Life Cycle Assessment of Milk Packaging in Canada: Evaluating Reusable Packaging under Prospective Energy Grid Scenarios

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Keywords: Milk Packaging, Life Cycle Assessment, Circular Economy, Single-Use Plastics, Energy Transitions

Plastic pollution remains a persistent environmental challenge in Canada, prompting growing policy attention toward single-use plastics. Yet, the life cycle implications of shifting materials or adopting reuse systems for food products, specifically milk packaging, are not well understood. This thesis conducts an ISO 14040/14044 aligned attributional life cycle assessment (LCA) comparing the environmental impacts of refrigerated milk packaging in Canada, including high-density polyethylene (HDPE) jugs, polyethylene terephthalate (PET) bottles, plastic milk pouches, liquid packaging board cartons, and glass bottles in both single-use and reusable systems. The functional unit is 12-L of pasteurized, refrigerated dairy milk. System boundaries are from cradle-to-grave for single-use formats and cradle-to-cradle for reuse scenarios, modeled in openLCA using the ecoinvent database and ImpactWorld+ impact methodology. Baseline packaging impacts are examined under current grid and recycling rates, and a scenario analysis is conducted under a prospective 2050 net-zero grid in Canada. Results show the packaging production stage dominates overall life cycle impacts, with lightweight flexible plastic milk bags performing best across most impact categories. Single-use glass exhibits the highest environmental impacts, while reusable glass shows improvement with increased reuse, though sanitization and transportation remain critical contributing stages as reuse increases. Under a decarbonized grid, reusable systems glass systems outperform select single-use packaging types but rarely surpass reusable plastic systems. Grid decarbonization improves electricity-intensive processes and strengthens relative performance of glass reuse, but does not outperform the advantages of lightweight, plastic-based systems. However, results are limited by data quality, availability, and quantification of microplastic impacts. Findings indicate that achieving circular packaging outcomes depends less on material substitution and more on system design. This study contributes novel, Canada-specific insight in how grid decarbonization and reuse interact in determining sustainable packaging strategy.

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List of Abbreviations

GHG	Greenhouse gas
GWP	Global Warming Potential
FNEU	Fossil fuel and nuclear energy use
HDPE	High-density Polyethylene
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LDPE	Low-density Polyethylene
LLDPE	Linear Low-density Polyethylene
LPB	Liquid Packaging Board
PET	Polyethylene Terephthalate
SUPs	Single-use Plastics
SMAA	Stochastic Multi-Attribute Analysis

1 Chapter – Introduction

Single-use plastics (SUPs) are increasingly used, contributing to global and intergenerational environmental impacts at an increasing pace (Borrelle et al., 2020; Diggle & Walker, 2022; Walker & Fequet, 2023). The plastics industry is a notable contributor to global greenhouse gas (GHG) emissions, a significant climate change driver, largely driven by plastic manufacturing processes (Cabernard et al., 2022; OECD, 2023; Shen et al., 2020). As consumption rates for single-use plastics continue to increase, the potential severity of their impacts is reflected in nationwide legislation limiting or banning their production (Ahmadi et al., 2023; Walker & Fequet, 2023). This legislation is exemplified in Canada's federal policy commitment, with the implementation of the Single-Use Plastics Prohibition Regulations in 2022 and overarching Strategy on Zero Plastic Waste in 2018 (Government of Canada, 2022). These regulations stem from increasing scientific literature and awareness regarding the negative impacts of plastics within the natural environment, in the form of microplastics and other associated effluents from production (Environment and Climate Change Canada & Health Canada, 2020).

Food packaging is one of the contributors to single-use plastic use and waste, making up approximately 60% of single-use plastics (Dey et al., 2021; Kan & Miller, 2022; Lewanska & Barczynska, 2025). The durability, low weight, and low cost have popularized SUP for their use in food packaging (Dey et al., 2021). Within the food sector, milk packaging is plastic-dominant, including paperboard cartons which feature plastic layering (Burek et al., 2018). Liquid milk is a continuing cornerstone of Canadian diets (Government of Canada, 2002). Furthermore, milk substitutes (e.g. soy beverages) are also increasingly being consumed in recent years (Auclair et al., 2019), and are provided to consumers in similar types of packaging. In this way, milk packaging presents itself as a unique subject to understand the environmental impacts of SUP food packaging and its material alternatives in Canada.

Life cycle assessment (LCA), a biophysical accounting tool, was originally developed for use on product life cycles (Bjørn et al., 2018; Hunt et al., 1996) to estimate the environmental impacts of products and services across the supply chain. The ISO's 14040/14044 guidelines and standards to LCA set the framework to ensure a rigorous, transparent, and systematic approach to

LCA (Finkbeiner, 2014). These standards outline four phases for an LCA (ISO, 2006a): selecting the goal and scope; collecting, validating, and relating data in the inventory analysis; evaluating the impact assessment results; and interpreting the impact assessment results in relation to the study's goal, scope, and limitations.

Recent studies have used LCA to quantify and interpret the environmental impacts of various types of milk packaging (Bertolini et al., 2016; Cappiello et al., 2022; Fry et al., 2010; Stefanini et al., 2021; Sun et al., 2021a). Nevertheless, studies are not conclusive on the least impactful material, as milk packaging types vary geographically, and study assumptions differ between authors (Food and Agriculture Organization of the United Nations, 2010; Miller, 2022). However, many studies have found that the manufacturing phase is among the most impactful phases of the packaging's life cycle (Brock & Williams, 2020; Cappiello et al., 2022; Fry et al., 2010; Stefanini et al., 2021).

Several studies find differing results on which plastic packaging has the highest impacts, while many LCA studies are united in finding that single use and reusable glass milk bottles have the highest overall impact of available milk packaging options (Brock & Williams, 2020; Cappiello et al., 2022; Stefanini et al., 2021). Similarly to plastic packaging, the manufacturing phase dominates the impacts as a result of high energy use (Fry et al., 2010). Although glass bottles can be designed for multiple reuse cycles, in practice this does not always occur, ending up in landfill or being recycled after a single use. When they are reused, the sterilization of the bottles for reuse contributes to environmental impacts due to the use of heating for sterilization (Ferrara et al., 2021).

A consistent factor driving the life cycle environmental effects of milk packaging across all options is electricity consumption during manufacturing and other processing steps. In many jurisdictions, this electricity is still largely generated from fossil fuel sources. However, grid composition and impending energy transitions have not yet been examined extensively within LCAs of packaging.

In Canada, the energy grid composition between provinces differs substantially, from Alberta's fossil fuel-dominated grid to Quebec's hydro-dominant grid (Government of Canada, 2019). Furthermore, studies of environmental impacts of milk packaging in Canada have been restricted to Eastern provinces, with the analysis being limited to plastic containers and cartons

(e.g. Sun et al., 2021a). Considering the recent controversy surrounding the inclusion of plastic products under the Canadian Environmental Protection Act, additional research on the life cycle impacts of single-use plastics and their alternatives is needed to inform policy decision-making (Harrison et al., 2023). This policy addition is aimed at addressing plastic pollution concerns, as opposed to labelling plastics as an inherently toxic material. Given the urgent policy concerns in Canada around single-use plastics' environmental impacts, this study could be used to inform both provincial and federal single-use plastics policy and net-zero goals. However, it is important to explore the range of milk packaging used across Canada to understand the environmental impacts of a suite of packaging materials that are representative of the variations in packaging used across the ten provinces. Additionally, it is also crucial to understand how national energy transitions to meet Canada's Net-Zero by 2050 targets could affect the of various packaging types so as to provide evidence for decision making (Government of Canada, 2024).

1.1 Purpose Statement

The purpose of this study is to quantify and compare the life cycle (cradle-to-grave/cradle) environmental impacts of various milk packaging options (plastic, carton, and glass) currently used across Canada, including different end-of-life management practices. Additionally, this study develops a scenario of proposed national energy transitions by 2050 to compare the environmental impacts and trade-offs of the various packaging options into the future and examine the viability of reusable glass as an alternative to single-use and reusable plastics. Milk packaging types included in the study have been determined by packaging availability across Canada, and include: paperboard cartons, paperboard cartons with caps, high density polyethylene (HDPE) jugs, polyethylene terephthalate (PET) bottles, plastic milk pouches, and glass bottles.

1.2 Thesis Structure

This thesis is composed of four sections: 1. Introduction, 2. Literature Review, 3. Manuscript, and 4. Conclusion and Recommendations. Section 1 provides an introduction to background knowledge on the broader issue of SUPs and scopes the research problem

surrounding milk packaging. Section 2 provides a literature review on the role of SUPs in food packaging and milk packaging, in addition to a broad overview of the environmental impacts of single-use plastics. Section 3 consists of a manuscript summarizing an LCA for commonly available milk packaging in Canada and an examination of reusable milk packaging under different reuse and electricity grid scenarios. Chapter 4 presents the contribution to sustainability management and to academic literature, as well as recommendations for the development of future research and policy on these findings.

2 Chapter – Literature Review

Single-use plastics, specifically single-use food packaging, are a growing risk to the environment in the 21st century, with over 40,000 tonnes released into the environment from Canadian waste pathways in 2019 alone (S. C. Government of Canada, 2023; Walker & Fequet, 2023). Single-use plastic has distinctive qualities and performance characteristics for packaging food that creates challenges in reducing or changing materials to maintain similar performance (Kan & Miller, 2022; Marsh & Begusu, 2007). Considering the historic role of milk in Canadian diets and the rising consumption of alternative milk beverages (Auclair et al., 2019), as well as the extensive use of packaging in the food industry, milk packaging is a unique case to study. This literature review covers the following topics: the role of SUPs and alternative materials in food packaging, with emphasis on milk packaging, and the environmental impacts of single-use plastics and alternative packaging materials, including liquid packaging board and glass.

2.1 Single-Use Plastics and Alternative Materials in Food Packaging

Single-use plastics hold a key role in the composition of most food packaging available globally today, with over one third of plastic produced used in food packaging (Dey et al., 2021; Ncube et al., 2020). Food packaging materials require specific performance characteristics due to the nature of the products they are used to contain (Dey et al., 2021; Marsh & Begusu, 2007) and the different functions that packaging plays in the product life cycle. At a broader level, food packaging is designed to protect and safely contain the food, and is also an important part of the customer interface with the product, providing space for printing of labeling and product information, and its shape and design often being part of the marketing appeal for the product. Food packaging protects and preserves food until its consumption, starting from initial packaging of the food, and lasting until at least the “best before” date of the product, sometimes spanning several months, requiring its materials to be durable and long-lasting (Dey et al., 2021). Plastics feature these material characteristics, in addition to their inexpensive production costs (Ibrahim et al., 2022). The material nature of plastics allows them to be shaped into various designs, supporting ease of manufacturing and transportation (Marsh & Begusu, 2007). Materials such as paperboard and glass may present similar features, however, plastic’s low weight enables more

cost-effective transportation once produced and moved through the supply chain (Andrady & Neal, 2009). Due to its multi-functionality and attractive cost, the food packaging industry has made single-use plastics a staple in their material selection. The dominance of plastics in food systems provides important context for understanding their significant role in specific product categories such as milk, where packaging requirements further intensify reliance on plastic formats.

Similar to broader food packaging, single-use plastics have been prevalent in milk packaging since the 1930s (Karaman et al., 2015; Richmond & Stine, 1982). Due to the short shelf life of refrigerated pasteurized milk, the most pertinent material characteristics of plastic packaging are its ability to contain the milk and to provide biological protection (Rejeesh & Anto, 2023). Milk packaging commonly uses high-density polyethylene (HDPE) and polyethylene terephthalate (PET) plastics in the form of bottles or jugs (Burek et al., 2018; Food and Agriculture Organization of the United Nations, 2010). Polyethylene is also featured in single-use plastic milk pouches, which is a popular form of packaging found in a few regions around the world, including Canada (Fry et al., 2010; Sun et al., 2021a; Xie et al., 2011). The long-standing reliance on HDPE, PET, and polyethylene-based pouches underscores how milk packaging has evolved around plastic performance attributes, contrasting alternatives such as liquid packaging board-based packaging.

Liquid packaging board milk cartons, also known as gable top cartons, comprise the other share of available milk packaging; approximately half in Canada (Food and Agriculture Organization of the United Nations, 2010; Rejeesh & Anto, 2023). These are composed of paperboard and low-density polyethylene (LDPE) film, which are combined to form liquid packaging board (LPB) (Bonadies et al., 2022; Fry et al., 2010). Cartons are also available in aseptic variants which include a layer of aluminum within their construction, often called “Tetrapaks” named after its manufacturer (Bonadies et al., 2022; Rejeesh & Anto, 2023). The combination of plastic and paperboard creates challenges for end-of-life processing, specifically when attempting to recycle the mixed materials (Bonadies et al., 2022). The challenges associated with mixed materials highlight the complex trade-offs introduced by partially composed plastic alternatives compared to fully plastic systems, emphasizing considerations for single material packaging with materials like glass or bioplastics.

Most refrigerated liquid milk packaged for mass-market sale uses plastic or carton packaging; however, glass bottles are still used minimally (Błażejewski et al., 2021). While glass meets the material requirements of the packaging, its heavy weight and associated transport costs have impeded larger adoption in modern times (Ibrahim et al., 2022). This contrasts their wide use following their creation in 1884 (Karaman et al., 2015). Glass bottles can be single-use or reusable, with reusable bottles returned, sanitized, and refilled for repeated consumption (Stefanini et al., 2021). Bioplastics have also emerged as novel packaging for milk products, compatible with the goals for lightweight, durable, and resilient packaging (Cappiello et al., 2022). Together, these developments reflect a shifting selection of packaging materials wherein traditional plastics are supplemented by a growing number of alternative materials, prompting closer examination of how these materials and their different properties translate into broader environmental outcomes.

2.2 The Environmental Impacts of Single-Use Plastics

Milk packaging presents itself as a unique case study under the umbrella of single-use food packaging; however, it shares similar environmental impacts to the broad single-use plastics product category. The rise in the production and consumption of single-use plastics is creating detrimental and lasting effects on both the marine environment, and increasingly for broader climate change (Ford et al., 2022; Lavers et al., 2022; Sharma et al., 2023; Walker & Fequet, 2023). Demand for these products and their consumption can be attributed to their unique material characteristics coupled with growing trends in convenience-focused consumer habits (Walker et al., 2021). This pattern of accelerated growth for plastics appears unabated since the material's adoption in the mid-20th century, at "a compound annual growth rate of 8.4%" from its creation until 2015 (Geyer et al., 2017, p.1; Lebreton & Andrady, 2019; Walker & Fequet, 2023). While the environmental impacts of single-use plastics are spread across their life cycle, most global warming potential impacts are concentrated within their production and end-of-life pathways (Sharma et al., 2023). The extraction and processing of raw materials associated with plastics is among the larger contributors to climate change, composed of oil and gas extraction and petroleum processing (Cabernard et al., 2022). At the end of the plastic life cycle, disposal causes further environmental impacts, even when managed within existing waste systems

(Borrelle et al., 2020). Considering these trends, the production and disposal of plastics, including milk packaging, are pushing climate and other planetary boundaries towards critical thresholds, making their fossil-fuel dependence and life cycle greenhouse gas emissions a central concern (Persson et al., 2022).

The role of plastics in contributing to marine pollution and detracting from human health are increasingly recognized; however, the climate change impacts of single-use plastics must also be considered as a risk to the global environment (Ford et al., 2022). The study of microplastics, while still early, explicitly identifies the human and ecological health risks of these materials in the environment (Lewanska & Barczynska, 2025). Fossil fuels are used to produce an estimated 93% of all plastic products, with extraction of raw materials and refining being a significant GHG contributor (OECD, 2023). The emissions produced by the plastics manufacturing process are also of concern. This is due to electricity use in plastic production, which relies heavily on non-renewable energy sources, mostly natural gas and coal (Cabernard et al., 2022). In this way, single-use plastics are a multifaceted and global environmental issue.

2.3 LCA studies of packaging

The results of various comparative LCA studies of milk packaging highlight that fully plastic packaging or liquid packaging board cartons may have the lowest overall impact (Bertolini et al., 2016; Brock & Williams, 2020; Cappiello et al., 2022; Sun et al., 2021a; Xie et al., 2011). In contrast, glass bottles commonly have the highest impacts across selected impact categories (Brock & Williams, 2020; Cappiello et al., 2022; Stefanini et al., 2021). This was most apparent in climate change impact categories, with similar results across others, such as abiotic resource depletion and acidification. Additionally, the manufacturing phase is a significant hotspot for all types of milk packaging in contributing to overall potential impacts (Brock & Williams, 2020; Cappiello et al., 2022; Fry et al., 2010; Stefanini et al., 2021).

In addition to manufacturing, end-of-life processes such as landfill and recycling were identified as critical factors in determining the overall impacts of the packaging (Brock & Williams, 2020; Burek et al., 2018; Cappiello et al., 2022; Ferrara & De Feo, 2018; Fry et al., 2010; Saleh, 2016). This is because these processes can act as major contributors or mitigators of environmental impacts, whether recycling or energy recovery is modelled. Within Fry et al.'s

(2010) study, end-of-life processing reduced impacts by over 20% for select packaging in certain impact categories. These findings are supported by those from Cappiello et al.'s (2022) study in which a recycling-based end-of-life treatment heavily reduces glass packaging's impacts across climate change, eutrophication, and acidification, changing its impact ranking against other packaging types in some of these categories.

Glass bottles, when compared with plastic bottles, cartons, and plastic pouches, are consistently ranked or assessed with the highest impacts across most categories (Brock & Williams, 2020; Cappiello et al., 2022; Stefanini et al., 2021). These findings are paralleled by other beverage packaging studies, such as water bottles and wine containers (Ferrara et al., 2021; Ferrara & De Feo, 2018). Glass packaging's ranking is often far higher than its compared packaging types in environmental impacts, often two or three times the total category impacts of its competing packaging, as demonstrated in Cappiello et al.'s (2022) study. As in studies of other packaging, the glass production phase for single-use glass bottles demonstrates the highest impacts across their life cycle. In one study featuring a scenario analysis of reusable versus single-use glass, the reusable glass bottle demonstrated lower overall impacts (Stefanini et al., 2021). However, when compared to PET plastic packaging in the same study, returnable glass surpassed plastic's impacts across various impact categories (Stefanini et al., 2021). The energy-intensive sanitation process is identified as a critical stage contributing to these impacts (Stefanini et al., 2021).

Comparisons of glass milk packaging to plastic and liquid packaging board emphasizes the energy-intensive production of glass melting as a critical contributor to the packaging's overall impacts (Brock & Williams, 2020; Stefanini et al., 2021). Between plastic material variants and liquid packaging board, variability in system boundaries, impact assessment methods, and broader methodological choices may account for differences in comparative outcomes observed across various milk packaging studies. For glass, the results are more consistent, ranking as the most impactful packaging type across several impact categories and methodologies. However, the energy sources used to supply electricity for these manufacturing and sanitation processes, such as coal or natural gas, have not been examined for their contributions to broader life cycle impacts. Considering the heightened impacts of manufacturing within the life cycle of these packaging systems, changes in grid composition could affect the impacts of single-use products, and the viability of reusable packaging under these conditions.

