made for each RPC needed. The impact of this could be calculated by doubling the impacts at the RPC production stage.

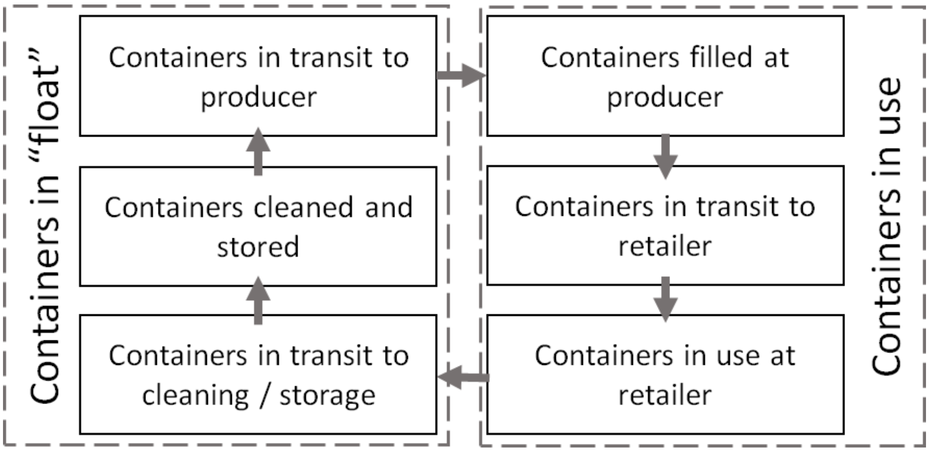

Figure B- 1: Illustration of the movement of RPCs in use and in float over time.

B2. Recycled material

This appendix provides further explanation and insight into the treatment of recycled materials in this study. As discussed in section 2.5.3, the main principle applied is a closed loop approach which is mathematically equivalent to the number of uses approach. One exception exists in the case of recovered OCC that are exported to other markets. This flow is modeled using a cut-off approach as it is not within the scope of the current study to assess the fate of the CCs once they leave the U.S. market.

Had these CCs been included in the model, the number of uses approach would have been employed in the baseline analysis. The concept of this approach is to evaluate the number of uses or lives (i.e., number of separate product systems) a material is likely to undergo before meeting a final disposal (e.g., landfill or incineration) and to distribute the material production impacts across these. A key assumption in applying the number of uses approach is identifying the number of uses of the material under evaluation. This can be done in different ways.

In the case of paper products such as CCs, methods for making such an evaluation have been presented in several places. Originally, in 1996, The International Working Group issued "Life Cycle Inventory Analysis. User's Guide," a TAPPI publication. In that publication, the "number of uses" formula was first described. Later, ISO/TR 14049 (ISO 2012a, 2nd edition), and a specific treatment for containerboard by Galeano et al. (2011) reflected similar approaches. The latter of these references emphasizes the relevance of this approach for systems, such as paper, where desired physical properties of the material are retained in the recycling process.

The approach for calculating the number of uses may vary depending on the amount of data available on recycling rates and knowledge about how these materials flow in the economy. Examples on how to calculate the number of uses under different data availability circumstances were presented in ISO 14049 standard, as are examples for handling the allocation (sharing) between the original and the subsequent uses. In addition to estimating the number of uses from industry data on recycling rates, the referenced User's Guide and the ISO 14049 standard illustrates estimates of number of uses based on laboratory testing of materials indicating the limits in the number of times recycling can take place before essential material structure is altered in the successive recycling process. Allocation of the burdens among virgin (original) product and subsequent uses is described.

In the case of the plastics used for RPCs, no adequate industry average exists of the same reliability as in CC and neither is there laboratory or pilot experimental work. Therefore, a theoretical model alone is used to derive the number of lives (product systems) for the material, as explained below.

Figure B-2 presents a depiction of a material undergoing multiple products lives prior to its eventual disposal. If the material is used for N number of products, 1/Nth of the raw material and waste responsibilities would be attributable to each product life.