As of 2024, Meng et al. (2024a) is the only study to examine milk packaging under a future electrical grid scenario analysis in the United States. The future scenarios are based on business-as-usual decarbonization targets for 2050 and a best-case scenario based on the Sustainable Development goals. However, these results were only applied to single-use HDPE and liquid packaging board milk packaging systems. Under the baseline 2050 grid scenario analysis, the liquid packaging board-based carton outperforms the HDPE jug, while the best-case scenario produces opposite results. Within this study, the recycling rate and the electricity grid composition are highlighted as parameters with influence over these systems. Despite these insights, the study does not extend its analysis to single-use or reusable glass packaging under future electricity grid scenarios. As such, the environmental impacts of glass reuse under these decarbonisation scenarios remain untested and any potential influence on the environmental impact profiles of other commonly used packaging types such as flexible plastics and PET. The limited analysis narrows the application of these findings for policy and calls for further examination of additional single-use packaging types and glass packaging, both single-use and reusable.

Recent Canadian energy transitions trend toward an increasing share of low-carbon and renewable electricity generation, with corresponding reductions in grid-related GHG emissions (Government of Canada, 2023a). However, existing LCAs of milk packaging have not systematically explored how changing grid compositions alter the comparative impacts of glass and other material packaging systems over time. This absence of a grid scenario analysis leaves a critical gap in understanding the conditions under which reusable glass milk packaging may represent a viable, lower-impact alternative to plastic-dominant packaging formats.

2.3.1 Methodological inconsistencies in LCA studies of packaging

The impacts most often considered are climate change, energy demand, eutrophication, acidification, and water use, highlighting the focus on environmental impacts common across packaging. However, emerging environmental risks such as microplastic formation and pollution remain unexplored. Although new methodologies have been developed for estimating the impact of microplastics (Woods et al., 2019, 2021), no LCA of milk packaging studies have included these impacts.

Different LCA studies examining the same product system may produce different outcomes due to variations in assumptions, system boundaries, and impact assessment methods (Marson et al., 2023; Raadal et al., 2025). Contributing factors include differing interpretations of system boundaries, geographical and technological context, and varying approaches to end-of-life modelling (Marson et al., 2023; Miller, 2022; Raadal et al., 2025). The absence of sensitivity analyses – a requirement of the ISO standards (14040:2006, 14044:2006) within these studies may leave model assumptions left untested, introducing uncertainty surrounding final results and the author's interpretations (International Organization for Standardization, 2006a, 2006b; Molina-Besch et al., 2019). Excluding activities or processes (e.g. end-of-life recycling, use phase) within the life cycle of products can change the final impact assessment results (Ekvall et al., 2020; Miller, 2022). Furthermore, different sources of data and their alignment with study data requirements can yield different results for the same product.

Although comparative LCAs of milk packaging are well established, several gaps limit their applicability in Canadian decision-making. Across studies, plastic and LPB cartons frequently demonstrate lower impacts than glass across common midpoint indicators, yet these conclusions remain highly sensitivity to methodological choices. Furthermore, ISO-aligned sensitivity and uncertainty analysis is often limited, leaving key assumptions insufficiently tested and reducing confidence in cross-study comparison. The electricity supply supporting major hotspots, such as glass melting, sanitization, and polymer production, is rarely examined; with only one study examining decarbonized grid scenarios for limited milk packaging types. As such, further exploration is needed to evaluate how reuse-based systems and other common milk packaging formats perform under evolving energy grids, and to clarify the conditions under which reuse can be a viable alternative to single-use packaging systems.

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Highlights:

- Reusable glass is a viable alternative to single-use packaging with optimized reuse and decarbonized energy
- Reusable HDPE performance plateaus quickly under a decarbonized grid, with limited gains at higher reuse rates
- Sanitization and transport dominate impacts in high reuse-rate systems
- A decarbonized grid substantially improves reusable glass bottle performance.

3.1 Introduction

Food packaging is among the major contributors to municipal solid waste in Canada. In 2020, food packaging composed almost one third of the national municipal waste stream (Diggle & Walker, 2020). Plastic is a popular food packaging material due to its low cost, light weight, and strength properties. However, SUPs have been targeted in Canada's Single-use Plastics Prohibition regulations (Government of Canada, 2022), which stem from the 2020 Zero Plastic Waste Agenda, seeking to eliminate plastic waste by 2030 (Canadian Council of Ministers on the Environment, 2018). These regulations are driven by evidence of plastic pollution within Canada and along its coastlines, in addition to the evidence of the negative impacts of plastic in ecosystems (Environment and Climate Change Canada & Health Canada, 2020). These initiatives are paired with recent policy initiatives in 2024, as Canadian provinces proceed with the introduction and enforcement of extended producer responsibility policies and measures (Anthesis, 2024). Despite these policies, little research has been done on alternative materials or how to reduce end-of-life impacts and increase circularity for food packaging systems.

Beverage packaging, as a type of food packaging, is an area of interest due to the diversity of materials used and how the packaging is handled at the end-of-life. Specifically, packaging for refrigerated milk, a high-volume staple product within Canada, uses a variety of

different packaging formats such as high-density polyethylene jugs, mixed paper and plastic cartons, flexible plastics such as milk pouches, and glass bottles. As Canadian provinces begin to implement Extended Producer Responsibility (EPR) measures and the broader federal government progresses its Zero Plastic Waste Agenda, it is important to understand the environmental impacts of packaging products to make decisions for viable alternatives based on evidence.

Life cycle assessment (LCA) is a common method used to examine the environmental impacts of products. Studies on the LCA of milk packaging consistently identify the manufacturing and end-of-life life cycle stages as primary contributors to environmental impacts, most evident for energy-intensive materials like glass (Brock & Williams, 2020; Cappiello et al., 2022; Fry et al., 2010; Stefanini et al., 2021a). Regardless of geography, single-use glass bottles are consistently associated with the highest climate change, eutrophication, and acidification impacts (Ferrara et al., 2021; Stefanini et al., 2021a) in the available literature. In comparison, HDPE and liquid packaging board have the lowest impacts (Brock & Williams, 2020; Meng et al., 2024a). However, methodological decisions in LCA studies, such as system boundaries, assumptions, and allocation methodology, can shift which packaging is shown to have the lowest impacts (Bertolini et al., 2016; Meng et al., 2024a; Sun et al., 2021b; Xie et al., 2011). Thus, it is still important to continue to study these systems and various material substitutions or alternatives in a rigorous and structured manner using LCA.

Although many LCA studies of packaging exist, including comparative LCAs of beverage packaging and milk containers in Europe and North America, these have largely focused on single-use formats, current energy mixes, and a restricted set of midpoint indicators, with limited focus on how reusable glass performs under decarbonized electricity grids. Recent global scenario analysis by Meng et al. (2024a) models decarbonized production conditions for milk packaging and other packaging types such as soft drinks, demonstrating the benefits gained by energy-intensive materials under such conditions. However, this analysis excludes dedicated reusable glass bottle systems and an examination of these systems under decarbonized conditions. Within Canada, Sun et al. (2021) conducted a simplified environmental impact assessment aligned with LCA concepts, quantifying embodied energy, greenhouse gas emissions, and water consumption of HDPE jugs, LPB cartons, and milk pouches, but excluded both single-

use and reusable glass. Furthermore, the analysis was limited to Toronto, ON and Halifax, N.S. which limits the applicability of the findings on a Canada-wide scale.

The purpose of this study is to evaluate the cradle-to-grave life cycle impacts of common milk packaging formats available in Canada (i.e. single-use plastic jugs, cartons, plastic pouch systems, and reusable glass bottles) based on current recycling and reuse rates. It also considers the same packaging using a projected 2050 net-zero electricity grid. This study builds upon existing packaging studies from other regions, and provides an evaluation of a broader set of packaging formats. Furthermore, it expands on past studies by explicitly examining how grid decarbonization and reuse rates affect the relative performance of reusable glass against single-use alternatives. The findings of this study are intended to inform the debate on material substitutions and reuse in food packaging, emerging Canadian policy discussions on single-use plastics, extended producer responsibility, and circular economy strategy.

3.2 Methods

This study uses Life Cycle Assessment (LCA) based on the ISO 14040/14044 (2006a, 2006b) standards and guidelines. The LCA was conducted using openLCA version 2.4 software (GreenDelta, 2024).

3.2.1 Goal and Scope

The product systems under study are plastic-based and glass packaging that contains refrigerated liquid dairy milk. The goals of this study are to:

- compare the environmental impacts associated with the life cycle of commonly available refrigerated milk packaging in Canada under current recycling, reuse and recovery scenarios;
- identify hotspots and impact trade-offs associated with milk packaging systems;
- determine the reuse frequency at which the reusable 1 L glass bottle achieves lower total impacts than single-use milk packaging types

- examine how Canada's projected 2050 low-carbon electricity grid composition influences the life cycle impacts of reusable glass milk packaging when compared to single-use alternatives

3.2.1.1 Product systems description

The product systems modeled are cartons, cartons with caps, PET bottles, HDPE jugs, plastic milk pouches, and glass bottles. All packaging is modelled as single use with the exception of the glass bottle which is also available in a reusable format in Canada. A summary of each packaging system is provided in Table 1 and details are presented in the *Life Cycle Inventory* section.

Table 1 Summary of Milk Packaging Life Cycle Stages

Packaging Type	Raw Material Extraction / Production	Packaging Conversion / Manufacturing	Transport Between Stages	Filling / Sanitization	End-of-Life Management
HDPE Jug (1 L, 2 L, 4 L)	HDPE pellets; LDPE pellets	Blow moulding (jug), injection moulding (cap), extrusion (label)	Ground freight (market), refrigerated ground freight (50 km)	Filling and sealing at the dairy processor	Collection and recycling rates as per Table 9
PET Bottle (1.5 L)	PET resin (bottle-grade, amorphous), HDPE pellets	Stretch blow moulding (bottle), injection moulding (cap), plastic film extrusion (label)	Ground freight (market), refrigerated ground freight (50 km)	Filling and sealing at the dairy processor	Collection and recycling rates as per Table 9
LPB Carton (1 L, 2 L)	Solid bleached and unbleached board carton, LDPE pellets	Lamination of solid bleached and unbleached board carton with extruded of LDPE film (carton)	Ground freight (200 km), refrigerated ground freight (50 km)	Cutting and forming of LPB, filling, and sealing	Collection and recycling rates as per Table 9
LPB Carton w/ Cap (1 L, 2 L)	Solid bleached and unbleached board carton, LDPE pellets, and HDPE pellets	Lamination of solid bleached and unbleached board carton with extruded of LDPE film (carton); injection moulding (cap)	Ground freight (200 km), refrigerated ground freight (50 km)	Cutting and forming of LPB, filling, and sealing with cap	Collection and recycling rates as per Table 9
Milk Pouch (4 L total, 3 × 1.3 L)	LLDPE and LDPE pellets; TiO_2 pigment; HDPE pellets	Plastic film extrusion (pouch); injection moulding (tie)	Ground freight (200 km), refrigerated ground freight (50 km)	Form-fill-seal at dairy; HDPE tie moulded	Collection and recycling rates as per Table 9
Glass Bottle – Single Use (1 L)	Packaging glass (72.75% silica, 13% soda ash, 10.5% lime) and 30% recycled glass cullet	Glass melting (bottle); enamel printing (printed label); and injection moulding (cap)	Ground freight (676 km), refrigerated ground freight (50 km)	Sanitization, filling, and sealing at the dairy processor	Collection and recycling rates as per Table 9
Glass Bottle – Reusable (1 L)	Same as single use	Same as single use	Same as single use, in addition to return logistics	Sanitization after each cycle; reused 10–40 times	Collection and recycling rates as per Table 9 after service life

3.2.1.2 Functional Unit

The primary function of packaging is to contain and protect milk from getting spoiled or contaminated. This study only considers packaging for refrigerated milk (i.e. aseptic packaging for long-term storage is not included). It is assumed that all the packaging performs similarly, without failures, such as breakage. The common milk packaging volumes in Canada are 1L, 1.5L, 2L, and 4L. Since only complete containers can be purchased to fulfill the function, the functional unit for this study is production of milk packaging to contain and protect 12 litres (L) of pasteurized milk until disposal, recycling, or reuse.

The reference flow is the amount of product and associated product systems that are needed to fulfill the functional unit. The reference flows for each type of packaging are provided in Table 2.

Table 2 Reference flows of the packaging required to meet the functional unit of 12 L of milk contained.

Container Volume (L)	Reference Flow (number of packages)	HDPE Jug	PET Bottle	Carton	Carton with cap	Milk Pouch*	Glass Bottle
1	12	X	-	X	X	-	X
1.5	8	-	X	-	-	-	-
2	6	X		X	X	-	-
4	3	X	-	-	-	X	-

*(including 3 pouches and external plastic packaging)

3.2.1.3 System Boundaries

The system boundaries (Figure 1) are cradle-to-grave/cradle, including transportation between all life cycle stages. Stages include raw materials, packaging production, and filling, sealing, and sanitization at the dairy processor. Furthermore, the system includes refrigerated distribution to retail, followed by end-of-life management through municipal and depot-based collection systems where the collection and sorting of municipal solid waste and recyclables occur. For reusable glass bottles, the product system is extended to encompass return logistics from retailer to the dairy processor where washing, sanitization, and further filling and capping

processes are completed to return the bottle into service. The use phase is excluded as it is assumed that there are no differences in energy use for refrigeration by the various packaging types. In addition, the production of milk and milk losses due to packaging failure have been excluded for comparability within the literature; the limitations of such exclusions are discussed in the Limitations section. Production and transportation of secondary packaging is excluded due to lack of information regarding the specific types of secondary packaging used for the HDPE jug and cartons. Secondary packaging (i.e. cardboard dividers, milk crates, and pallets) contains and protects the milk packaging during transportation between stages. The exclusion of secondary packaging is examined within the sensitivity analysis.

The geographic boundary of this study is all of the provinces in Canada, excluding the three northern territories.

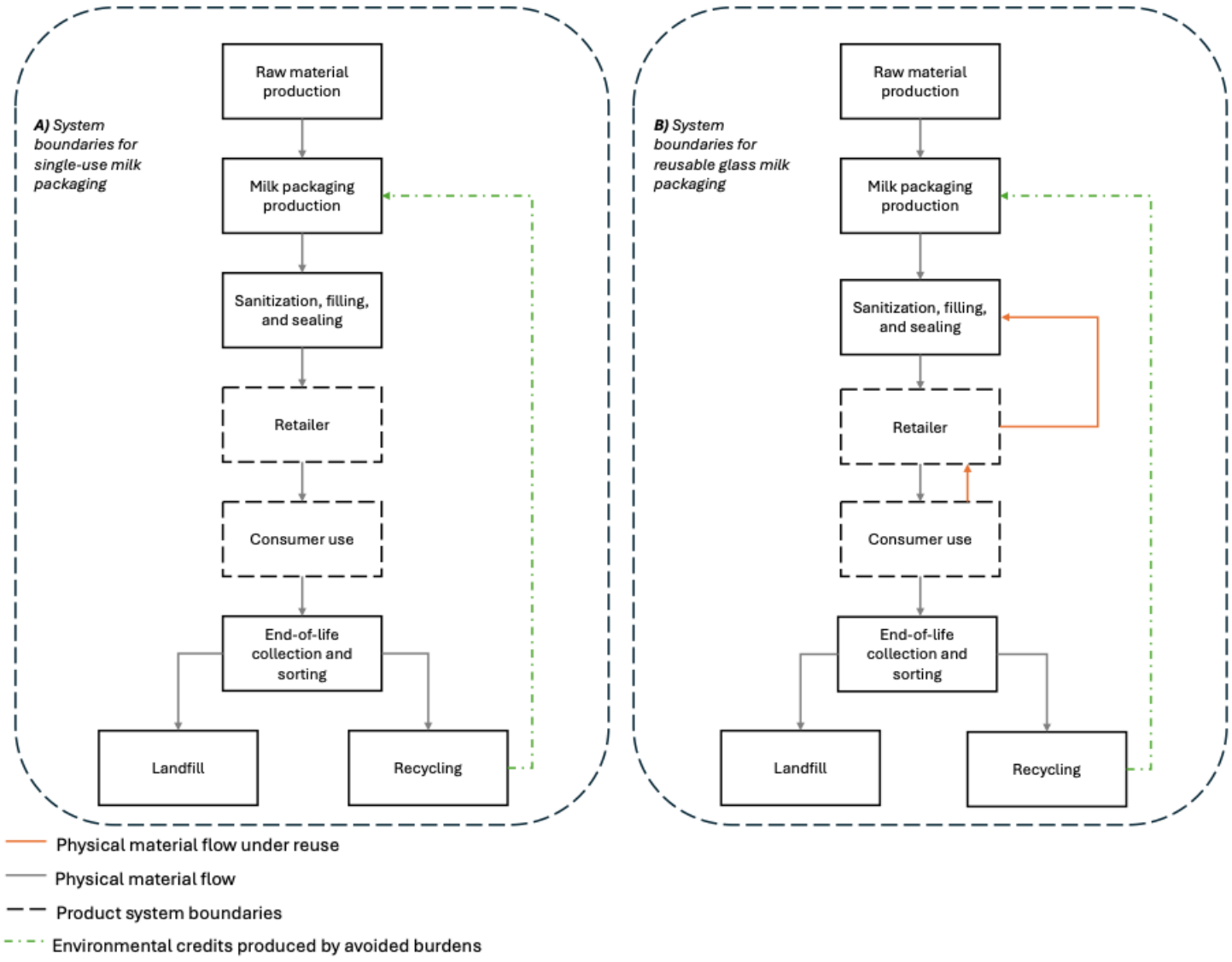


Figure 1 a) Single-use and b) reusable system boundary diagram

3.2.1.4 Recycling modeling approach

For packaging systems that include recycling, two main approaches, the cut-off approach and the avoided burdens approach, are commonly applied. Under the cut-off approach, the life cycle of the packaging ends once the recyclable material leaves the system for recycling as shown in Figure 2a (Wernet et al., 2016). Any impacts or benefits associated with producing and using recycled material are attributed entirely to the product system which uses that recycled content. In contrast, the avoided burdens approach keeps the recycling system within the system boundary as shown in Figure 2b (Fry et al., 2010). When packaging material is collected and recycled, the recycled material (e.g. recycled plastic) is assumed to substitute virgin material (i.e. virgin plastic) in the economy, thus avoiding emissions associated with plastic production. This creates a credit for the packaging material.

This study uses the avoided burdens approach and applies it through the allocation at point of substitution (APOS) ecoinvent© database. The APOS database contains assumptions regarding the final use of recycled materials, specifically toward close-loop and open-loop recycling (Wernet et al., 2016). Closed-loop recycling assumes that recycled material is returned to the same product system from which it was produced, while open-loop recycling assumes that secondary packaging is used in different applications. Because milk packaging is often downcycled into other products, recycling is treated as an open-loop system in this study (Ekvall et al., 2020). While the APOS version of the ecoinvent database was used for the main modelling within this study, a sensitivity analysis (Section 3.3.2) was performed using the cut-off approach and respective ecoinvent© database of the 1 L HDPE jug to examine the influence of recycling approach on the results.