The number of lives that a material will undergo before its final disposal is determined by the rate of recovery of that material from each of the product systems it enters. If the same percent of material is recovered (C) from one product life and used in the next life over the lifetime of the material, the number of uses can be calculated as:

$$\text{Number of lives} = N = 1 / (1-C)$$

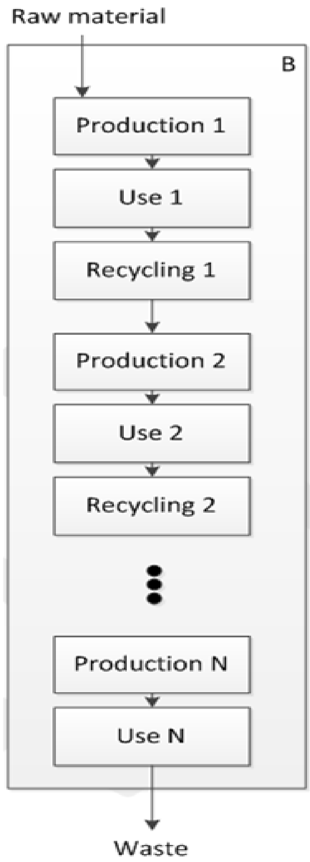

Figure B- 2: Representation of a material undergoing several products lives prior to its disposal.

An alternate method for determining the allocation of material production across multiple lives is the "closed loop" representation, which is depicted in Figure B-3 and discussed further in ISO 14049 and Bauman and Tilman (2004), among other places. This is the approach taken in the present study for the RPC system and for the CCs that are not exported to other markets. In applying this approach, the amount of material recovered is represented as being re-used in the same product system, actually or virtually replacing the virgin production of that material. In this case, C in Figure B-3 represents the amount recovered and sent to recycling (also termed C in the above discussion of calculation of the number of lives).

We can see that if the collection rate is the same between all lives of the material, these two representations of the recycling system produce the same result. In the case of the number of lives calculation, the allocation of virgin material impact is equal to 1/N, which is shown in the equation above to be equal to (1-C). In the case of the closed loop recycling, the virgin material impact is equal to the flow of A in Figure B-3 which is also (1-C). Therefore, the results shown here could also be considered to be the results obtained through application of a closed loop recycling allocation method.

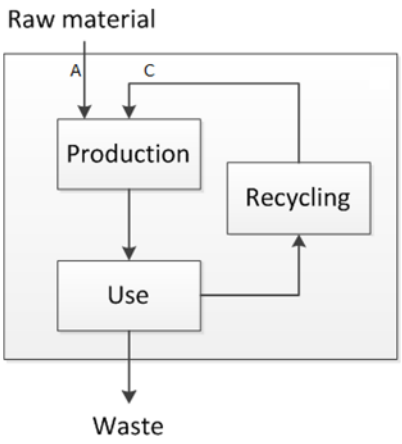

Figure B- 3: Generic closed-loop product system diagram with recycling.

B3. Carbon balance

Figure B-4 depicts the flow of biogenic carbon through the CC system. Although these flows are ignored in impact assessment, except for carbon sequestered beyond 100 years, the balance is presented for transparency. The net total (inputs minus outputs) is not zero due to rounding errors. Additional details on carbon flows, including greater resolution in Materials & production, can be found in NCASI (2023).