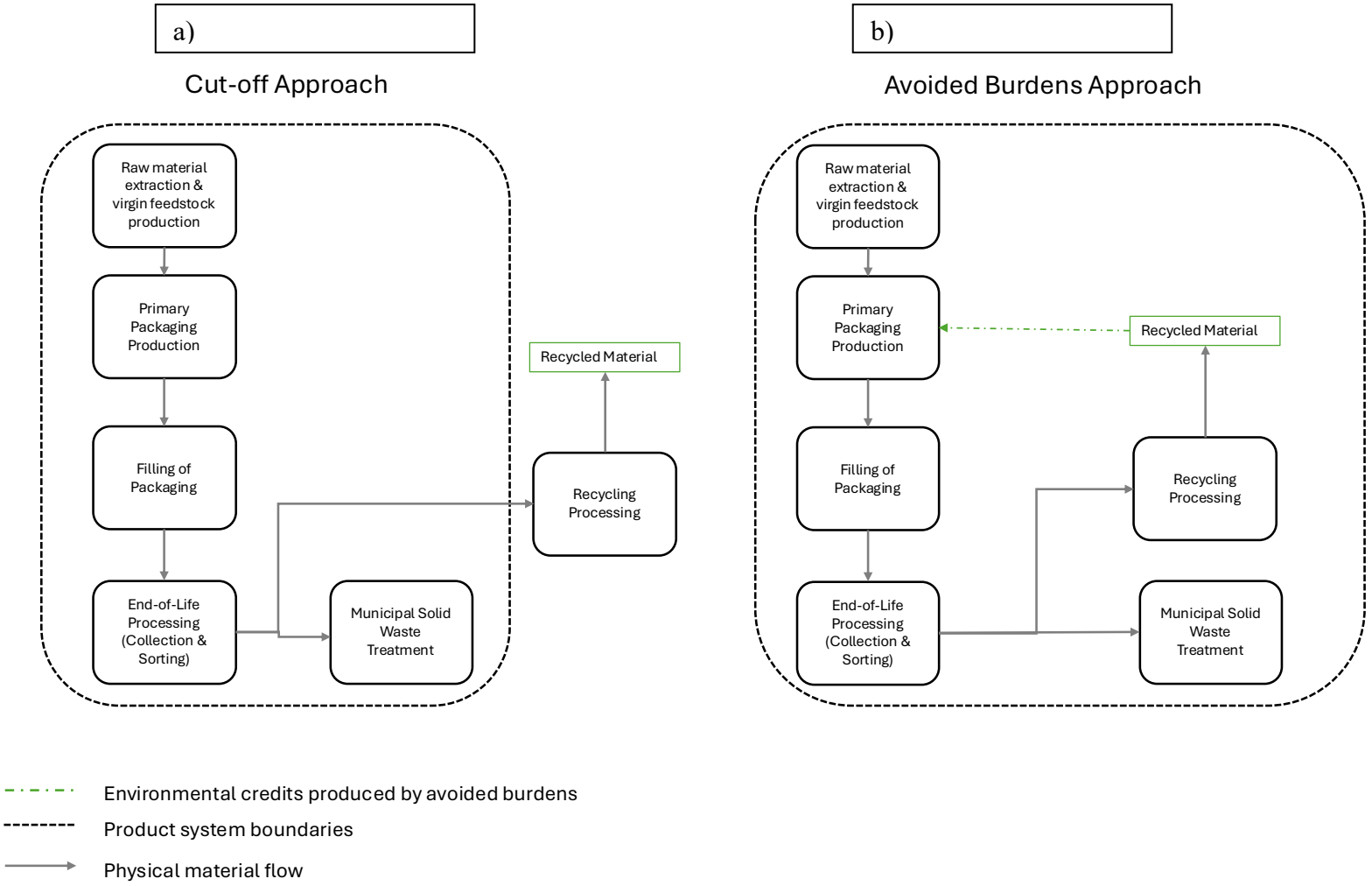


Figure 2 System boundary representation of the a) cut-off and b) avoided burdens end-of-life modelling approaches

3.2.1.5 Impact Categories

The goal of this study is to quantify environmental impacts associated with the life cycle of milk packaging, based on current and future use. Impact World+ Midpoint v2.1 ecoinvent©-based impact assessment method was used using the Canadian regionalized characterization of impacts (Bulle et al., 2019). The method includes a range of impacts that are relevant based on the packaging materials and a changing electricity grid, specifically: Climate change (short term); Fossil and nuclear energy use; Freshwater acidification; Freshwater ecotoxicity; Freshwater eutrophication; Human toxicity cancer; Ionizing radiations; Land occupation, biodiversity; Land transformation, biodiversity; Marine eutrophication; Particulate matter formation; Photochemical ozone formation; Terrestrial acidification; and Water scarcity. These impact categories were selected to capture the key environmental trade-offs associated with milk packaging materials and energy use, and are sensitive to material intensity, emissions, land use, and projected changes to the Canadian electricity grid. Full justification for including these impact categories can be found in Appendix I.

3.2.2 Life Cycle Inventory / Data Collection

Primary data on the material composition of each packaging type were collected based on discussions with milk and packaging companies and partners as well as industry experts. Where possible, data has been collected to be representative of the geographic, temporal, and technological conditions in Canada. A summary of packaging specifications and composition is provided in Table 3.

Table 3 Packaging Mass Composition for 1 Package

Material			HDPE Jug	HDPE Jug	HDPE Jug	PET Bottle	Flexible Plastic Milk Pouch	Carton without cap	Carton without cap	Carton with cap	Carton with cap	Glass Bottle
Volume	Unit		1 L	2 L	4 L	1.5 L	4 L	1 L	2 L	1 L	2 L	1 L
Primary Packaging												
Container Body												
HDPE	g		34.87	45.99	65.19							
LDPE	g						7.42	6.73	12.97	6.92	12.74	
LLDPE	g						15.86					
PET	g					51.17						
Solid bleached and unbleached board carton	g							25.33	48.81	26.01	47.23	
Titanium dioxide	g						0.67					
Glass	g											642.19
Closure/Cap System												
HDPE	g		2.37	2.37	2.42	2.99	0.46					
LDPE	g											5
Label/Branding												
HDPE	g											
LDPE	g		1.42	1.25	1.1							
Total Packaging Mass	g		38.66	49.61	68.71	54.16	24.41	32.06	61.78	32.93	59.97	647.19

3.2.2.1 High-density Polyethylene (HDPE) Jug

Single-use high-density polyethylene (HDPE) milk jugs are found in 1L, 2L, and 4L sizes in Canada (Sun et al., 2021b). It is assumed that primary packaging production for hard plastic packaging and flexible plastics occurs in Canada at the dairy processor prior to filling (Burek et al., 2018). HDPE pellets are converted into bottles by blow moulding and into HDPE caps using injection moulding (Kershner, 2020); the LDPE label is made using extrusion (Fry et al., 2010). Filled HDPE bottles are assumed to be distributed 50 km by refrigerated freight truck between the dairy processor and retail locations (L.E.K. Consulting Australia Ltd., 2021). LCI data is provided in Table 4. It is assumed that after use, the bottles are collected by garbage truck or dropped off at a bottle depot at the recycling rates provided in Table 11. LCI data for other volumes of HDPE jugs, such as 2 L and 4 L, are included in Supplementary Information.

Table 4 LCI for production of a single 1L HDPE jug

Model Parameter	Amount	Units	ecoinvent Processes	System Modelling Assumptions and Data Source
Packaging Production				
Inputs				
HDPE Pellets (jug)	0.035	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Author measured*
LDPE Pellets (label)	0.001	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | APOS, U - GLO	*Author measured*
HDPE Pellets (cap)	0.000	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Author measured*
Blow Moulding	0.035	kg	blow moulding | blow moulding | APOS, U | Custom - CA	*Fry et al., 2010*
Extrusion	0.001	kg	extrusion, plastic film | extrusion, plastic film | APOS, U | Canada - CA	*Fry et al., 2010*
Injection Moulding	0.000	kg	injection moulding | injection moulding | APOS, U | Custom - CA	*Fry et al., 2010*
Filling				
Inputs				
Electricity, medium voltage	0.001	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Stefanini et al., 2021*
Refrigerated transport	2	kg*km	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | APOS, U - GLO	*Menig et al., 2022; L.E.K. Consulting Australia Ltd., 2021*
End-of-Life				
Processes				
Waste Polyethylene Collection & Sorting			market for waste polyethylene, for recycling, sorted | waste polyethylene, for recycling, sorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Polyethylene Recycling	0.025	kg	market for waste polyethylene, for recycling, unsorted | waste polyethylene, for recycling, unsorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Municipal Solid Waste Collection & Treatment	0.013	kg	market for municipal solid waste | municipal solid waste | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*

3.2.2.2 Polyethylene Terephthalate (PET) Bottle

Single-use polyethylene terephthalate (PET) bottles are 1.5 L sizes in Canada. This study assumes the PET bottles are formed from virgin PET resin through single-stage stretch blow moulding at the dairy processor (Fry et al., 2010). It is assumed shrink-sleeve labels are produced from PET-G, a commonly used material in shrink-sleeves (The Association of Postconsumer Recyclers, 2014), a plastic film extrusion process. Since PET-G was not available in ecoinvent, amorphous PET was used as a proxy. As with other rigid plastic formats, filled PET bottles are transported 50 km by refrigerated truck from the dairy processor to retail (L.E.K. Consulting Australia Ltd., 2021). LCI data is provided in Table 5. It is assumed that after use, the bottles are collected by garbage truck or dropped off at a bottle depot at the recycling rates provided in Table 11.

Table 5 LCI for a single 1.5 L PET bottle.

Model Parameter	Amount	Units	ecoinvent processes	System Modelling Assumptions and Data Source
Packaging Production				
Inputs				
PET, Bottle Grade Pellets	0.052	kg	market for polyethylene terephthalate, granulate, bottle grade | polyethylene terephthalate, granulate, bottle grade | APOS, U - GLO	*Author measured*
PET, Amorphous	0.006	kg	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | APOS, U - GLO	*Assumes amorphous PET in place of PET-G for label production*
HDPE Pellets	0.000	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Fry et al., 2010*
Stretch Blow Moulding	0.052	kg	stretch blow moulding | stretch blow moulding | APOS, U | Custom - CA	*Fry et al., 2010*
Extrusion	0.006	kg	extrusion, plastic film | extrusion, plastic film | APOS, U | Canada - CA	*Fry et al., 2010*
Injection Moulding	0.000	kg	injection moulding | injection moulding | APOS, U | Custom - CA	*Fry et al., 2010*
Filling				
Inputs				
Electricity, medium voltage	0.001	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Stefanini et al., 2021*
Refrigerated transport	3	kg*km	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | APOS, U - GLO	*Menig et al., 2022; L.E.K. Consulting Australia Ltd., 2021*
End-of-Life				
Processes				
Municipal Solid Waste Collection & Treatment	0.021	kg	market for municipal solid waste | municipal solid waste | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Waste Polyethylene Collection & Sorting			market for waste polyethylene, for recycling, unsorted | waste polyethylene, for recycling, unsorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Polyethylene Recycling			market for waste polyethylene, for recycling, sorted | waste polyethylene, for recycling, sorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Polyethylene Terephthalate Recycling	0.03895 (0.001946-HDPE, 0.03701 - PET)	kg	market for waste polyethylene terephthalate, for recycling, sorted | waste polyethylene terephthalate, for recycling, sorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*

3.2.2.3 Cartons with and without caps

Liquid packaging board (LPB) is a multi-layer material widely used in refrigerated milk packaging systems (Bonadies et al., 2022). The LPB carton systems modelled within this study are composed of paper and LDPE (Bonadies et al., 2022). The LCI uses author-measured packaging mass, purchased from the grocery store and deconstructed to weigh each material where possible. Small mass differences between capped and uncapped cartons reflect minor design and measurement variations. Due to the difficulty in weighing LDPE laminate and paperboard separately, this study assumes liquid packaging board mass based on documented material composition percentages. Industry interviews with Elopak Canada Inc. indicate that a majority of LPB production and converting occur in the province of Quebec. LPB production is represented by Quebec-based solid bleached and unbleached board carton combined with LDPE thin plastic film extrusion for the LDPE coating, which is then laminated onto the paperboard with branding and regulatory information printed on with ink. Liquid packaging board transport assumes the transport value of 200 km, as observed in the feedstock transport within Canada for milk pouch systems in Fry et al.'s (2010) study. For capped formats, HDPE pellets are converted via injection moulding into caps and spout inserts. LPB is transported to the dairy processor by ground freight.

At the dairy processor, LPB rolls are cut, folded, and heat-sealed into cartons, filled, and capped if required (Fry et al., 2010; MadeHow, 1994). Filled cartons are distributed 50 km by refrigerated freight from the dairy processor to retail location, similar to other packaging formats (L.E.K. Consulting Australia Ltd., 2021). LCI data is provided in Table 6 and Table 7.

It is assumed that after use, the bottles are collected by garbage truck or dropped off at a bottle depot at the recycling rates provided in Table 11.

Table 6 LCI for a single 1 L liquid packaging board carton without a plastic cap

Model Parameter	Amount	Units	ecoinvent processes	System Modelling Assumptions and Data Source
Packaging Production				
Inputs				
Solid bleached and unbleached board carton	0.025	kg	solid bleached and unbleached board carton production | solid bleached and unbleached board carton | APOS, U | Custom - CA-QC	*Carton Council of Canada, 2023; Elopak, 2024*
LDPE Pellets	0.007	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | APOS, U - GLO	*Carton Council of Canada, 2023; Elopak, 2024*
Extrusion	0.007	kg	extrusion, plastic film | extrusion, plastic film | APOS, U | Canada - CA	*Fry et al., 2010*
Primary Packaging Transport	7	kg*km	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	*Fry et al., 2010, assumes the same feedstock distance as milk pouches*
Filling				
Inputs				
Electricity, medium voltage	0.001	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Stefanini et al., 2021*
Refrigerated transport	2	kg*km	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | APOS, U - GLO	*Menig et al., 2022; L.E.K. Consulting Australia Ltd., 2021*
End-of-Life				
Processes				
Waste Paperboard Collection & Sorting	0.025	kg	market for waste paperboard, unsorted | waste paperboard, unsorted | APOS, U | Custom - CA	*Carton Council of Canada, 2023*
Municipal Solid Waste Collection & Treatment	0.013	kg	market for municipal solid waste | municipal solid waste | APOS, U | Custom - CA	*Carton Council of Canada, 2023*
Paperboard Recycling	0.025	kg	treatment of waste paperboard, unsorted, sorting | waste paperboard, sorted | APOS, U | Custom - CA	*Carton Council of Canada, 2023*

Table 7 LCI for a single 1 L liquid packaging board carton with a plastic cap

Model Parameter	Amount	Units	ecoinvent processes	System Modelling Assumptions and Data Source
Packaging Production				
Inputs				
Solid bleached and unbleached board carton	0.026	kg	solid bleached and unbleached board carton production | solid bleached and unbleached board carton | APOS, U | Custom - CA-QC	*Author-measured using composition from Bonadies et al. (2022)*
HDPE Pellets	0.003	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Author-measured; Sun et al. (2021)*
LDPE Pellets	0.007	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | APOS, U - GLO	*Author-measured using composition from Bonadies et al. (2022)*
Extrusion	0.007	kg	extrusion, plastic film | extrusion, plastic film | APOS, U | Canada - CA	*Author-measured using composition from Bonadies et al. (2022)*
Injection Moulding	0.003	kg	injection moulding | injection moulding | APOS, U | Custom - CA	*Author-measured*
Primary Packaging Transport	7	kg*km	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	*Assumes same feedstock transport distance as milk pouches; Fry et al., 2010*
Filling				
Inputs				
Electricity, medium voltage	0.001	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Stefanini et al., 2021*
Refrigerated transport	2	kg*km	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | APOS, U - GLO	*Menig et al., 2022; L.E.K. Consulting Australia Ltd., 2021*
End-of-Life				
Processes				
Waste Paperboard Collection & Sorting			market for waste paperboard, unsorted | waste paperboard, unsorted | APOS, U | Custom - CA	*Carton Council of Canada, 2023*
Paperboard Recycling	0.002	kg	treatment of waste paperboard, unsorted, sorting | waste paperboard, sorted | APOS, U | Custom - CA	*Carton Council of Canada, 2023*
Waste Polyethylene Collection & Sorting			market for waste polyethylene, for recycling, unsorted | waste polyethylene, for recycling, unsorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Polyethylene Recycling	0.002	kg	market for waste polyethylene, for recycling, sorted | waste polyethylene, for recycling, sorted | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022*
Municipal Solid Waste Collection & Treatment	0.014	kg	market for municipal solid waste | municipal solid waste | APOS, U | Custom - CA	*Beverage Container Recycling Network of Canada (BCRNC), 2022; Carton Council of Canada, 2023*

3.2.2.4 Plastic Milk Pouches

The single-use milk bag or pouch is commonly found in the eastern provinces in Canada, specifically Ontario, Quebec, New Brunswick, Nova Scotia, and Prince Edward Island. These milk pouches are sold packaged in groups of three 1.3L plastic inner pouches for a total of 4 L, with an outer plastic storage bag used for transport. Inner and outer bags are produced from a mixed composition of linear low-density polyethylene (LLDPE) and LDPE, with titanium dioxide pigment added to achieve opacity of the outer bag. The material composition is applied from Fry et al.'s (2010) study which use Canadian-based milk pouches and was applied to author-measured packaging mass measurements. LLDPE and LDPE pellets are then processed via blown-film extrusion. After extrusion, the film is printed with branding and regulatory information. These long tubes of film are transported in rolls to the dairy processor by ground freight an average distance of 200 km as per Fry et al.'s (2010) study. At the dairy processor, the tubes are formed, filled, and sealed into pouches, which are put into the external bag, and closed with an injection moulded HDPE tie. These pouches are assumed to be distributed the same distances as in the rigid plastic and LPB packaging systems to the retail locations. LCI data is provided in Table 8. It is assumed that after use, the bottles are collected by garbage truck or dropped off at a bottle depot at the recycling rates provided in Table 11.