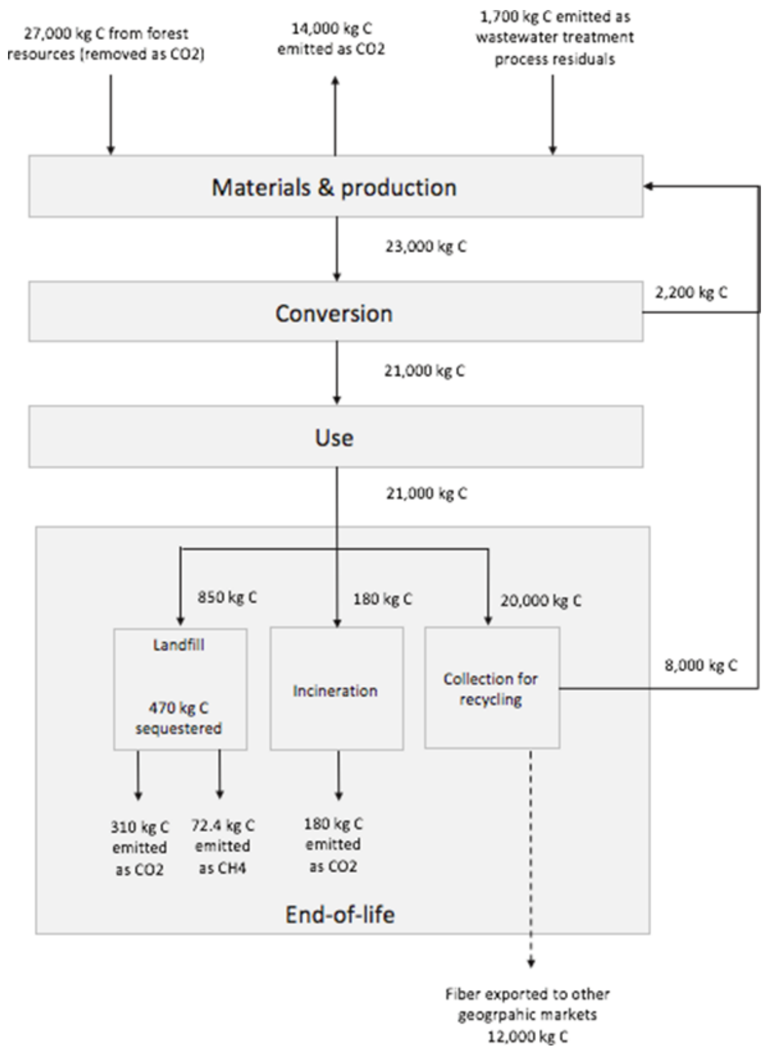

Figure B- 4: Biogenic carbon balance for the CC system includes only major flows of carbon.

Appendix C: Full results

Please refer to the associated Excel file.

Appendix D: Comparison to previous studies

While it is not a goal of this study to conduct a literature review of comparable LCAs or to fully understand the potential reasons for similarities and differences between studies, it is worth considering findings from prior relevant work to understand the spectrum of conclusions drawn on the topic of the comparative environmental performance of CCs and RPCs. The following two paragraphs offer a very high-level summary of some relevant literature in this space. Sections D1 and D2 provide a deeper dive into each study with a focus on Franklin Associates (2017) as the study has a scope particularly similar to the present study.

This study differs from previous life cycle studies comparing RPCs and CCs in several key ways. Specifically, it focuses on the North American market and incorporates an internationally recognized impact assessment method (TRACI 2.1) together with an equally recognized alternate (ReCiPe 2016). Levi et al. (2011), the University of Stuttgart (2007) and Rizo (2005) focus on the Italian, Spanish and European markets, respectively. Three studies of the North American market, Franklin Associates (2004), Franklin Associates (2013), and Franklin Associates (2017) are useful references regarding the appropriate geographical context but are limited in scope. The 2004 study by Franklin Associates includes only the inventory stage of analysis and is therefore not a valid basis for comparisons. Franklin Associates (2017) is the most appropriate study to compare the results found in the present LCA.

Except in the cases of Franklin Associates (2017) and the University of Stuttgart (2007), the consistent conclusion of each of these prior studies is that there are trade-offs between the container types. Franklin Associates (2017) and the University of Stuttgart (2007) show a very different result, concluding that in every metric evaluated, RPCs are environmentally advantageous, or no significant difference exists between CCs and RPCs. They are the only such studies that consequently do not find the existence of trade-offs between the systems.

D1. Comparison with Franklin Associates (2017)

The study offered by Franklin Associates (2017) is most similar to the present study with regard to context and approach. Additionally, the present study employs much of the data describing the RPC life cycle provided by Franklin Associates (2017), as cited throughout this report. It is thus the most comparable study to-date and can be compared at a more granular level than for other studies. Table D-1 summarizes the differences between the present study and the Franklin Associates (2017) study in terms of model inputs and offers some insight regarding how these disparities affect the conclusions reached by each study. Additional explanation is provided in the subsections that follow. It is recognized that a deeper comparison of the studies could be performed. This exercise is beyond the scope of the current analysis.