Table 8 LCI for three 1.3 L flexible plastic milk pouches contained within a plastic bag required for 12 L functional unit

Model Parameter	Amount	Units	ecoinvent processes	System Modelling Assumptions and Data Source
Packaging Production				
Inputs				
HDPE Pellets	0.000	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Author-measured at a composition sourced from Fry et al., 2010*
LDPE Pellets	0.008	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | APOS, U - GLO	*Author-measured at a composition sourced from Fry et al., 2010*
LLDPE Pellets	0.016	kg	market for polyethylene, linear low density, granulate | polyethylene, linear low density, granulate | APOS, U - GLO	*Author-measured at a composition sourced from Fry et al., 2010*
Titanium Dioxide	0.001	kg	market for titanium dioxide | titanium dioxide | APOS, U - RoW	*Author-measured at a composition sourced from Fry et al., 2010*
Extrusion	0.025	kg	extrusion, plastic film | extrusion, plastic film | APOS, U | Canada - CA	*Author-measured at a composition sourced from Fry et al., 2010*
Injection Moulding	0.000	kg	injection moulding | injection moulding | APOS, U | Custom - CA	*Author-measured at a composition sourced from Fry et al., 2010*
Uncut Milk Bag Roll Transport	5	kg*km	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	*Fry et al., 2010*
Filling				
Inputs				
Electricity, medium voltage	0.002	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Stefanini et al., 2021*
Refrigerated transport	1	kg*km	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | APOS, U - GLO	*Menig et al., 2022; L.E.K. Consulting Australia Ltd., 2021*
End-of-Life				
Processes				
Waste Polyethylene Collection & Sorting	0.001	kg	market for waste polyethylene, for recycling, sorted | waste polyethylene, for recycling, sorted | APOS, U | Custom - CA	*Canada Plastics Pact, 2024*
Municipal Solid Waste Collection & Treatment	0.023	kg	market for municipal solid waste | municipal solid waste | APOS, U | Custom - CA	*Canada Plastics Pact, 2024*
Polyethylene Recycling	0.001	kg	market for waste polyethylene, for recycling, unsorted | waste polyethylene, for recycling, unsorted | APOS, U | Custom - CA	*Canada Plastics Pact, 2024*

3.2.2.5 Single-Use & Reusable Glass Bottles

The glass bottle systems are a 1 L soda-lime glass milk bottle used either as single-use or reusable depending on available reuse infrastructure. This format is most commonly used at smaller dairy processors and farms in Canada (Somogyi & Chesnot, 2024). Raw materials include silica, soda ash, lime, and waste glass (cullet), with 30% cullet used within each virgin batch (Pellegrino, 2002; Stanpac Inc., 2024). The ecoinvent© process for white packaging glass was modified to 72.75% silica, 13% soda ash, and 10.5% lime based on U.S. glass production data (Pellegrino, 2002). The assumed glass composition is examined in the Sensitivity Analysis under Section 3.3.2. Production occurs in Dunkirk, Indiana. Background electricity for primary production of the glass bottle is using the ReliabilityFirst Corporation (RFC) grid local to Indiana. The bottle is transported a distance of 676 km to Smithville, Ontario for printing with ceramic enamel, detailed in Table 10

The bottle cap is moulded with coloured LDPE at the printing facility. The printed bottles and caps are transported to the dairy processor. Both single-use and reusable glass bottles undergo sanitization before filling, using water and chemicals. The bottles are filled and capped, then transported by refrigerated ground freight to the retail location. For the single-use bottle, it is assumed to only complete one-use cycle prior to end-of-life treatment. LCI data is provided in Table 9

For reusable bottles, it is assumed that after use, the bottles are disposed back into the traditional waste and recycling stream, or retail store if entered back into the reuse system. Reuse and recycling rates are provided in Table 11.

Table 9 LCI for one single 1 L glass bottle

Model Parameter	Amount	Units	ecoinvent processes	System Modelling Assumptions and Data Source
Packaging Production				
Inputs				
Packaging Glass	0.637	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Pellegrino, 2002; Stanpac, 2024*
LDPE Pellets	0.000	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | APOS, U - GLO	*Pellegrino, 2002; Stanpac, 2024*
Injection Moulding	0.000	kg	injection moulding | injection moulding | APOS, U | Custom - CA	*Stanpac, 2024*
Bottle Transport	432	kg*km	transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	*Stanpac, 2024; assumes an average approximate distance from Dunkirk, IN*
Printing				
Inputs				
Steel mesh	0.000	kg	market for steel, unalloyed | steel, unalloyed | APOS, U - GLO wire drawing, steel | wire drawing, steel | APOS, U - RoW	*Assumes an average 225 mesh count per inch, with a 90 µm opening (Ferro Corporation, 2014; Stanpac, 2024)*
Polyethylene mesh	0.073	kg	extrusion of plastic sheets and thermoforming, inline | extrusion of plastic sheets and thermoforming, inline | APOS, U | Custom - CA market for polyethylene, high density, granulate | polyethylene, high density, granulate | APOS, U - GLO	*Assumes an average 36.3g/m^2 density, based on a 84 µm opening and 210 threads per inch. (Ferro Corporation, 2014; Stanpac, 2024)*
Ceramic enamel	0.000	kg	enamelling | enamelling | APOS, U - CA	*(Stanpac, 2024)*
Sanitization				
Inputs				
Fresh water	0.980	L	market for tap water | tap water | APOS, U - CA-QC	*Central Fabricating & Welding, 2024*
Waste water	0.981	L	market for wastewater, unpolluted | wastewater, unpolluted | APOS, U - RoW	*Assumes wastewater volume as total combined volume of fresh water and other chemicals*
Iodine sanitizer	0.000	L	market for iodine | iodine | APOS, U - GLO	*Central Fabricating & Welding, 2024*
Sodium hydroxide	0.000	L	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, U - GLO	*Assumes a 50% concentration, Central Fabricating & Welding, 2024*
Electricity	0.002	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Central Fabricating & Welding, 2024*
Filling				
Inputs				
Electricity, medium voltage	0.001	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CA	*Stefanini et al., 2021*
Refrigerated transport	115	kg*km	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling | APOS, U - GLO	*Menig et al., 2022; L.E.K. Consulting Australia Ltd., 2021*
End-of-Life				
Processes				
Municipal Solid Waste Collection & Treatment	0.141	kg	market for municipal solid waste | municipal solid waste | APOS, U | Custom - CA	*CM Consulting, 2018; Beverage Container Recycling Network of Canada (BCRNC), 2022*
Waste Polyethylene Collection & Sorting			market for waste polyethylene, for recycling, unsorted | waste polyethylene, for recycling, unsorted | APOS, U | Custom - CA	*CM Consulting, 2018; Beverage Container Recycling Network of Canada (BCRNC), 2022*
Polyethylene Recycling	0.004	kg	market for waste polyethylene, for recycling, sorted | waste polyethylene, for recycling, sorted | APOS, U | Custom - CA	*CM Consulting, 2018; Beverage Container Recycling Network of Canada (BCRNC), 2022*
Waste Packaging Glass Collection & Sorting			market for waste glass from unsorted public collection, sorting | waste packaging glass, unsorted | APOS, U | Custom - CA	*CM Consulting, 2018; Beverage Container Recycling Network of Canada (BCRNC), 2022*
Glass Recycling	0.497	kg	market for glass cullet, sorted | glass cullet, sorted | APOS, U - RoW	*CM Consulting, 2018; Beverage Container Recycling Network of Canada (BCRNC), 2022*

The reusable system shares all upstream processes with the single use variant but extends the sanitization and use phase through several return cycles. Following consumption, bottles are returned via deposit-return programs at retail locations and transported back to the dairy. Intact bottles are sanitized with chemicals and heat, then repeat the downstream processes that follow the filling stage. Glass bottles can be used between a 10 to 40 times if undamaged and retaining branding by the dairy processor (Miller's Dairy, 2024). End-of-life collection and treatment processes are similar to the other packaging types, with the exception of recycling rates and glass cullet-specific recycling pathways. The LDPE caps are single-use and follow the recycling rates and end-of-life treatment applicable to rigid plastics.

3.2.2.6 Transportation, Filling, and Recycling and Reuse

Transportation distances and assumptions are provided in Table 10. Filling processes at the dairy processor are characterized by limited data within the Canadian context. For all packaging, electricity inputs for the filling process have been sourced from the filling and capping process of a 1L glass bottle from Stefanini et al. (2021) and scaled to their respective volumes.

Table 10 LCI for packaging transportation stages and end-of-life collection

Transport	Applies to	Distance (km)	Vehicle	Key assumptions	Source(s)
Primary packaging feedstock to dairy processor	Plastic-based packaging, and plastic-based components in other packaging types	Market-based	ecoinvent RoW market transport	Assumes market processes to be representative of feedstock distances	*ecoinvent*
Primary packaging feedstock to dairy processor	Pouch film; LPB carton rolls	200	Road freight, 7.5–16 t truck (EURO 6)	EURO 6 aligned with US EPA 2010; harmonized with Canadian standards. 7.5–16 t used as ecoinvent proxy for 4.5–14.9 t common intraprovincial trucks.	*Jin et al. (2021); CCME (2013); Fry et al. (2010); Canadian Vehicle Survey (2009)*
Glass bottle manufacturer to printing at Stanpac Inc.	Glass bottles only	676	Road freight, 32 t truck (EURO 6)	Assumes a 32 t freight truck due to long-haul distance and approximate distance from Dunkirk, IN to Smithville, ON due to generalized supplier location	*Stanpac Inc. (2024); Larson et al. (2024); Google Maps*
Dairy processor to retailer	All packaging formats	50	Refrigerated road freight, 7.5–16 t (EURO 6)	Refrigerant assumed R134a due to freight fleet age	*L.E.K. Consulting (2021); RTOC (2011); Menig et al. (2022)*
Municipal waste collection	All municipal waste	Market-based	ecoinvent RoW market processes	Uses RoW market collection distances	*ecoinvent*
Recycling collection & sorting	PE, PET, paperboard, glass	Market-based	ecoinvent market processes (modified)	Uses RoW market collection distances. Consumer transport set to gasoline reflecting a majority of passenger vehicle sales since 2017. Market processes average curbside municipal pick-up and depot/drop-off systems	*ecoinvent; Statistics Canada (2024)*

Recycling rates for the various packages are provided in Table 11. It is assumed that the remaining packaging is landfilled as the remaining percentage of unrecycled waste or packaging collected by the garbage truck.

Table 11 Recycling Rates

Packaging Type	**Recycling Rate**	**Landfill Rate**	**Source**
Glass	78%	22%	(CM Consulting, 2018)
Rigid Plastic (HDPE, PET)	65%	35%	(Edwards et al., 2024)
Flexible Plastic (Milk Pouch)	4%	96%	(Canada Plastics Pact, 2024)
Carton	60%	40%	(Carton Council of Canada, 2024)

Glass bottles can be reused 10 to 40 times (Stanpac Inc., personal communication, July 31, 2024), so an average of 25 reuses is used within the baseline system. As Canadian provinces show differences in their individual recycling rates and programs, the range of 10 to 40 is examined in the sensitivity analysis. Breakage rates for the glass bottles are assumed to be embedded in the reuse rates as specific rates were not provided.

3.2.2.7 Scenario Analysis: Canadian Electricity Grid – Current and 2050

As the study is conducted on packaging systems produced within Canada, processes associated with the production and filling of the milk packaging use the Canadian average electricity grid for their electricity energy inputs. The market group for electricity within Canada is representative up to 2022 and is assumed to be representative of the 2025 national electricity grid. It should be noted that certain provinces such as Alberta have continued the transition of phasing out coal-powered electricity generation since 2022, in addition to other decarbonization strategies implemented by other provinces within this temporal range. The limitations of the ecoinvent© database are examined within the *Limitations* section. In modelling the 2050 Canadian electricity grid, various technologies such as carbon capture, utilization, and storage (CCUS) or small modular reactors (SMR) could not be modelled due to limited processes within the ecoinvent© database. As such, the percentage share of certain generation technologies, including natural gas combustion electricity production with carbon capture, was assumed by the non-CCUS paired variant of generation technology, such as the use of standard nuclear plant

electricity generation for SMR uranium-based generation. This decision was applied to all generation technologies paired with CCUS such as coal, bioenergy, and natural gas-based electricity generation. Furthermore, market processes within ecoinvent© represent electricity demands from the market as opposed to the total energy composition generated nationally. Table 12 includes a breakdown of percentages corresponding to the energy sources described in the Canadian Provincial Electricity Generation Technology Breakdown 2020 to 2050 Net-Zero dataset (Canada Energy Regulator, 2023).

Table 12 Electricity Generation Technology Breakdown for 2025 and 2050 Canadian Electrical Grids

Electricity Generation Technology	**2025**	**2050**
Coal and Coke	1.13%	0.00%
Coal with CCUS	0.10%	0.00%
Solar (Utility scale)	1.12%	3.90%
Solar (Distributed)	0.63%	0.90%
Offshore Wind	0.00%	1.76%
Onshore Wind	9.05%	26.83%
Hydro	60.14%	36.83%
Uranium	11.72%	7.03%
Uranium SMR	0.00%	11.94%
Bioenergy	1.24%	0.71%
Bioenergy with CCUS	0.00%	3.97%
Natural Gas	14.68%	0.72%
Natural Gas with CCUS	0.00%	5.34%
Oil	0.20%	0.07%
kg CO_2 equivalent	**0.191**	**0.0751**

3.3 Results

This chapter presents the life cycle impact assessment results as follows: environmental impacts for all single-use packaging under current production, use, reuse, and recycling conditions; hotspot and trade-off analysis of various single-use packaging; break-even analysis for reusable glass containers relative to other containers based on current conditions; and scenario analysis using electricity grid changes into 2050. The packaging options are compared on the basis of a functional unit of 12 L.

3.3.1 Impacts and hotspots – Single-Use Packaging

3.3.1.1 Packaging impacts across categories

The impacts and rankings based on current single-use and recycling conditions are shown in Table 13. Of all the plastic packaging, the 4 L milk pouch has the lowest GWP impacts (0.25 kg CO2 eq) and fossil and nuclear energy use (FNEU) (6.5 MJ deprived). The 2-L and 1-L carton, as well as the 2-L carton with caps also had relatively low GWP and FNEU, ranging from 0.40 to 0.45 kg CO2 eq) and 10 to 12 MJ deprived, respectively. The HDPE 4-L jug and the 1-L carton with cap had similar GWP impacts (~0.48 kg CO_2 eq). The high mass of paperboard compared to plastic within the cartons reduces the GWP impacts. Cartons with caps had slightly higher GWP due to the additional mass of the caps. The PET bottle had the highest GWP of all the plastic packaging. The packaging with the lowest impacts had a combination of low mass of plastic or materials and a high volume-to-packaging ratio. In contrast, the glass bottle had the highest impacts. The GWP is 44 times higher than that of the 4-L milk pouch, and the FNEU is about 25 times higher.

For the other impact categories, the milk pouch still had the lowest impacts across all impact categories, except freshwater acidification and freshwater toxicity. The 4-L HDPE jug, which ranked 5th and 6th for GWP and FNEU, had the second lowest impacts for most of the other impacts. The glass and PET consistently have the highest and second highest impacts across most of the other impact categories.

Cartons with and without caps show substantially higher land occupation and transformation that their plastic alternatives of similar volume, reflecting the land intensity of

paperboard production. Cartons also had generally lower toxicity-related impacts compared to plastics. The PET bottle had the highest ozone layer depletion impact, likely as a result of the intense chemical processing required for the feedstock production of PET resin.

In addition, within the freshwater eutrophication category, all HDPE jugs report small, but negative values, due to the avoided burdens approach, as some of the HDPE jugs are recycled. The milk pouch and PET bottle are also recycled, but the avoided burdens are insufficient to lower the higher overall impacts and differences in materials that contribute to the impacts.

Table 13 ImpactWorld+ life cycle impact assessment results for all single-use milk packaging across all impact categories at a functional unit of packaging production to contain and protect 12 L of pasteurized, refrigerated dairy milk.

Impact categories	Unit	Carton - 1L	Carton - 2L	Carton w/ Cap - 1L	Carton w/ Cap - 2L	Glass Bottle - 1L	HDPE Jug - 1L	HDPE Jug - 2L	HDPE Jug - 4L	Milk Pouch - 4L	PET Bottle - 1.5L
Climate change, long term	kg CO2 eq (long)	**3** (4.2E-01)	**2** (4.0E-01)	**6** (4.8E-01)	**4** (4.5E-01)	**10** (9.5E+00)	**8** (1.1E+00)	**7** (6.9E-01)	**5** (4.8E-01)	**1** (2.0E-01)	**9** (1.6E+00)
Climate change, short term	kg CO2 eq (short)	**3** (5.4E-01)	**2** (5.2E-01)	**6** (6.2E-01)	**4** (5.8E-01)	**10** (1.1E+01)	**8** (1.3E+00)	**7** (8.5E-01)	**5** (5.9E-01)	**1** (2.5E-01)	**9** (1.9E+00)
Fossil and nuclear energy use	MJ deprived	**3** (1.1E+01)	**2** (1.0E+01)	**5** (1.4E+01)	**4** (1.2E+01)	**10** (1.6E+02)	**8** (4.0E+01)	**7** (2.6E+01)	**6** (1.8E+01)	**1** (6.5E+00)	**9** (4.5E+01)
Freshwater acidification	kg SO2 eq	**4** (1.6E-03)	**3** (1.5E-03)	**6** (1.7E-03)	**5** (1.6E-03)	**10** (4.9E-02)	**8** (3.3E-03)	**7** (2.1E-03)	**2** (1.5E-03)	**1** (6.3E-04)	**9** (4.9E-03)
Freshwater ecotoxicity	CTUe	**9** (9.9E+01)	**7** (9.5E+01)	**6** (9.4E+01)	**8** (9.6E+01)	**10** (1.8E+03)	**4** (4.9E+01)	**2** (3.1E+01)	**1** (2.2E+01)	**3** (3.8E+01)	**5** (5.5E+01)
Freshwater eutrophication	kg PO4 P-lim eq	**9** (1.2E-04)	**8** (1.2E-04)	**6** (6.2E-05)	**7** (7.4E-05)	**10** (1.7E-04)	**1** (-1.0E-03)	**2** (-6.6E-04)	**3** (-4.6E-04)	**4** (-2.1E-06)	**5** (3.3E-05)
Human toxicity cancer	CTUh	**4** (8.3E-09)	**3** (8.0E-09)	**6** (8.8E-09)	**5** (8.4E-09)	**10** (1.3E-07)	**8** (1.5E-08)	**7** (9.5E-09)	**2** (6.6E-09)	**1** (2.5E-09)	**9** (2.7E-08)
Human toxicity non-cancer	CTUh	**4** (4.1E-08)	**3** (4.0E-08)	**7** (4.5E-08)	**5** (4.2E-08)	**10** (9.5E-07)	**8** (6.6E-08)	**6** (4.3E-08)	**2** (3.0E-08)	**1** (1.3E-08)	**9** (1.9E-07)
Ionizing radiations	Bq C-14 eq	**3** (4.1E+00)	**2** (4.0E+00)	**6** (7.0E+00)	**5** (6.3E+00)	**10** (1.1E+02)	**8** (1.3E+01)	**7** (8.4E+00)	**4** (5.8E+00)	**1** (2.9E+00)	**9** (5.0E+01)
Land occupation, biodiversity	m2 arable land eq .yr	**8** (5.4E-01)	**7** (5.2E-01)	**9** (5.6E-01)	**6** (5.0E-01)	**10** (6.1E-01)	**5** (8.8E-02)	**3** (5.7E-02)	**2** (3.9E-02)	**1** (7.4E-03)	**4** (6.8E-02)
Land transformation, biodiversity	m2 arable land eq	**8** (3.5E-04)	**7** (3.4E-04)	**9** (3.6E-04)	**6** (3.3E-04)	**10** (1.5E-03)	**4** (1.1E-04)	**3** (7.3E-05)	**2** (5.1E-05)	**1** (2.0E-05)	**5** (1.7E-04)
Marine eutrophication	kg N N-lim eq	**5** (2.5E-04)	**4** (2.4E-04)	**7** (2.7E-04)	**6** (2.5E-04)	**10** (3.3E-03)	**8** (3.2E-04)	**3** (2.0E-04)	**2** (1.4E-04)	**1** (1.0E-04)	**9** (4.0E-04)
Mineral resources use	kg deprived	**6** (1.2E-02)	**4** (1.1E-02)	**7** (1.2E-02)	**5** (1.1E-02)	**10** (2.9E-01)	**8** (1.5E-02)	**3** (9.8E-03)	**2** (6.8E-03)	**1** (4.1E-03)	**9** (3.3E-02)
Ozone layer depletion	kg CFC-11 eq	**7** (9.8E-09)	**4** (9.5E-09)	**8** (1.1E-08)	**6** (9.8E-09)	**9** (1.2E-07)	**5** (9.6E-09)	**3** (6.2E-09)	**2** (4.3E-09)	**1** (2.3E-09)	**10** (6.9E-06)
Particulate matter formation	kg PM2.5 eq	**6** (3.9E-04)	**4** (3.7E-04)	**7** (4.0E-04)	**5** (3.8E-04)	**10** (1.1E-02)	**8** (5.6E-04)	**3** (3.6E-04)	**2** (2.5E-04)	**1** (1.1E-04)	**9** (8.0E-04)
Photochemical ozone formation	kgNOxeq	**5** (1.7E-03)	**3** (1.6E-03)	**6** (1.7E-03)	**4** (1.6E-03)	**10** (3.0E-02)	**8** (2.8E-03)	**7** (1.8E-03)	**2** (1.2E-03)	**1** (4.8E-04)	**9** (3.8E-03)
Terrestrial acidification	kg SO2 eq	**4** (1.7E-03)	**3** (1.6E-03)	**6** (1.8E-03)	**5** (1.7E-03)	**10** (5.2E-02)	**8** (3.5E-03)	**7** (2.3E-03)	**2** (1.6E-03)	**1** (6.6E-04)	**9** (5.1E-03)
Water scarcity	m3 world-eq	**6** (1.4E+00)	**5** (1.4E+00)	**8** (1.6E+00)	**7** (1.5E+00)	**10** (5.5E+00)	**4** (1.3E+00)	**3** (8.6E-01)	**2** (6.0E-01)	**1** (4.3E-01)	**9** (3.6E+00)

Ranking is based on unrounded model values and shown in bold, while characterized results are rounded to two significant digits for consistency and are shown in brackets.

3.3.1.2 Contribution Analysis – Single-use Packaging

Figure 3 shows the milk packaging hotspots for GWP. Packaging production is the hotspot for all packaging, representing between 80% to 98% of total impacts in most categories with the exception of marine eutrophication. The processes within packaging production contributing the most to impacts were those with relatively high heat and electricity demand, specifically: solid bleached and unbleached carton board production, plastic feedstock production, and glass production. These processes show large contributions specifically within categories including GWP, FNEU, and particulate matter formation. In addition, chemical-based processes producing effluents such as the pulping process involved in carton board production made high contributions to toxicity-based impact categories detailed in Supplementary Information.

Municipal solid waste treatment was a moderate hotspot, representing between 1% and 18% of the total impacts for all impact categories. In particular, municipal solid waste treatment contributes significantly to marine eutrophication at up to 78% and freshwater ecotoxicity categories where leachate associated with these processes produces burdens detailed in Figure 16 and Figure 9, respectively.

The recycling collection and sorting contributed 1% to 10% of GWP and 0% to 29% of all categories. This is partially due to the avoided burden credits associated with final recycling of polyethylene-based materials, most evident in freshwater eutrophication.

Finally, the filling and transport stages contributed minimally to the GWP life cycle impacts. In other categories, filling impacts were ranged from 0% to 3%, with an outlier within value up to 30% in ionizing radiation due to the contributions from nuclear power generation within the Canadian electricity grid as seen in Figure 13. Transport ranged from 0% to 5%, with high values observed in ozone layer depletion detailed in Figure 18, partially attributed to refrigerants used in transport between the dairy processor and retail distribution.

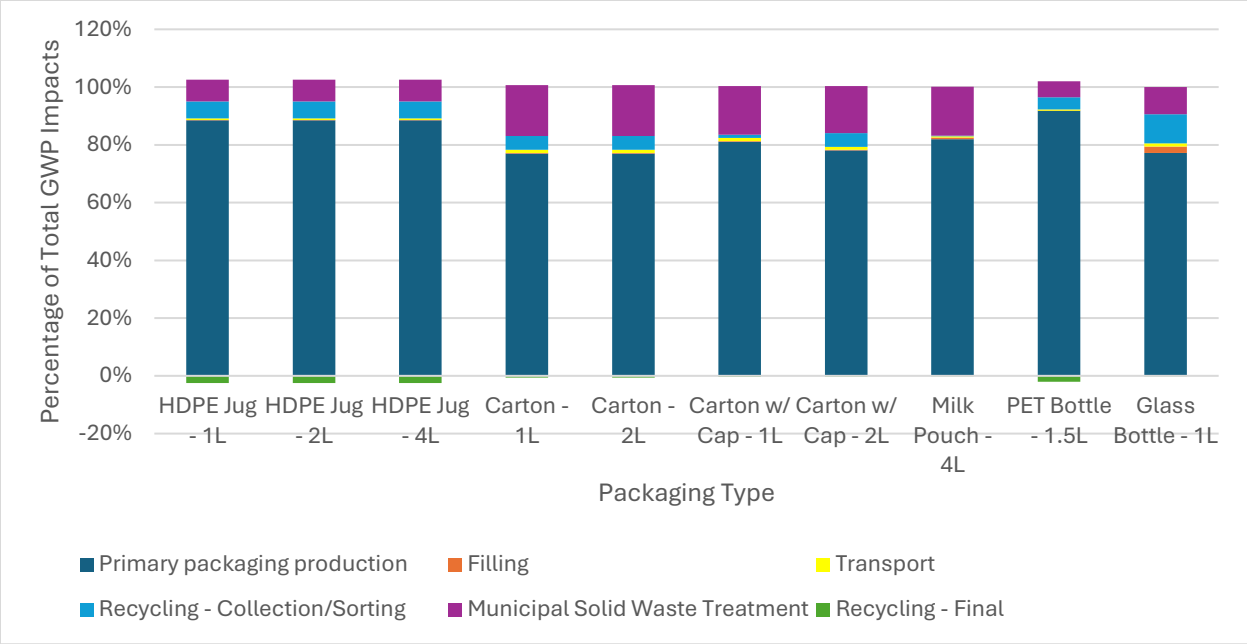


Figure 3 - Contribution analysis to GWP for single-use milk packaging.

3.3.2 Sensitivity Analysis of Current Recycling and Reuse Scenarios

A comprehensive sensitivity analysis was conducted to evaluate the robustness of the results, specifically to test assumptions within the modelling of the packaging system life cycle stages. The sensitivity analysis was conducted on material composition of glass, the liquid packaging board production process, transportation emission standards, the location of where the plastic packaging was converted, the location of plastic source, secondary packaging, cut-off vs avoided impacts approach, and recycling rates. Across all sensitivity analyses, no significant changes in intra-category rankings were observed with the exception of select impact categories. Variations were observed in freshwater eutrophication when recycling rates lowered, and the cut-off approach was applied. These outcomes indicate the importance and sensitivity of end-of-life modelling choices as emphasized by previous literature (Fry et al., 2010; Raadal et al., 2025), and highlight end-of-life processes and allocation approach as consistent areas of uncertainty within packaging LCAs.

Detailed sensitivity analysis discussion can be found in Supplementary Information (Appendix J)

3.3.3 Impacts and hotspots– Reusable Packaging

This section presents the life cycle impact assessment results for reusable plastic and glass milk packaging systems, assuming the minimum (10), maximum (40), and average (25) reuses for glass systems.

Total GWP impacts decrease from 1.03 kg CO2 eq to 0.53 kg CO2 eq at 10 and 25 reuses; however, values begin to rise after 40 reuses as detailed in Figure 3. This can be explained by considering the shifts in high contribution stages as reuses increase. At 10 reuses, the hotspot is primary packaging production, while at 25 reuses packaging production and sanitization are similar, and transportation impacts have increased. At 40 reuses, about 68% of the total impacts are associated with the sanitization and transportation stages.

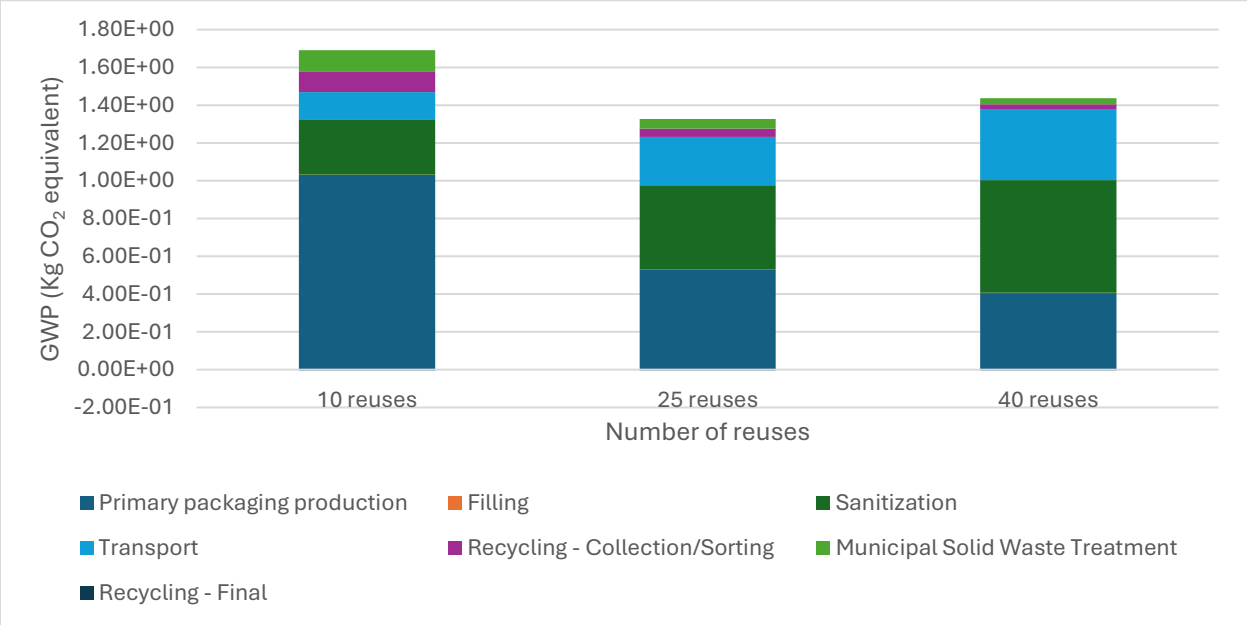


Figure 4 – GWP contribution analysis for reusable glass.

Although 40 reuses reduce the impact of the energy-intensive primary packaging production, the increased sanitization and transport offset this reduction. Sanitization, including the washing and drying of the glass bottles, consumes notable electricity and heat within this process. Similarly, the fossil fuel-based freight transport impacts associated with return logistics have exceeded the contributions of primary packaging production. End-of-life stages including waste sorting and collection, municipal solid waste treatment, and final recycling. Between 10 to

40 reuses, impacts associated with collection and sorting decreased to 2% from 7%. Similar trends are observed with municipal solid waste treatment.

A break-even analysis was conducted to determine at what reuse rate the glass bottle would have lower impacts than the PET and HDPE 1-L jugs. Reusable glass shows lower impacts for a limited number of single-use packaging alternatives (Table 14). Energy-intensive washing and sanitization and additional transport for additional glass bottle reuse cycles limits the potential to reduce total impacts across categories under the current fossil-fuel heavy energy scenarios.

Table 14 Break-even analysis between reusable glass bottles and a single-use 1.5 L PET bottle and 1 L HDPE jug, for various rates of glass bottle reuse

Impact Category	**PET Bottle (1.5L)**	**HDPE Jug – 1L**
Climate Change, ST	10 reuses	25 reuses
Fossil and nuclear energy use	25 reuses	Never
Freshwater Acidification	25 reuses	40 reuses
Freshwater Ecotoxicity	25 reuses	Never
Freshwater Eutrophication	Never	Never
Human Toxicity Cancer	25 reuses	25 reuses
Human Toxicity Non-Cancer	25 reuses	25 reuses
Ionizing Radiation	Never	Never
Land Occupation - Biodiversity	25 reuses	40 reuses
Land Transformation - Biodiversity	40 reuses	Never
Marine Eutrophication	25 reuses	Never
Mineral Resource Use	25 reuses	40 reuses
Ozone Layer Depletion	Never	Never
Particulate Matter Formation	25 reuses	Never
Photochemical Ozone Formation	25 reuses	Never

Impact Category	PET Bottle (1.5L)	HDPE Jug – 1L
Terrestrial Acidification	25 reuses	Never
Water Scarcity	Never	Never

3.4 Scenario Analysis- Canada's Future Energy Grid

The scenario analysis compares the performance of the various packaging systems under the projected 2050 Canadian net-zero electricity grid, for the following systems: reusable 1 L glass bottles; all single-use milk packaging systems; and reusable HDPE and PET jugs. The latter are plausible, reusable packaging materials within the broader SUP and packaging policy. The net-zero electricity grid was used for the packaging production and all other downstream stages, with transportation emission standards and recycling rates remaining the same.

Under the 2050 grid, the reusable 4-L HDPE jug at 10 reuses has the lowest GWP and FNEU (0.10 kg CO2 eq and 3.4 MJ deprived) of all reusable and single-use packaging. The reusable 4-L HDPE maintains lowest GWP and FNEU impacts against all packaging types across all reuse rates, but total impacts continually increase, as opposed to a reduction at 25 reuses. Increases in reuse and associated per-reuse processes drive total impacts, with little reductions in primary packaging impacts from amortization. Cartons have relatively low GWP and FNEU results (0.46-0.52 kg CO2 eq; FNEU 11-14 MJ deprived). Cartons with caps are consistently higher than non-capped cartons, as observed previously due to the added cap mass.

For all the single-use systems, the 2050 grid primarily delivers broad reductions in climate and air-emission indicators, with the same rankings as the baseline results. However, decarbonization shifts burdens to other impact categories. All single-use packaging demonstrated higher ionizing radiation, likely due to increased nuclear electricity generation in the 2050 grid. Cartons reverse rankings in ionizing radiation from those in the 2025 baseline, highlighted by worsened performance against the HDPE jugs. In addition, water scarcity increases across packaging, likely due to increased water use by an increased share of nuclear energy generation, reinforcing that a net-zero grid does not uniformly benefit all impact categories.

Table 15 Life cycle impact assessment results for all single-use and reusable milk packaging across all impact categories under a 2050 grid scenario, at 25 reuses

Impact categories	Unit	Carton - 1L	Carton - 2L	Carton w/ Cap - 1L	Carton w/ Cap - 2L	Glass Bottle - 1L	Glass Bottle - 1L - (Reuse)	HDPE Jug - 1L	HDPE Jug - 2L	HDPE Jug - 4L	HDPE - 4L - (Reuse)	Milk Pouch - 4L	PET Bottle - 1.5L	PET Bottle - 1.5L - (Reuse)
Climate change, long term	kg CO2 eq (long)	**5** (3.6E-01)	**4** (3.5E-01)	**7** (4.3E-01)	**6** (4.0E-01)	**13** (8.9E+00)	**11** (1.0E+00)	**10** (9.6E-01)	**9** (6.2E-01)	**8** (4.3E-01)	**1** (1.0E-01)	**2** (1.7E-01)	**12** (1.6E+00)	**3** (2.9E-01)
Climate change, short term	kg CO2 eq (short)	**5** (4.8E-01)	**4** (4.6E-01)	**8** (5.6E-01)	**6** (5.2E-01)	**13** (1.0E+01)	**10** (1.1E+00)	**11** (1.2E+00)	**9** (7.7E-01)	**7** (5.4E-01)	**1** (1.1E-01)	**2** (2.3E-01)	**12** (1.9E+00)	**3** (3.4E-01)
Fossil and nuclear energy use	MJ deprived	**5** (1.1E+01)	**4** (1.1E+01)	**7** (1.4E+01)	**6** (1.3E+01)	**13** (1.5E+02)	**10** (2.6E+01)	**11** (3.9E+01)	**9** (2.5E+01)	**8** (1.8E+01)	**1** (3.9E+00)	**2** (6.3E+00)	**12** (4.6E+01)	**3** (8.5E+00)
Freshwater acidification	kg SO2 eq	**5** (1.3E-03)	**4** (1.3E-03)	**8** (1.5E-03)	**7** (1.4E-03)	**13** (4.8E-02)	**11** (3.6E-03)	**10** (2.9E-03)	**9** (1.9E-03)	**6** (1.3E-03)	**1** (2.3E-04)	**2** (5.4E-04)	**12** (5.2E-03)	**3** (8.7E-04)
Freshwater ecotoxicity	CTUe	**10** (9.4E+01)	**8** (9.1E+01)	**9** (9.2E+01)	**11** (9.4E+01)	**13** (1.8E+03)	**12** (1.7E+02)	**6** (3.5E+01)	**4** (2.3E+01)	**2** (1.7E+01)	**3** (1.8E+01)	**5** (3.4E+01)	**7** (7.7E+01)	**1** (1.5E+01)
Freshwater eutrophication	kg PO4 P-lim eq	**11** (1.2E-04)	**11** (1.2E-04)	**9** (6.6E-05)	**10** (7.8E-05)	**13** (1.6E-04)	**4** (-1.4E-04)	**1** (-1.0E-03)	**2** (-6.6E-04)	**3** (-4.6E-04)	**6** (-4.0E-05)	**7** (-2.1E-06)	**8** (5.2E-05)	**5** (-4.0E-05)
Human toxicity cancer	CTUh	**6** (8.2E-09)	**5** (7.9E-09)	**8** (9.1E-09)	**7** (8.7E-09)	**13** (1.4E-07)	**11** (1.8E-08)	**10** (1.5E-08)	**9** (9.6E-09)	**4** (6.7E-09)	**2** (2.7E-09)	**1** (2.5E-09)	**12** (3.2E-08)	**3** (5.3E-09)
Human toxicity non-cancer	CTUh	**7** (3.9E-08)	**5** (3.8E-08)	**9** (4.4E-08)	**8** (4.1E-08)	**13** (9.6E-07)	**11** (9.6E-08)	**10** (6.0E-08)	**6** (3.9E-08)	**4** (2.7E-08)	**1** (1.1E-08)	**2** (1.2E-08)	**12** (1.5E-07)	**3** (2.5E-08)
Ionizing radiations	Bq C-14 eq	**6** (2.0E+01)	**5** (1.9E+01)	**10** (2.4E+01)	**8** (2.2E+01)	**13** (1.4E+02)	**12** (9.3E+01)	**7** (2.1E+01)	**3** (1.3E+01)	**2** (9.1E+00)	**9** (2.2E+01)	**1** (4.5E+00)	**11** (6.1E+01)	**4** (1.4E+01)
Land occupation, biodiversity	m2 arable land eq .yr	**11** (5.4E-01)	**9** (5.2E-01)	**12** (5.8E-01)	**9** (5.2E-01)	**13** (6.7E-01)	**6** (8.8E-02)	**8** (9.5E-02)	**5** (6.2E-02)	**4** (4.4E-02)	**3** (1.8E-02)	**1** (8.8E-03)	**7** (9.0E-02)	**2** (1.6E-02)
Land transformation, biodiversity	m2 arable land eq	**11** (3.6E-04)	**9** (3.5E-04)	**12** (3.8E-04)	**9** (3.5E-04)	**13** (1.5E-03)	**7** (1.8E-04)	**6** (1.2E-04)	**5** (7.9E-05)	**4** (5.6E-05)	**2** (3.3E-05)	**1** (2.2E-05)	**8** (2.3E-04)	**3** (3.7E-05)
Marine eutrophication	kg N N-lim eq	**8** (2.4E-04)	**7** (2.3E-04)	**10** (2.7E-04)	**8** (2.4E-04)	**13** (3.3E-03)	**4** (1.2E-04)	**11** (3.1E-04)	**6** (2.0E-04)	**5** (1.4E-04)	**1** (1.7E-05)	**3** (1.0E-04)	**12** (4.1E-04)	**2** (7.1E-05)
Mineral resources use	kg deprived	**7** (1.1E-02)	**6** (1.1E-02)	**9** (1.2E-02)	**8** (1.2E-02)	**13** (3.1E-01)	**11** (2.4E-02)	**10** (1.5E-02)	**5** (9.9E-03)	**4** (6.9E-03)	**1** (2.5E-03)	**2** (4.1E-03)	**12** (3.9E-02)	**3** (6.1E-03)
Ozone layer depletion	kg CFC-11 eq	**7** (9.5E-09)	**6** (9.2E-09)	**9** (1.1E-08)	**8** (9.9E-09)	**11** (1.4E-07)	**10** (2.4E-08)	**5** (8.8E-09)	**4** (5.7E-09)	**2** (3.9E-09)	**3** (4.1E-09)	**1** (2.2E-09)	**13** (7.0E-06)	**12** (8.1E-07)
Particulate matter formation	kg PM2.5 eq	**7** (3.4E-04)	**6** (3.2E-04)	**9** (3.6E-04)	**8** (3.5E-04)	**13** (1.1E-02)	**11** (6.9E-04)	**10** (4.6E-04)	**5** (3.0E-04)	**4** (2.1E-04)	**1** (4.1E-05)	**2** (8.8E-05)	**12** (8.9E-04)	**3** (1.4E-04)
Photochemical ozone formation	kgNOxeq	**6** (1.4E-03)	**5** (1.4E-03)	**8** (1.5E-03)	**7** (1.5E-03)	**13** (2.9E-02)	**10** (2.5E-03)	**11** (2.5E-03)	**9** (1.6E-03)	**4** (1.1E-03)	**1** (2.1E-04)	**2** (4.3E-04)	**12** (4.0E-03)	**3** (6.8E-04)
Terrestrial acidification	kg SO2 eq	**6** (1.4E-03)	**4** (1.4E-03)	**8** (1.6E-03)	**7** (1.5E-03)	**13** (5.1E-02)	**11** (3.7E-03)	**10** (3.1E-03)	**9** (2.0E-03)	**5** (1.4E-03)	**1** (2.5E-04)	**2** (5.7E-04)	**12** (5.4E-03)	**3** (9.1E-04)
Water scarcity	m3 world-eq	**8** (1.9E+00)	**7** (1.8E+00)	**10** (2.1E+00)	**9** (1.9E+00)	**13** (9.0E+00)	**12** (5.4E+00)	**6** (1.7E+00)	**4** (1.1E+00)	**2** (7.5E-01)	**5** (1.2E+00)	**1** (4.9E-01)	**11** (3.9E+00)	**3** (8.9E-01)