Table D-1: Summary of differences in data and assumptions between the Franklin Associates (2017) study and present study and the implications of these differences on study results.

Data/ Assumption	Franklin Associates 2017's approach	Present study's approach	Implications of difference
Inventory data: foreground processes	CC system: Based on 2010 industry operations RPC system: Based on data provided by IFCO	CC system: Based on 2020 industry operations RPC system: Same as Franklin Associates (2017)	As per NCASI (2023), containerboard industry operations were stable from 2010-2014, with the exception of significant reductions in respiratory effects and water use. Franklin Associate (2017) overestimates CC system impacts for these indicators.
Inventory data: background processes	Primarily the USLCI 2012 Database; Some data from Ecoinvent v2.2 for materials production, adjusted to align with the (less complete) USLCI Database	Primarily Ecoinvent v3.10	The impacts for both container systems are likely underestimated by Franklin Associates. The improved ecoinvent impacts for materials and transportation over the years
CC recycled content (kg recycled fiber per kg containerboard)	38.4%	31.8%	Updated based on NCASI 2023
RPC cleaning process	Based on technology used by IFCO facilities	Same as Franklin Associates (2017), except for amounts of electricity, detergent and water used. Present study uses composite values for these inputs based 70% on the Franklin Associates (2017) process and 30% on a less efficient process.	The present study will show a higher impact for the cleaning process if the background databases are the same. Since the composite process is based primarily on the Franklin Associates (2017) process, the difference is relatively small.
Interpretation approach	Concludes based on the market-weighted average. Arbitrarily assigns a flat amount (%) of difference required to conclude a significant difference exists between results of the two container systems; Does not consider statistical uncertainty or uncertainty of individual indicators.	Concludes based on all results for individual commodities. Considers statistical uncertainty and indicator uncertainty when drawing conclusions.	The Franklin Associates (2017) study loses some resolution and insight by concluding based on an aggregated level of results. The present study applies a more objective approach to interpreting results.

D1.1 Approach

Franklin Associates (2017) and the present study both compare RPCs to CCs used to transport and display produce[18], considering all life cycle stages: raw material production, use, re-use (for RPCs), and end-of-life. Franklin Associate (2017) considers delivery to Canada as well as the U.S., while the present study is limited to the U.S.

Both studies apply closed-loop modeling. Franklin Associates (2017) represents the system as an entirely closed loop, while the present study applies a closed loop only to the portion of recovered fiber that stays on the U.S. market. The present study cuts off the exported fiber once it is recovered from the US market.

With regard to modeling the end-of-life of materials, both studies apply a type of system expansion approach. Franklin Associates (2017) uses the avoided burden method, providing credits for producing recycled material and capturing energy during incineration. The present study employs the number of uses method for the closed loop portion of the system, also applying credits for recycling and waste-to-energy, and cuts off the exported fiber once it is recovered. Franklin Associates (2017) implements a second method, the cut-off method, as a sensitivity analysis, finding no difference in study conclusions. The present LCA does not conduct a sensitivity analysis regarding end-of-life modeling since, under closed-loop conditions, the number of lives method (plus credits) and avoided burden method should yield approximately equivalent results. This is true for the closed-loop portion of a system. It is not possible to test the cut-off approach regarding the exported fiber as the fate of that material is outside the scope of this study (see section 2.5 for further explanation).

Biogenic carbon is treated nearly the same in the two studies, both studies using the flows approach (see section 3.1.2). However, Franklin Associates (2017) treats the flow of biotic carbon dioxide as net zero. The present study also ignores biogenic carbon, except for long-term (>100 years) sequestration of carbon in a landfill. Both studies count the impact of other biotic carbon sources [i.e., methane that is a product of fiber (CC) degradation].

[18] Franklin Associate (2013) also evaluates non-display-ready (NDR) CCs, the results of which are not considered here.