Ranking is based on unrounded model values and shown in bold, while characterized results are rounded to two significant digits for consistency and are shown in brackets.

Single-use PET bottles have the highest GWP impacts among plastics (1.87 kg CO2 eq), while the GWP of reusable PET bottles drops to 0.34-0.37 kg CO2 eq across the 10 to 40 reuses. Reusable PET bottles have slightly worse performance relative to the 4-L milk bag and 4-L reusable HDPE milk jug and has lower GWP compared to all other packaging at 25 reuses. Single-use glass remains the highest-impact option (10.3 kg CO2 eq). Reusable glass impacts reduce substantially at 10 and 40 reuses (1.11-1.38 kg CO2 eq); however, it still has the highest impacts compared to both single-use and reusable plastics.

Reusable HDPE shows the lowest GWP at 10 reuses. This suggests that the operational burdens (i.e. sanitization, transportation) are not being offset by the amortization of the impacts of the primary packaging production as seen in the glass and PET reuse (Figure 5). The 2050 reuse scenarios for glass and PET bottles show that impacts reduce quickly at 25 reuses and then increase slightly at 40 reuses, as a result of reuse logistics (see next section). For all reusable packaging systems, operational burdens remain a limiting factor in reducing impacts under a decarbonized grid, with underlying performance driven by low-mass and high-volume packaging design.

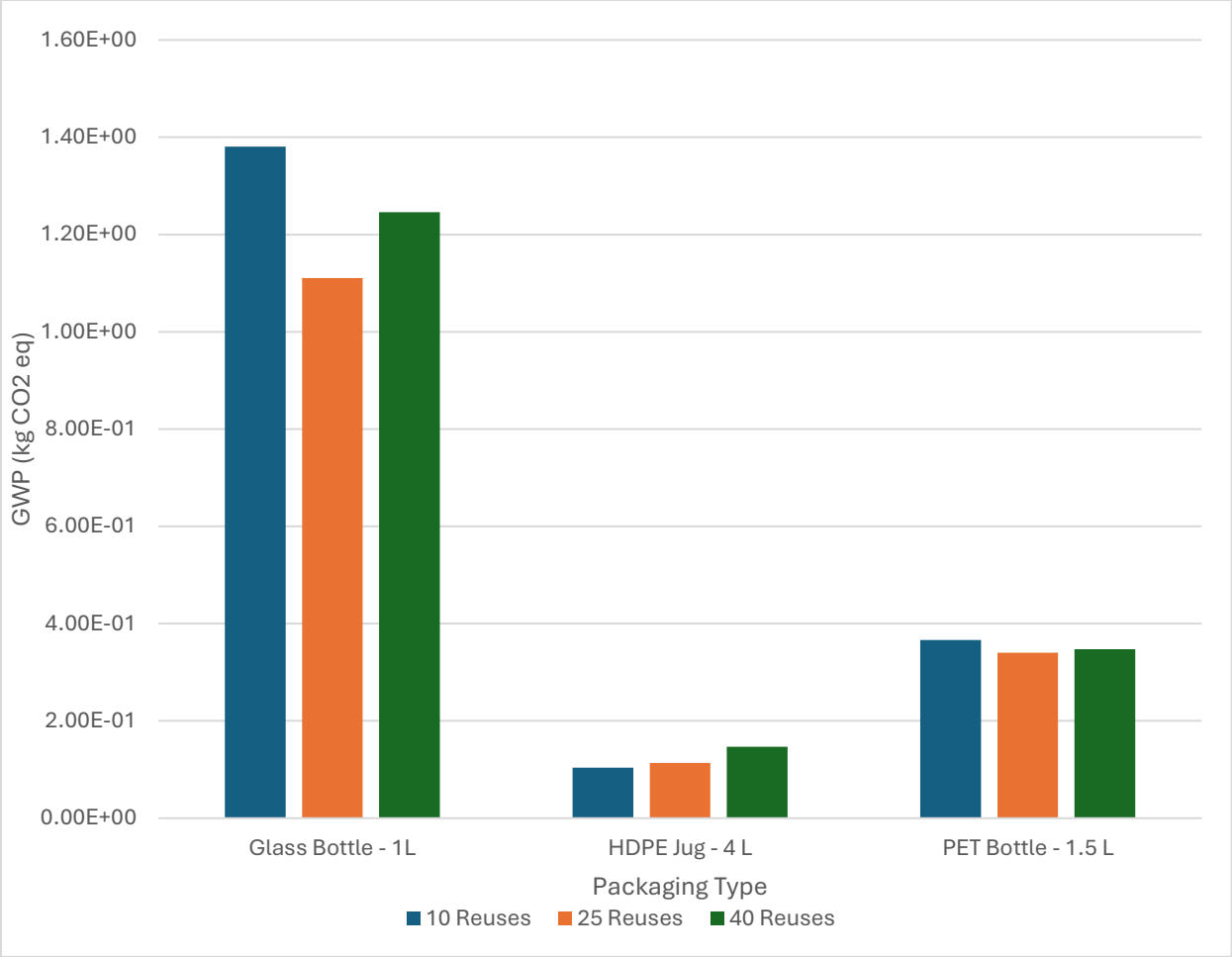


Figure 5 GWP contribution analysis for reusable glass under 2050 grid scenario

3.4.1 Hotspots: Reuse and decarbonized grid

Across reuse scenarios, hotspot structure is influenced primarily by operational burdens rather than grid decarbonization for the 1L glass bottle (Figure 5). Under the 2050 grid, total GWP impacts decline by 13% (40 reuses) to 18% (10 reuses) relative to the 2025 grid. However, the dominant contributors shift primarily with reuse frequency than with grid decarbonization. At 10 reuses, primary packaging production remains the main GWP hotspot contributing (61% in 2025; 68% in 2050), while sanitization contributes to 17% and 14%, respectively. This indicates that decarbonization reduces absolute impacts but can increase the relative contributions of less grid-sensitive stages.

As reuses increase, downstream operations become increasingly influential under both grids. At 25 reuses, sanitization and filling, and transport, comprise a total of 53% in 2025 and 54% in 2050 of the GWP, driven mainly by sanitization. At 40 reuses, downstream reuse operations rise to 68% of total impacts in 2025 and 70% in 2050, again with sanitization as the largest contributor. These results suggest that while the 2050 grid scenario improves overall packaging performance, further reductions for reusable glass depend on reducing operational burdens as reuse rates increase.

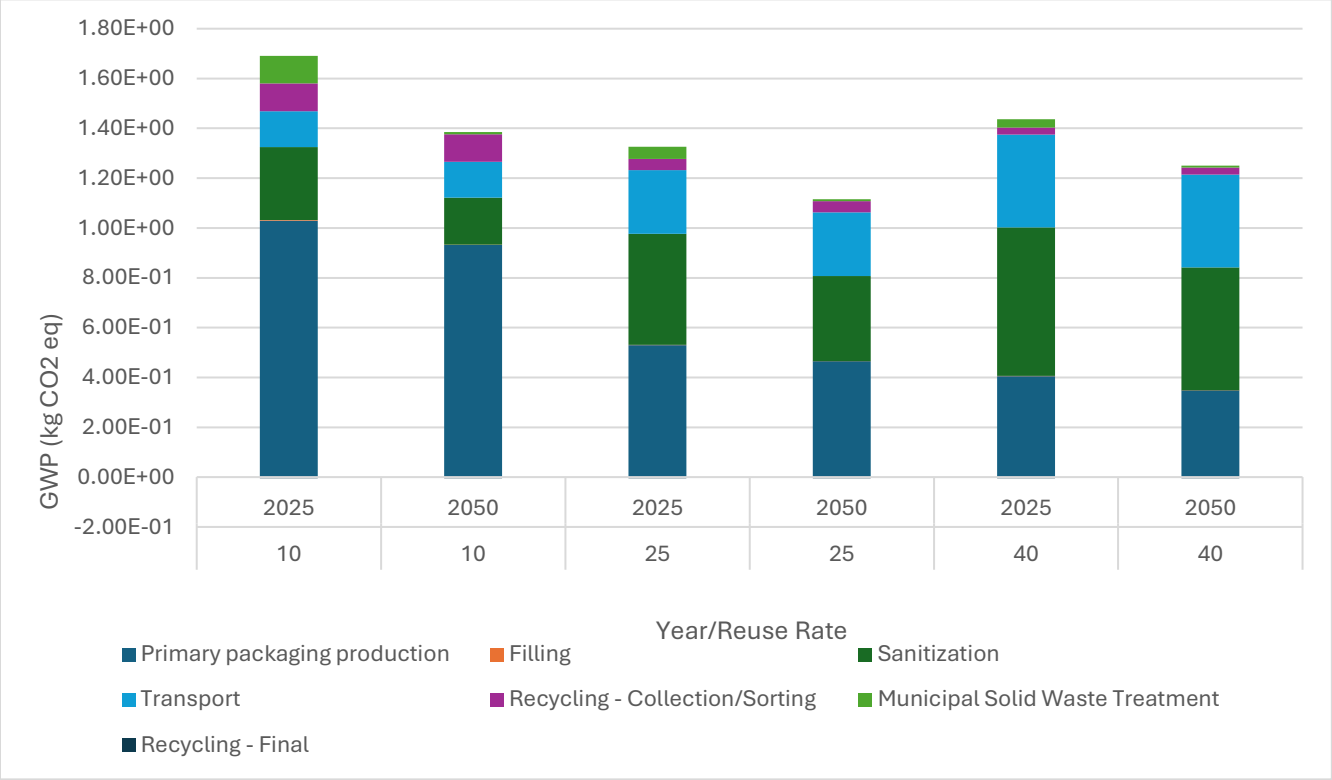


Figure 6 Climate change, short term: life cycle stage contributions by reuse rate and year for the reusable glass bottle

3.5 Discussion

The goals of this study were to compare the environmental impacts associated with the life cycle of commonly available refrigerated milk packaging in Canada under current recycling, reuse and recovery scenarios, with a particular emphasis on glass bottles, and to identify hotspots and trade-offs. Additionally, this study aimed to determine the reuse frequency at which a 1 L

glass bottle achieves lower total impacts than single-use milk packaging types. Finally, this study explored how Canada's projected 2050 low-carbon electricity grid composition influences the life cycle impacts of reusable glass and plastic milk packaging when compared to single-use alternatives. By situating reusable milk packaging within a prospective decarbonized grid, this study helps close a persistent gap in packaging LCAs, where static, present-day comparisons are prevalent. This analysis contributes to the literature in providing a forward-looking evaluation of reusable milk packaging that connects reuse with prospective energy transitions, broadening the understanding of variables and conditions under which reuse can be an effective circular economy tool.

Key Findings & Comparability

Similar to other studies, impacts are driven by packaging mass per functional unit. End-of-life assumptions such as allocation approach also are important factors. Under the 2025 grid, the single-use plastic milk pouch was the lowest impact packaging across a majority of the impact categories, due to the low mass of plastic required to deliver the 12 L functional unit; in contrast, single-use glass has the highest impacts. When expressed on a per-litre basis, this study's findings closely match Sun et al. (2021b) at 0.020 kg CO2 eq to their 0.019 kg CO2 eq for the 4-L milk bag, 0.110 kg CO2 eq to 0.114 kg CO2 eq for the 1-L HDPE jug, and 0.052 kg CO2 eq to 0.066 kg CO2 eq for the 1-L carton with cap. This study confirms Sun et al.'s (2021b) findings that milk bags are the lowest impact milk packaging option in Canada and emphasize the key role of packaging mass as a lever in reducing impacts. These findings align with wider beverage and packaging, which generally show single-use glass has higher climate and energy impacts than lighter packaging types (Brock & Williams, 2020; Cappiello et al., 2022; Ferrara et al., 2021). Among the remaining lightweight formats, results are more context dependent. For example, Meng et al. (2024a) report more favourable performance for HDPE over cartons, while Brock & Williams (2020) identify cartons as the preferred milk packaging type relative to plastics and glass. These differences are likely driven by methodological and contextual choices, including functional unit, end-of-life modeling approach, assumed recycling rates, and background energy sources (Bher & Auras, 2024).

The environmental performance of reusable glass compared to other packaging systems is dependent on reuse cycles, sanitization efficiency, and return logistics, and less so on the packaging material. Also, as glass reuses increase, the hotspot shifts from primary packaging

production to sanitization and transportation. This shift is consistent with reuse literature, where performance is dictated by reuse rate, sanitization energy, and transport distance (Le Féon et al., 2024a), and with glass versus plastic comparisons showing retail distribution transport assumptions can change conclusions (Ferrara et al., 2021).

Scenario Analysis

Under the 2050 grid, decarbonized electricity improves performance of energy-intensive stages, including glass production and sanitization; however, transportation and sanitization remain constraints to environmental performance relative to other packaging, even at higher reuse rates and a more decarbonized grid. Such findings are consistent with those from Le Feon et al. (2024a), in which reusable glass performance can be improved with reuses but only to a ceiling set by impacts produced by system-specific constraints such as bottle mass and transportation distances.

A distinct insight is the performance of reusable plastics relative to reusable glass under the 2050 scenario. Under these scenario conditions, the reusable 4-L HDPE jug and 1.5-L PET bottle have the lowest impacts in GWP and FUNE, and for key indicators, outperform glass by substantial margins. For the HDPE jug, increasing beyond 10 reuses reduces environmental performance, compared to the PET and glass reuse systems. These findings substantiate a mechanism identified by Le Feon et al. (2024b) where lighter container mass reduces both transport burdens and the amount of reuses required to offset primary packaging production impacts. With respect to material substitution, these results suggest that reuse strategies based on lightweight materials may deliver more reliable environmental performance than switching to heavier alternatives such as glass. Meng et al. (2024a) have cautioned the replacement of plastics with alternatives which risks increasing GWP under current conditions.

A novel insight emerging from the scenario analysis suggests that reuse under a decarbonized grid is not inherently beneficial for all packaging types, as impacts for the reusable lightweight HDPE jug increased as reuse cycles increased. Such findings present a distinct contribution to growing literature related to milk packaging and circularity. However, these findings are based on a narrow set of impact categories, and microplastic impacts, as well as biodiversity issues have not been studied to date and limit the ability to understand which packaging has the lowest

trade-offs. Moreover, these results demonstrate that decarbonizing the electricity grid does not produce uniform benefits across all impact categories.

3.6 Limitations

There are some limitations that require further investigation. First, the system boundaries excluded milk production and losses due to packaging failure. While this choice allows for comparability with previous literature, it omits potential differences and impacts associated with milk containment and protection associated with resealable and non-resealable packaging formats, such as milk pouches. Second, end-of-life modelling uses the avoided burdens approach which provides environmental credits for the displacement of virgin material by recycling. Although the sensitivity analysis examining the cut-off approach demonstrated that relative rankings were robust, end-of-life modelling remains a significant source of uncertainty in packaging LCAs (Fry et al., 2010; Raadal et al., 2025). Third, carbon capture and storage for the 2050 scenario was not accounted for in this study. Finally, current LCA methods and databases do not comprehensively capture microplastic emissions nor model their fate (Corella-Puertas et al., 2023; Miller, 2022), which may lead to underestimation of human and ecosystem-related impacts associated with plastics, both in this study and in prior studies.

Despite these limitations, this study contributes to the broader literature on packaging LCA by providing a comprehensive comparison of milk packaging in the Canadian context. Furthermore, the integration of reusable glass reuse scenarios under prospective 2050 grid decarbonization offer novel insights into the potential impacts of energy transitions on circular packaging strategies. These strengths provide a foundation for further improvement, while the limitations give opportunity for future research.

3.7 Conclusion

This study provides a comprehensive life cycle assessment of Canadian milk packaging systems and reinforces a consistent conclusion across packaging LCAs. Impacts are primarily shaped by primary packaging production and system design choices, rather than any single downstream stage. By modelling both current and prospective energy grids, the study shows how

energy transitions can shift the relative importance of production, logistics, and circularity assumptions, and therefore why packaging strategies should be evaluated alongside infrastructure conditions.

From a policy perspective, the findings support moving away from material substitution as a default approach and toward approaches reducing packaging mass and improving circular performance. In practice, this includes lightweighting, design for recyclability, and higher recycled content mandates within national packaging policy and extended producer responsibility frameworks. Circular economy efforts would also benefit from aligning packaging initiatives with grid decarbonization, in addition to targeted improvements within reuse logistics and cleaning infrastructure.