D2. Comparison with NCASI study

The present study also incorporates updated modeling data for CCs based on the NCASI (2023) study, allowing for a comparison against CC modeling based on 2014 data which was referenced in the Quantis (2019) study. Figure D-1 highlights the differences between CC modeling in the present study, based on 2020 data, and the previous 2014 data used in Quantis (2019). Both datasets are compared relative to the RPC system modeled in this study using Franklin Associates (2017) data.

The observed differences between CC system impacts are primarily due to methodological updates and differences in the LCI databases rather than changes in operations. The present study uses ecoinvent v3.10, which incorporates updated emissions data, resource use, and process improvements, whereas the Quantis (2019) study relied on ecoinvent v3.3. These updates in databases and methodologies account for the variations in impact categories, with both increases and decreases observed across the results.

The updates in NCASI (2023) data ensure more accurate representation of current industry practices for the containerboard system. While these advancements provide greater confidence in CC modeling, the comparison highlights the ongoing reliance on legacy RPC data from Franklin Associates (2017). The consistent use of RPC data emphasizes the importance of maintaining methodological consistency for comparability, although future updates for RPC modeling are recommended to ensure alignment with current practices.

By incorporating 2020 CC system data and ecoinvent v3.10, the present study provides a more accurate and up-to-date representation of containerboard's environmental impacts. While the directional trends remain consistent with the 2014 CC results, except for smog formation given the uncertainty in its composition and contributing factors, the observed differences emphasize the importance of refined methodologies and updated databases in ensuring robust and reliable impact assessments.

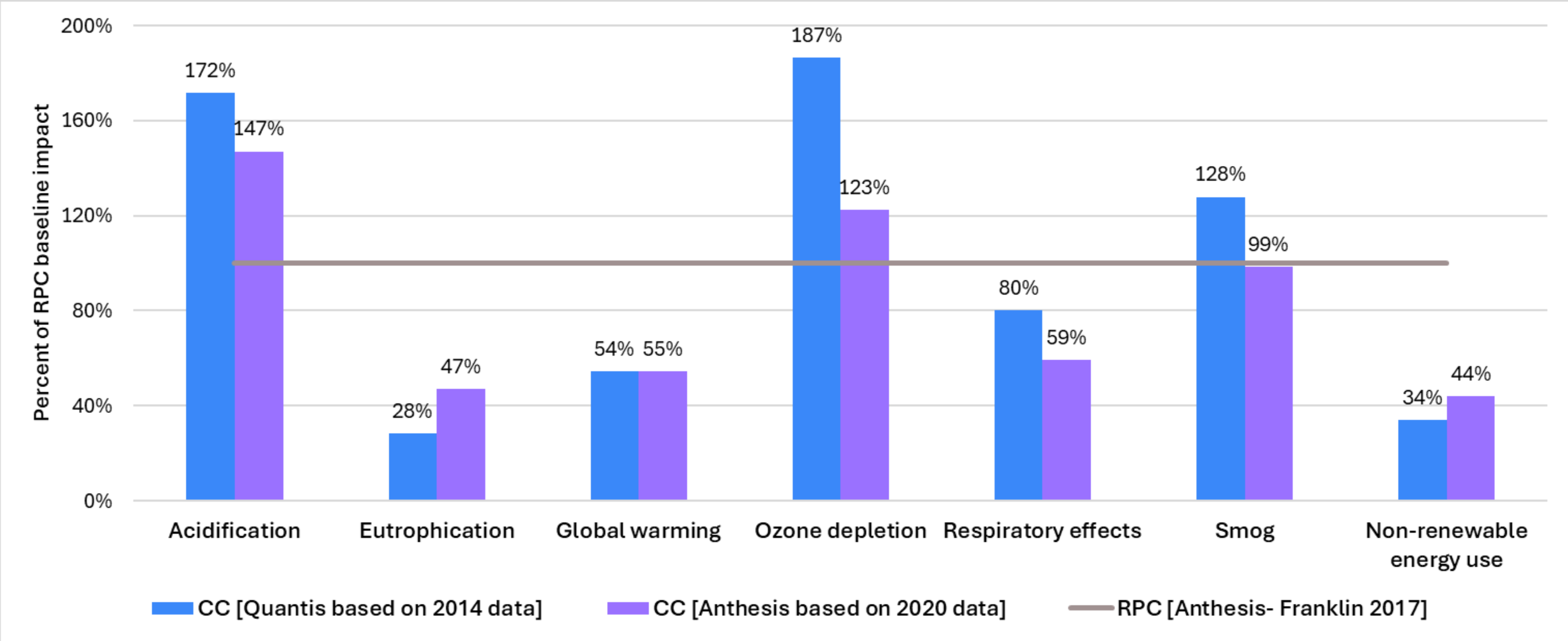

Figure D- 1: Comparison of Current Study Using NCASI 2020 Data with Quantis Study Using NCASI 2014 Data for CC Modeling Relative to RPC Baseline. For each indicator, a score higher than 100% indicates greater impact than the RPC baseline results.

Appendix E: Critical review report and comment log

The following pages include the critical review statement and the reviewer attestation for this study.

Lisa A. Peterson, PhD, PE
LCA Review Panel Chair
839 Alleghenyville Rd
Mohnton, PA 19540
610-914-1356

April 24, 2025

Critical Review Statement for the LCA Study:

"LIFE CYCLE ASSESSMENT OF CORRUGATED CONTAINERS AND REUSABLE PLASTIC CONTAINERS FOR PRODUCE TRANSPORT AND DISPLAY"

Version: 1.4

Dated: April 22, 2025

Commissioned by: Corrugated Packaging Alliance/Fibre Box Association

Prepared by: Anthesis Consulting Group Ltd

Review Panel:

Lisa Peterson, PhD, PE (Panel Chair)
Owner
Aftan Engineering, LLC

Bradley Kurzynowski
Fiber Manager
Sustainable Packaging Coalition

Richard Venditti, PhD
Elis Signe Olsson Professor, Forest Biomaterials, Paper Science and Engineering
NC State College of Natural Resources

The members of the critical review panel were chosen to ensure the required LCA competence and expertise in the scientific and technical aspects of the studied product system. All three panel members are independent external experts.

References:

International Organization for Standardization. (2006). Environmental management -- Life cycle assessment – Principles and framework (ISO 14040:2006).
International Organization for Standardization. (2006). Environmental management -- Life cycle assessment -- Requirements and guidelines (ISO 14044:2006).

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International Organization for Standardization. (2014).
Environmental management -- Life cycle assessment -- Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006. (ISO/TS 14071:2024).

The scope of the critical review:

The review panel has the task to assess whether:

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 (2006) and ISO 14044 (2006)
- the methods used to carry out the LCA are scientifically and technically valid
- the data used are appropriate and reasonable in relation to the goal of the study
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The full analysis of individual datasets and calculations underlying the results was outside the scope of this review. Nonetheless, datasets as noted in Appendix A were reviewed.
This review statement is valid for the final version (V1.4) of the report dated April 22, 2025.

The review was performed at the conclusion of the study over three rounds of commenting by the panel between 01/23/2025 and 04/22/2025. The review resulted in a total of 256 comments of editorial nature (65%) and general, scientific, or technical nature (35%) from the review panel. Of the general, scientific, and technical comments, 30 of the comments (12%) were confirmations of ISO requirements being met, requiring no modifications or actions on the part of the LCA practitioner. The review panel found the LCA practitioner's responses to each issue to be satisfactory and complete. The comments and their processing are available as an excel file from Anthesis upon request. As per ISO 14040:2006, clause 7.1, this critical review neither verifies nor validates the goals chosen for the LCA, nor the ways in which the LCA results are used.

General remarks
The study uses LCA to perform a quantitative study comparing corrugated containers and reuseable plastic containers for the transport and display of eight types of produce in the United States. The scope of the LCA study is found to be appropriate and in accordance with the goal of the study. The study relies on a combination of primary data, prior work, publicly available resources, and expert insights. Overall, the analysis is found to be adequate and the handling of uncertainty analysis satisfactory to substantiate the conclusions regarding the environmental impacts of the categories defined in the goal and scope.