Future research direction should include developing Canadian-specific inventories for feedstock production, packaging converting and filling processes, and by more explicit data metrics for systems where food loss and refrigeration are relevant. Methodologically, decision-support tools that integrate uncertainty and stakeholder priorities such as Stochastic Multi-Attribute Analysis (SMAA) offer a clear pathway to translate trade-offs into transparent and context-specific guidance.

Overall, this study advances packaging LCA evidence by providing a Canada-specific comparison across single-use and reusable formats and by testing how relative performance changes under prospective grid decarbonization. As circular economy infrastructure and life cycle data improve, this work provides a foundation for more regionally-specific and transparent assessments to guide policy and packaging design across the food and beverage sector and beyond.

4 Conclusion & Recommendations - Sustainability Management

This study demonstrates the critical role of Life Cycle Assessment within sustainability management, particularly as organizations and policymakers seek to balance environmental performance, operational feasibility, and long-term circular economy objectives. By evaluating Canadian milk packaging systems using a life cycle assessment approach in alignment with ISO guidelines (14040/14044), the study responds to methodological inconsistencies and gaps within the packaging LCA literature. Meta-analytical studies, such as Bher and Auras (2024), highlight substantial discrepancies across existing studies arising from diverse system boundaries, data quality, and modelling assumptions. By adopting a transparent and consistent methodology across all commonly available packaging formats in Canada, this thesis contributes to greater clarity within the literature and strengthens the reliability of LCA as a decision-making tool within sustainability management.

A central finding of the study is that the environmental performance of reusable glass bottles is not fixed but influenced by system-specific conditions. The results reaffirm that reusable glass is not inherently superior to single-use alternatives; rather, its performance is determined by reuse rate, sanitization energy demand, and return-transport distances. These findings align with Le Féon et al. (2024a), who emphasize that the environmental outcomes of reusable glass bottle systems is highly-context specific and contingent on combined technological, operational, and regional energy characteristics. This thesis extends this insight to the Canadian context, demonstrating that the benefits of reusable glass are only under particular reuse infrastructure and that these benefits increase as Canada's electricity grid becomes decarbonized.

Under the 2025 grid, single-use glass has the worst environmental performance for all impacts apart from ozone layer depletion. Reusable glass decreases impacts up to 88% at 25 reuses against the single-use glass bottle. Due to energy-intensive sanitization and transport-related emissions, the reusable glass bottle has worse environmental performance for most impacts compared to most of the single-use packaging formats.

However, when modelled under a 2050 net-zero grid, these constraints are reduced substantially as demonstrated by an 18% reduction in total impacts at 10 reuses for GWP. In this future scenario, reusable glass has similar or lower impacts to the 1.5-L PET bottle across several impact categories and the 1-L HDPE jug across climate change and energy categories. Reusable glass does not outperform any non-glass, single-use packaging in freshwater ecotoxicity, ionizing radiations, and water scarcity at any reuse rate. In contrast, the reusable plastic scenarios in 2050 indicate that lightweight reusable plastic systems can still outperform reusable glass at common reuse rates, largely due to lower container mass. In this way, grid decarbonization does not make reuse universally superior, but expands the conditions under which reuse can be competitive, while reinforcing that container mass and logistics remain major determinants of performance across reuse systems.

This thesis also contributes to sustainability management by situating packaging decision within broader socio-technical and policy environments. As Canadian jurisdictions expand extended producer responsibility frameworks, consider further developing single-use plastics regulations, and explore circular economy strategies, these findings underscore that environmental outcomes cannot be adequately evaluated through material-based decisions alone. Instead, successful implementation of reuse systems requires coordination across energy policy, waste governance, transportation logistics, and consumer participation. By illustrating how environmental performance shifts under changing national electricity grid conditions, the study highlights the value of LCA for informing long-term sustainability planning.

In conclusion, this thesis provides a rigorous and regionally-specific analysis of single-use and reusable milk packaging systems, contributing to the broader literature om sustainable packaging. Furthermore, it reinforces the need for evidence-based, context-specific decision-making and demonstrates how system-level interactions shape the viability of reuse against single-use alternatives. Nevertheless, a major gap in all packaging research is the lack of accounting for microplastic impacts and other impact categories due to lack of information and data, or lack of impact assessment methods to handle these environmental issues.

4.1 Recommendations

The findings of this thesis indicate that the successful integration of reusable packaging into Canadian sustainability strategy requires a systems-based approach with a pragmatic outlook toward operations and accounts for long-term infrastructure change, exemplified in the 2050 net-zero agenda. For industry, reuse systems should be implemented only where the conditions, such as high reuse rates, optimized return logistics, and energy-efficient sanitization, can be realistically achieved. Investments into efficient washing infrastructure and equipment, return systems, and durable packaging stock that minimizes breakage will be essential in ensuring real-world performance can meet and outperform modelled outcomes. Similarly, efforts to reduce transportation distances through co-location of washing and filling facilities, route optimization, and regional system design should be prioritized to mitigate the increasing transportation burdens observed in the baseline current day scenarios and those modelled in the future.

Sanitization was identified as a dominant contributor to the impacts of reusable glass under several reuse rates, as such the environmental performance of reuse systems is strongly influenced by Canada's progress toward grid decarbonization. Policymakers and industry should therefore consider the timing of reuse system strategy and prospective deployment relative to changes in electricity generation. Reuse systems operating under high carbon intensity mixes may underperform and generate unintended trade-offs, whereas systems launched in conjunction with low-carbon energy sources are likely to demonstrate improved environmental performance.

At a governance level, regionalized policy design is necessary to ensure that reuse mandates align with infrastructural capacity. While this study approaches packaging at a national level, a uniform national reuse target may risk creating situations in which certain jurisdictions realize environmental benefits while others experience net increases in impacts. In addition, significant governance attention should be placed on enabling infrastructure rather than the packaging itself. The sensitivity results highlight that the viability of reuseable systems is not dependant on bottle design but rather on supporting logistics. An infrastructure-focused investment strategy by both federal and provincial governments could allow for stronger foundations forwarding circular economy strategy, as opposed to shifting consumer behaviour or isolated industry activities and innovation.

In conclusion, although reusable glass can surpass single-use packaging under certain conditions, its advantages emerge only when optimized reuse rates, efficient return logistics, low-carbon energy supply, and evidence-based governance operate in unison. The path to sustainable packaging will be defined less by the materials themselves than by the policies, infrastructures, and behaviours that shape their performance, emphasizing a future where system-wide coordination determines sustainability.

References

Ahmadi, L., Shadbahr, J., Shim, G. W., & Hawco, M. (2023). Review of the global evolution of regulations on single-use plastics and lessons drawn for Canada. *Waste Management & Research*, 0734242X231184451. https://doi.org/10.1177/0734242X231184451

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977–1984. https://doi.org/10.1098/rstb.2008.0304

Anthesis. (2024, March 12). *EPR Canada: Provincial Updates & Compliance Guide*. https://www.anthesisgroup.com/insights/epr-canada-updates-and-prep-advice/

Auclair, O., Han, Y., & Burgos, S. A. (2019). Consumption of Milk and Alternatives and Their Contribution to Nutrient Intakes among Canadian Adults: Evidence from the 2015 Canadian Community Health Survey—Nutrition. *Nutrients*, *11*(8), Article 8. https://doi.org/10.3390/nu11081948

Bertolini, M., Bottani, E., Vignali, G., & Volpi, A. (2016). Comparative Life Cycle Assessment of Packaging Systems for Extended Shelf Life Milk. *Packaging Technology & Science*, *29*(10), 525–546. https://doi.org/10.1002/pts.2235

Bher, A., & Auras, R. (2024). Life cycle assessment of packaging systems: A meta-analysis to evaluate the root of consistencies and discrepancies. *Journal of Cleaner Production*, *476*, 143785. https://doi.org/10.1016/j.jclepro.2024.143785

Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. Z. (2018). LCA History. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 17–30). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_3

Błażejewski, T., Walker, S. R., Muazu, R. I., & Rothman, R. H. (2021). Reimagining the milk supply chain: Reusable vessels for bulk delivery. *Sustainable Production and Consumption*, *27*, 1030–1046. https://doi.org/10.1016/j.spc.2021.02.030

Bonadies, I., Capuano, R., Avolio, R., Castaldo, R., Cocca, M., Gentile, G., & Errico, M. E. (2022). Sustainable Cellulose-Aluminum-Plastic Composites from Beverage Cartons Scraps and Recycled Polyethylene. *Polymers*, *14*(4), 807. https://doi.org/10.3390/polym14040807

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G. H., Hilleary, M. A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L. R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., & Rochman, C. M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*, *369*(6510), 1515–1518. https://doi.org/10.1126/science.aba3656

Brock, A., & Williams, I. D. (2020). Life Cycle Assessment of Beverage Packaging. *Detritus*, (13), 47. https://doi.org/10.31025/2611-4135/2020.14025

Burek, J., Kim, D., Nutter, D., Selke, S., Auras, R., Cashman, S., Sauer, B., & Thoma, G. (2018). Environmental Sustainability of Fluid Milk Delivery Systems in the United States. *Journal of Industrial Ecology*, *22*(1), 180–195. https://doi.org/10.1111/jiec.12531

Cabernard, L., Pfister, S., Oberschelp, C., & Hellweg, S. (2022). Growing environmental footprint of plastics driven by coal combustion. *Nature Sustainability*, *5*(2), 139–148. https://doi.org/10.1038/s41893-021-00807-2

Canada Energy Regulator. (2023). *Canada's Energy Future Data Appendices.* [Dataset]. https://doi.org/10.35002/zjr8-8x75

Canada Plastics Pact. (2024). *Plastic Packaging Flows: A Progress Report* (pp. 1–125). https://plasticspact.ca/wp-content/uploads/2025/05/Canada-wide-Plastic-Packaging-Flows-2024-Progress-Report-Canada-Plastics-Pact.pdf

Canadian Council of Ministers on the Environment. (2018). *Strategy on Zero Plastic Waste* (PN 1583). https://ccme.ca/en/res/strategyonzeroplasticwaste.pdf

Cappiello, G., Aversa, C., Genovesi, A., & Barletta, M. (2022). Life cycle assessment (LCA) of bio-based packaging solutions for extended shelf-life (ESL) milk. *Environmental Science and Pollution Research*, *29*(13), 18617–18628. https://doi.org/10.1007/s11356-021-17094-1

Carton Council of Canada. (2024, January). *Carton Recycling*. https://www.recyclecartons.ca/carton-recycling/#howarewedoing

CM Consulting. (2018). *Who pays what? An analysis of beverage container collection and costs in Canada*. https://www.cmconsultinginc.com/wp-content/uploads/2018/10/WPW-2018-FINAL-5OCT2018.pdf

Corella-Puertas, E., Hajjar, C., Lavoie, J., & Boulay, A.-M. (2023). MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments. *Journal of Cleaner Production*, *418*, 138197. https://doi.org/10.1016/j.jclepro.2023.138197

Dey, A., Dhumal, C. V., Sengupta, P., Kumar, A., Pramanik, N. K., & Alam, T. (2021). Challenges and possible solutions to mitigate the problems of single-use plastics used for packaging food items: A review. *Journal of Food Science and Technology*, *58*(9), 3251–3269. https://doi.org/10.1007/s13197-020-04885-6

Diggle, A., & Walker, T. R. (2020). Implementation of harmonized Extended Producer Responsibility strategies to incentivize recovery of single-use plastic packaging waste in Canada. *Waste Management*, *110*, 20–23. https://doi.org/10.1016/j.wasman.2020.05.013

Diggle, A., & Walker, T. R. (2022). Environmental and Economic Impacts of Mismanaged Plastics and Measures for Mitigation. *Environments*, *9*(2), Article 2. https://doi.org/10.3390/environments9020015

Edwards, S., Wasserman, M., Carhart, J., Heath, R., Thirroueiz, E., Giroux, L., & Millette, S. (2024). *Achieving 90% Recovery of Plastic Beverage Containers*.

Ekvall, T., Bjorklund, A., Sandin, G., Jelse, K., Lagergren, J., & Rydberg, M. (2020). *Modeling recycling in life cycle assessment* (Nos. 47270–1). IVL Swedish Environmental Research Institute. https://www.diva-portal.org/smash/get/diva2:1549446/FULLTEXT01.pdf

Environment and Climate Change Canada & Health Canada. (2020). *Science Assessment of Plastic Pollution* (Nos. En14-424/2020E-PDF; p. 195). file:///C:/Users/alexa/Downloads/Science-assessment-plastic-pollution.pdf

Ferrara, C., & De Feo, G. (2018). Life Cycle Assessment Application to the Wine Sector: A Critical Review. *Sustainability*, *10*(2), Article 2. https://doi.org/10.3390/su10020395

Ferrara, C., De Feo, G., & Picone, V. (2021). LCA of Glass Versus PET Mineral Water Bottles: An Italian Case Study. *Recycling*, *6*(3), Article 3. https://doi.org/10.3390/recycling6030050

Finkbeiner, M. (2014). The International Standards as the Constitution of Life Cycle Assessment: The ISO 14040 Series and its Offspring. In W. Klöpffer (Ed.), *Background and Future Prospects in Life Cycle Assessment* (pp. 85–106). Springer Netherlands. https://doi.org/10.1007/978-94-017-8697-3_3

Food and Agriculture Organization of the United Nations. (2010). *Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment*. https://www.fao.org/3/k7930e/k7930e00.pdf

Ford, H. V., Jones, N. H., Davies, A. J., Godley, B. J., Jambeck, J. R., Napper, I. E., Suckling, C. C., Williams, G. J., Woodall, L. C., & Koldewey, H. J. (2022). The fundamental links between climate change and marine plastic pollution. *Science of The Total Environment*, *806*, 150392. https://doi.org/10.1016/j.scitotenv.2021.150392

Fry, J. M., Hartlin, B., Wallén, E., & Aumônier, S. (2010). *Life cycle assessment of example packaging systems for milk*. https://kidv.nl/media/engelse_rapporten/life-cycle-assessment-of-example-packaging-systems-for-milk.pdf?1.2.2

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). *Production, use, and fate of all plastics ever made*. *3*(7). https://doi.org/10.1126/sciadv.1700782

Government of Canada. (2002, September 27). *History of Canada's Food Guides from 1942 to 2007* [Education and awareness;guidance]. https://www.canada.ca/en/health-canada/services/canada-food-guide/about/history-food-guide.html

Government of Canada. (2019). *CER – Provincial and Territorial Energy Profiles – Canada*. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-canada.html#

Government of Canada. (2022, July 13). *Single-use Plastics Prohibition Regulations: Overview*. Single-Use Plastics Prohibition Regulations - Overview. https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste/single-use-plastic-overview.html

Government of Canada. (2023, May 24). *CER – Canada's Energy Transition: Historical and Future Changes to Energy Systems – Update – An Energy Market Assessment*. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/canadas-energy-transition/canadas-energy-transition-historical-future-changes-energy-systems-update-energy-market-assessment-trends-canada.html

Government of Canada. (2024, February 2). *Net-zero emissions by 2050—Canada.ca*. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

Government of Canada, S. C. (2023, June 9). *The message in a bottle: Plastic packaging waste*. https://www.statcan.gc.ca/o1/en/plus/3797-message-bottle-plastic-packaging-waste

GreenDelta. (2024). *openLCA* (Version 2.4) [Window x64]. GreenDelta. https://www.openlca.org/download/

Harrison, M., Sugar, S., Vaillancourt, C., Fong, A., & Sathananthan, G. (2023, November 23). *Federal Court rules that the basis for the Canadian Government's prohibitions on Single-Use Plastics is unconstitutional | McCarthy Tétrault*. McCarthy Tetraut. https://www.mccarthy.ca/en/insights/blogs/consumer-markets-perspectives/federal-court-rules-basis-canadian-governments-prohibitions-single-use-plastics-unconstitutional

Hunt, Robert G., Franklin, W. E., & Hunt, R. G. (1996). LCA — How it came about. *The International Journal of Life Cycle Assessment*, *1*(1), 4–7. https://doi.org/10.1007/BF02978624

Ibrahim, I. D., Hamam, Y., Sadiku, E. R., Ndambuki, J. M., Kupolati, W. K., Jamiru, T., Eze, A. A., & Snyman, J. (2022). Need for Sustainable Packaging: An Overview. *Polymers*, *14*(20), 4430. https://doi.org/10.3390/polym14204430

International Organization for Standardization. (2006a). *ISO 14040:2006*. ISO. https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). *ISO 14044:2006*. ISO. https://www.iso.org/standard/38498.html

Kan, M., & Miller, S. A. (2022). Environmental impacts of plastic packaging of food products. *Resources, Conservation and Recycling*, *180*, 106156. https://doi.org/10.1016/j.resconrec.2022.106156

Karaman, A. D., Özer, B., Pascall, M. A., & Alvarez, V. (2015). Recent Advances in Dairy Packaging. *Food Reviews International*, *31*(4), 295–318. Scopus. https://doi.org/10.1080/87559129.2015.1015138

Lavers, J., Bond, A., & Rolsky, C. (2022). *Far from a distraction: Plastic pollution and the planetary emergency*. *272*. https://doi.org/10.1016/j.biocon.2022.109655

Le Féon, S., Gésan-Guiziou, G., Yannou-Le Bris, G., Aubin, J., & Pénicaud, C. (2024a). Life cycle assessment based optimization of scenarios of reusable glass bottles using context-specific key parameters. *Cleaner Environmental Systems*, *15*, 100225. https://doi.org/10.1016/j.cesys.2024.100225

Le Féon, S., Gésan-Guiziou, G., Yannou-Le Bris, G., Aubin, J., & Pénicaud, C. (2024b). Life cycle assessment based optimization of scenarios of reusable glass bottles using context-specific key parameters. *Cleaner Environmental Systems*, *15*, 100225. https://doi.org/10.1016/j.cesys.2024.100225

Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, *5*(1), 1–11. https://doi.org/10.1057/s41599-018-0212-7

L.E.K. Consulting Australia Ltd. (2021). *Milk—Supply Chain Benchmarking Report*.