Lisa A. Peterson, PhD, PE
LCA Review Panel Chair
839 Alleghenyville Rd
Mohnton, PA 19540
610-914-1356

Conformance Statement

Overall, the critical review finds the methodology to be clearly defined and the modeling assumptions to be well documented and explained. The methods used to carry out the LCA are scientifically and technically valid. The use of data is appropriate and reasonable in relation to the goal of the study. The quality of the chosen methodology and its application in the analysis is adequate for the purposes of the study. The reporting of the study and its results is transparent and consistent. The interpretation and discussion of the results covers the relevant aspects in accordance with the goal of the study, and the conclusions are clearly expressed in relation to the results and in accordance with the defined goal. The study was determined to be in conformance with the applicable ISO standards.

Lisa Peterson, PhD, PE	Bradley Kurzynowski	Richard Venditti, PhD
Aftan Engineering, LLC	Sustainable Packaging Coalition	North Carolina State Univ

Self declaration of reviewer independence and competencies (ISO/TS 14071)

Re: Life Cycle Assessment of Corrugated Containers and Reusable Plastic Containers for Produce Transport and Display, Version 1.4, April 22, 2025

Practitioner: Anthesis Group

Commissioner: Fibre Box Association

I, Lisa A. Peterson, hereby declare that:

1) I am an external reviewer; and I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study.
2) I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study.
3) I do not have a vested financial, political, or other interest in the outcome of the study.

My competencies relevant to the critical review include knowledge of and proficiency in:

1) ISO 14040 and ISO 14044;
2) LCA methodology and practice;
3) Critical review practice;
4) Scientific disciplines relevant to the impact categories of the study;
5) Environmental, technical, and other relevant performance aspects of the product system assessed; and
6) English language used for the study.

I declare that the above statements are truthful and complete. I will immediately notify commissioner, practitioner, and fellow reviewers of the study if the validity of any of these statements changes during the review process.

Lisa A Peterson

Lisa A Peterson (signed April 24, 2025)

To learn more about Aftan Engineering and the other things we do in support of environmental modeling, ergonomic and automation solutions for industry, and continuous improvement consulting, check out our webpage at www.aftansustainability.com

Best wishes for a sustainable future which includes planet, people and profit. Three cheers for our planet, our health and our prosperity.

Self declaration of reviewer independence and competencies (ISO/TS 14071)

Re: Life Cycle Assessment of Corrugated Containers and Reusable Plastic Containers for Produce Transport and Display, Version 1.4, April 22, 2025

Practitioner: Anthesis Group

Commissioner: Fibre Box Association

I, Bradley Kurzynowski, hereby declare that:

1) I am an external reviewer; and I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study.
2) I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study.
3) I do not have a vested financial, political, or other interest in the outcome of the study.

My competencies relevant to the critical review include knowledge of and proficiency in:

1) ISO 14040 and ISO 14044;
2) LCA methodology and practice;
3) Critical review practice;
4) Scientific disciplines relevant to the impact categories of the study;
5) Environmental, technical, and other relevant performance aspects of the product system assessed; and
6) English language used for the study.

I declare that the above statements are truthful and complete. I will immediately notify commissioner, practitioner, and fellow reviewers of the study if the validity of any of these statements changes during the review process.

Bradley Kurzynowski (signed April 24, 2025)

Self declaration of reviewer independence and competencies (ISO/TS 14071)

Re: Life Cycle Assessment of Corrugated Containers and Reusable Plastic Containers for Produce Transport and Display, Version: 1.4, April 22, 2025.

Practitioner: Anthesis Group

Commissioner: Fibre Box Association

I, Richard A. Venditti, hereby declare that:

1) I am an external reviewer; and I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study.
2) I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study.
3) I do not have a vested financial, political, or other interest in the outcome of the study.

My competencies relevant to the critical review include knowledge of and proficiency in:

1) ISO 14040 and ISO 14044;
2) LCA methodology and practice;
3) Critical review practice;
4) Scientific disciplines relevant to the impact categories of the study;
5) Environmental, technical, and other relevant performance aspects of the product system assessed; and
6) English language used for the study.

I declare that the above statements are truthful and complete. I will immediately notify commissioner, practitioner, and fellow reviewers of the study if the validity of any of these statements changes during the review process.

Rich Venditti

Richard A. Venditti (signed April 24, 2025)