Lewanska, M., & Barczynska, R. (2025). Microplastics from Food Packaging: Polymer Degradation Pathways, Environmental Distribution, and Effects on the Human Gastrointestinal Tract. *Polymers*, *17*(21), 2923. https://doi.org/10.3390/polym17212923

MadeHow. (1994). *How milk carton is made—Material, manufacture, making, used, processing, dimensions, product, machine*. https://www.madehow.com/Volume-4/Milk-Carton.html

Marsh, K., & Begusu, B. (2007). *Food Packaging—Roles, Materials, and Environmental Issues*. https://ift.onlinelibrary.wiley.com/doi/10.1111/j.1750-3841.2007.00301.x

Marson, A., Piron, M., Zuliani, F., Fedele, A., & Manzardo, A. (2023). Comparative Life Cycle Assessment in the plastic sector: A systematic literature review. *Cleaner Environmental Systems*, *9*, 100119. https://doi.org/bio

Meng, F., Brandão, M., & Cullen, J. M. (2024a). Replacing Plastics with Alternatives Is Worse for Greenhouse Gas Emissions in Most Cases. *Environmental Science & Technology*, *58*(6), 2716–2727. https://doi.org/10.1021/acs.est.3c05191

Meng, F., Brandão, M., & Cullen, J. M. (2024b). Replacing Plastics with Alternatives Is Worse for Greenhouse Gas Emissions in Most Cases. *Environmental Science & Technology*, *58*(6), 2716–2727. https://doi.org/10.1021/acs.est.3c05191

Miller, S. A. (2022). The capabilities and deficiencies of life cycle assessment to address the plastic problem. *Frontiers in Sustainability*, *3*. https://www.frontiersin.org/articles/10.3389/frsus.2022.1007060

Molina-Besch, K., Wikström, F., & Williams, H. (2019). The environmental impact of packaging in food supply chains—Does life cycle assessment of food provide the full picture? *The*

International Journal of Life Cycle Assessment, *24*(1), 37–50. https://doi.org/10.1007/s11367-018-1500-6

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2020). Environmental Impact of Food Packaging Materials: A Review of Contemporary Development from Conventional Plastics to Polylactic Acid Based Materials. *Materials*, *13*(21), 4994. https://doi.org/10.3390/ma13214994

Organisation for Economic Co-operation and Development. (2023). *Climate change and plastics pollution: Synergies between two crucial environmental challenges*. https://www.oecd.org/environment/plastics/Policy-Highlights-Climate-change-and-plastics-pollution-Synergies-between-two-crucial-environmental-challenges.pdf

Pellegrino, J. L. (2002). *Energy and Environmental Profile of the U.S. Glass Industry*. https://www.energy.gov/sites/prod/files/2013/11/f4/glass2002profile.pdf

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environmental Science & Technology*, *56*(3), 1510–1521. https://doi.org/10.1021/acs.est.1c04158

Raadal, H. L., Saxegård, S. A., Modahl, I. S., & Callewaert, P. (2025). Comparison of single-use and reuse beverage containers in Norway using different recycling modelling approaches. *Journal of Cleaner Production*, *519*, 146003. https://doi.org/10.1016/j.jclepro.2025.146003

Rejeesh, C. R., & Anto, T. (2023). *Packaging of milk and dairy products: Approaches to sustainable packaging*. *62*. https://doi.org/10.1016/j.matpr.2022.07.467

Richmond, M. L., & Stine, C. M. (1982). Historical Aspects of Packaging Fluid Milk in the United States. *Journal of Dairy Science*, *65*(8), 1666–1672. Scopus. https://doi.org/10.3168/jds.S0022-0302(82)82396-5

Saleh, Y. (2016). Comparative life cycle assessment of beverages packages in Palestine. *Journal of Cleaner Production*, *131*, 28–42. https://doi.org/10.1016/j.jclepro.2016.05.080

Sharma, S., Sharma, V., & Chatterjee, S. (2023). Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment—A review. *Science of The Total Environment*, *875*, 162627. https://doi.org/10.1016/j.scitotenv.2023.162627

Shen, M., Huang, W., Chen, M., Song, B., Zeng, G., & Zhang, Y. (2020). (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. *Journal of Cleaner Production*, *254*, 120138. https://doi.org/10.1016/j.jclepro.2020.120138

Somogyi, A., & Chesnot, V. (2024). Glass packaging and its contribution to the UN Sustainable Development Goals. *International Journal of Applied Glass Science*, *15*(4), 342–349. https://doi.org/10.1111/ijag.16677

Stefanini, R., Borghesi, G., Ronzano, A., & Vignali, G. (2021a). Plastic or glass: A new environmental assessment with a marine litter indicator for the comparison of pasteurized milk bottles. *The International Journal of Life Cycle Assessment*, *26*(4), 767–784. https://doi.org/10.1007/s11367-020-01804-x

Stefanini, R., Borghesi, G., Ronzano, A., & Vignali, G. (2021b). Plastic or glass: A new environmental assessment with a marine litter indicator for the comparison of pasteurized

milk bottles. *The International Journal of Life Cycle Assessment*, *26*(4), 767–784. https://doi.org/10.1007/s11367-020-01804-x

Sun, J.-P., Calahoo, C., Brown, C., & White, M. A. (2021a). Environmental impact assessment of milk packaging in Canada. *Journal of Cleaner Production*, *325*, 129347. https://doi.org/10.1016/j.jclepro.2021.129347

Sun, J.-P., Calahoo, C., Brown, C., & White, M. A. (2021b). Environmental impact assessment of milk packaging in Canada. *Journal of Cleaner Production*, *325*, 129347. https://doi.org/10.1016/j.jclepro.2021.129347

The Association of Postconsumer Recyclers. (2014). *APR Full Sleeve Label Working Group – Final Report*. https://kidv.nl/media/publicaties/apr_shrink_lab.pdf?1.1.6

Walker, T. R., & Fequet, L. (2023). Current trends of unsustainable plastic production and micro(nano)plastic pollution. *TrAC Trends in Analytical Chemistry*, *160*, 116984. https://doi.org/10.1016/j.trac.2023.116984

Walker, T. R., McGuinty, E., Charlebois, S., & Music, J. (2021). Single-use plastic packaging in the Canadian food industry: Consumer behavior and perceptions. *Humanities and Social Sciences Communications*, *8*(1), 80. https://doi.org/10.1057/s41599-021-00747-4

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Woods, J. S., Rødder, G., & Verones, F. (2019). An effect factor approach for quantifying the entanglement impact on marine species of macroplastic debris within life cycle impact

assessment. *Ecological Indicators*, *99*, 61–66. https://doi.org/10.1016/j.ecolind.2018.12.018

Woods, J. S., Verones, F., Jolliet, O., Vázquez-Rowe, I., & Boulay, A.-M. (2021). A framework for the assessment of marine litter impacts in life cycle impact assessment. *Ecological Indicators*, *129*, 107918. https://doi.org/10.1016/j.ecolind.2021.107918

Xie, M., Li, L., Qiao, Q., Sun, Q., & Sun, T. (2011). A comparative study on milk packaging using life cycle assessment: From PA-PE-Al laminate and polyethylene in China. *Journal of Cleaner Production*, *19*(17–18), 2100–2106. Scopus. https://doi.org/10.1016/j.jclepro.2011.06.022

Appendix A - Baseline Single-Use Packaging Results

Impact categories	Unit	Carton - 1L	Carton - 2L	Carton w/ Cap - 1L	Carton w/ Cap - 2L	Glass Bottle - 1L	HDPE Jug - 1L	HDPE Jug - 2L	HDPE Jug - 4L	Milk Pouch - 4L	PET Bottle - 1.5L
Climate change, long term	kg CO2 eq (long)	4.17E-01	4.01E-01	4.85E-01	4.52E-01	9.53E+00	1.08E+00	6.95E-01	4.82E-01	1.96E-01	1.60E+00
Climate change, short term	kg CO2 eq (short)	5.37E-01	5.17E-01	6.21E-01	5.79E-01	1.10E+01	1.32E+00	8.46E-01	5.87E-01	2.54E-01	1.86E+00
Fossil and nuclear energy use	MJ deprived	1.05E+01	1.02E+01	1.36E+01	1.24E+01	1.57E+02	3.98E+01	2.56E+01	1.77E+01	6.54E+00	4.49E+01
Freshwater acidification	kg SO2 eq	1.58E-03	1.52E-03	1.72E-03	1.60E-03	4.92E-02	3.34E-03	2.14E-03	1.49E-03	6.30E-04	4.89E-03
Freshwater ecotoxicity	CTUe	9.89E+01	9.53E+01	9.37E+01	9.64E+01	1.82E+03	4.89E+01	3.15E+01	2.18E+01	3.76E+01	5.52E+01
Freshwater eutrophication	kg PO4 P-lim eq	1.20E-04	1.20E-04	6.15E-05	7.44E-05	1.70E-04	-1.03E-03	-6.60E-04	-4.60E-04	-2.09E-06	3.29E-05
Human toxicity cancer	CTUh	8.30E-09	8.00E-09	8.79E-09	8.36E-09	1.34E-07	1.47E-08	9.48E-09	6.58E-09	2.49E-09	2.74E-08
Human toxicity non-cancer	CTUh	4.13E-08	3.98E-08	4.49E-08	4.18E-08	9.47E-07	6.64E-08	4.27E-08	2.96E-08	1.34E-08	1.86E-07
Ionizing radiations	Bq C-14 eq	4.11E+00	3.97E+00	7.00E+00	6.31E+00	1.11E+02	1.31E+01	8.43E+00	5.84E+00	2.92E+00	4.97E+01
Land occupation, biodiversity	m2 arable land eq .yr	5.40E-01	5.20E-01	5.57E-01	5.01E-01	6.09E-01	8.80E-02	5.66E-02	3.93E-02	7.39E-03	6.84E-02
Land transformation, biodiversity	m2 arable land eq	3.50E-04	3.40E-04	3.60E-04	3.30E-04	1.46E-03	1.10E-04	7.31E-05	5.07E-05	1.99E-05	1.70E-04
Marine eutrophication	kg N N-lim eq	2.50E-04	2.40E-04	2.70E-04	2.50E-04	3.29E-03	3.20E-04	2.00E-04	1.40E-04	1.00E-04	4.00E-04
Mineral resources use	kg deprived	1.18E-02	1.14E-02	1.20E-02	1.15E-02	2.91E-01	1.52E-02	9.78E-03	6.78E-03	4.09E-03	3.26E-02
Ozone layer depletion	kg CFC-11 eq	9.83E-09	9.47E-09	1.06E-08	9.81E-09	1.17E-07	9.60E-09	6.17E-09	4.28E-09	2.34E-09	6.93E-06
Particulate matter formation	kg PM2.5 eq	3.90E-04	3.70E-04	4.00E-04	3.80E-04	1.10E-02	5.60E-04	3.60E-04	2.50E-04	1.10E-04	8.00E-04
Photochemical ozone formation	kgNOxeq	1.65E-03	1.59E-03	1.65E-03	1.59E-03	2.99E-02	2.75E-03	1.77E-03	1.22E-03	4.80E-04	3.79E-03
Terrestrial acidification	kg SO2 eq	1.68E-03	1.62E-03	1.82E-03	1.71E-03	5.16E-02	3.49E-03	2.25E-03	1.56E-03	6.60E-04	5.13E-03
Water scarcity	m3 world-eq	1.43E+00	1.38E+00	1.61E+00	1.45E+00	5.52E+00	1.34E+00	8.61E-01	5.97E-01	4.25E-01	3.58E+00

Appendix B – Baseline Reusable Packaging Results, 10 Reuses

Impact categories	Unit	Carton - 1L	Carton - 2L	Carton w/ Cap - 1L	Carton w/ Cap - 2L	Glass Bottle - 1L - Reusable	Glass Bottle - 1L - Single-use	HDPE Jug - 1L	HDPE Jug - 2L	HDPE Jug - 4L	Milk Pouch - 4L	PET Bottle - 1.5L
Climate change, long term	kg CO2 eq (long)	4.17E-01	4.01E-01	4.85E-01	4.52E-01	1.49E+00	9.53E+00	1.08E+00	6.95E-01	4.82E-01	1.96E-01	1.60E+00
Climate change, short term	kg CO2 eq (short)	5.37E-01	5.17E-01	6.21E-01	5.79E-01	1.69E+00	1.10E+01	1.32E+00	8.46E-01	5.87E-01	2.54E-01	1.86E+00
Fossil and nuclear energy use	MJ deprived	1.05E+01	1.02E+01	1.36E+01	1.24E+01	3.03E+01	1.57E+02	3.98E+01	2.56E+01	1.77E+01	6.54E+00	4.49E+01
Freshwater acidification	kg SO2 eq	1.58E-03	1.52E-03	1.72E-03	1.60E-03	6.35E-03	4.92E-02	3.34E-03	2.14E-03	1.49E-03	6.30E-04	4.89E-03
Freshwater ecotoxicity	CTUe	9.89E+01	9.53E+01	9.37E+01	9.64E+01	2.45E+02	1.82E+03	4.89E+01	3.15E+01	2.18E+01	3.76E+01	5.52E+01
Freshwater eutrophication	kg PO4 P-lim eq	1.20E-04	1.20E-04	6.15E-05	7.44E-05	-1.20E-04	1.70E-04	-1.03E-03	-6.60E-04	-4.60E-04	-2.09E-06	3.29E-05
Human toxicity cancer	CTUh	8.30E-09	8.00E-09	8.79E-09	8.36E-09	2.04E-08	1.34E-07	1.47E-08	9.48E-09	6.58E-09	2.49E-09	2.74E-08
Human toxicity non-cancer	CTUh	4.13E-08	3.98E-08	4.49E-08	4.18E-08	1.34E-07	9.47E-07	6.64E-08	4.27E-08	2.96E-08	1.34E-08	1.86E-07
Ionizing radiations	Bq C-14 eq	4.11E+00	3.97E+00	7.00E+00	6.31E+00	6.23E+01	1.11E+02	1.31E+01	8.43E+00	5.84E+00	2.92E+00	4.97E+01
Land occupation, biodiversity	m2 arable land eq .yr	5.40E-01	5.20E-01	5.57E-01	5.01E-01	9.32E-02	6.09E-01	8.80E-02	5.66E-02	3.93E-02	7.39E-03	6.84E-02
Land transformation, biodiversity	m2 arable land eq	3.50E-04	3.40E-04	3.60E-04	3.30E-04	2.00E-04	1.46E-03	1.10E-04	7.31E-05	5.07E-05	1.99E-05	1.70E-04
Marine eutrophication	kg N N-lim eq	2.50E-04	2.40E-04	2.70E-04	2.50E-04	3.80E-04	3.29E-03	3.20E-04	2.00E-04	1.40E-04	1.00E-04	4.00E-04
Mineral resources use	kg deprived	1.18E-02	1.14E-02	1.20E-02	1.15E-02	3.64E-02	2.91E-01	1.52E-02	9.78E-03	6.78E-03	4.09E-03	3.26E-02
Ozone layer depletion	kg CFC-11 eq	9.83E-09	9.47E-09	1.06E-08	9.81E-09	2.36E-08	1.17E-07	9.60E-09	6.17E-09	4.28E-09	2.34E-09	6.93E-06
Particulate matter formation	kg PM2.5 eq	3.90E-04	3.70E-04	4.00E-04	3.80E-04	1.31E-03	1.10E-02	5.60E-04	3.60E-04	2.50E-04	1.10E-04	8.00E-04
Photochemical ozone formation	kgNOxeq	1.65E-03	1.59E-03	1.65E-03	1.59E-03	4.05E-03	2.99E-02	2.75E-03	1.77E-03	1.22E-03	4.80E-04	3.79E-03
Terrestrial acidification	kg SO2 eq	1.68E-03	1.62E-03	1.82E-03	1.71E-03	6.65E-03	5.16E-02	3.49E-03	2.25E-03	1.56E-03	6.60E-04	5.13E-03
Water scarcity	m3 world-eq	1.43E+00	1.38E+00	1.61E+00	1.45E+00	3.75E+00	5.52E+00	1.34E+00	8.61E-01	5.97E-01	4.25E-01	3.58E+00

Appendix C - Baseline Reusable Packaging Results, 25 Reuses

Impact categories	Unit	Carton - 1L	Carton - 2L	Carton w/ Cap - 1L	Carton w/ Cap - 2L	Glass Bottle - 1L - Reusable	Glass Bottle - 1L - Single-use	HDPE Jug - 1L	HDPE Jug - 2L	HDPE Jug - 4L	Milk Pouch - 4L	PET Bottle - 1.5L
Climate change, long term	kg CO2 eq (long)	4.17E-01	4.01E-01	4.85E-01	4.52E-01	1.19E+00	9.53E+00	1.08E+00	6.95E-01	4.82E-01	1.96E-01	1.60E+00
Climate change, short term	kg CO2 eq (short)	5.37E-01	5.17E-01	6.21E-01	5.79E-01	1.32E+00	1.10E+01	1.32E+00	8.46E-01	5.87E-01	2.54E-01	1.86E+00
Fossil and nuclear energy use	MJ deprived	1.05E+01	1.02E+01	1.36E+01	1.24E+01	2.72E+01	1.57E+02	3.98E+01	2.56E+01	1.77E+01	6.54E+00	4.49E+01
Freshwater acidification	kg SO2 eq	1.58E-03	1.52E-03	1.72E-03	1.60E-03	4.04E-03	4.92E-02	3.34E-03	2.14E-03	1.49E-03	6.30E-04	4.89E-03
Freshwater ecotoxicity	CTUe	9.89E+01	9.53E+01	9.37E+01	9.64E+01	1.79E+02	1.82E+03	4.89E+01	3.15E+01	2.18E+01	3.76E+01	5.52E+01
Freshwater eutrophication	kg PO4 P-lim eq	1.20E-04	1.20E-04	6.15E-05	7.44E-05	-1.40E-04	1.70E-04	-1.03E-03	-6.60E-04	-4.60E-04	-2.09E-06	3.29E-05
Human toxicity cancer	CTUh	8.30E-09	8.00E-09	8.79E-09	8.36E-09	1.68E-08	1.34E-07	1.47E-08	9.48E-09	6.58E-09	2.49E-09	2.74E-08
Human toxicity non-cancer	CTUh	4.13E-08	3.98E-08	4.49E-08	4.18E-08	1.00E-07	9.47E-07	6.64E-08	4.27E-08	2.96E-08	1.34E-08	1.86E-07
Ionizing radiations	Bq C-14 eq	4.11E+00	3.97E+00	7.00E+00	6.31E+00	8.41E+01	1.11E+02	1.31E+01	8.43E+00	5.84E+00	2.92E+00	4.97E+01
Land occupation, biodiversity	m2 arable land eq .yr	5.40E-01	5.20E-01	5.57E-01	5.01E-01	7.46E-02	6.09E-01	8.80E-02	5.66E-02	3.93E-02	7.39E-03	6.84E-02
Land transformation, biodiversity	m2 arable land eq	3.50E-04	3.40E-04	3.60E-04	3.30E-04	1.50E-04	1.46E-03	1.10E-04	7.31E-05	5.07E-05	1.99E-05	1.70E-04
Marine eutrophication	kg N N-lim eq	2.50E-04	2.40E-04	2.70E-04	2.50E-04	2.10E-04	3.29E-03	3.20E-04	2.00E-04	1.40E-04	1.00E-04	4.00E-04
Mineral resources use	kg deprived	1.18E-02	1.14E-02	1.20E-02	1.15E-02	2.34E-02	2.91E-01	1.52E-02	9.78E-03	6.78E-03	4.09E-03	3.26E-02
Ozone layer depletion	kg CFC-11 eq	9.83E-09	9.47E-09	1.06E-08	9.81E-09	2.34E-08	1.17E-07	9.60E-09	6.17E-09	4.28E-09	2.34E-09	6.93E-06
Particulate matter formation	kg PM2.5 eq	3.90E-04	3.70E-04	4.00E-04	3.80E-04	7.50E-04	1.10E-02	5.60E-04	3.60E-04	2.50E-04	1.10E-04	8.00E-04
Photochemical ozone formation	kgNOxeq	1.65E-03	1.59E-03	1.65E-03	1.59E-03	2.73E-03	2.99E-02	2.75E-03	1.77E-03	1.22E-03	4.80E-04	3.79E-03
Terrestrial acidification	kg SO2 eq	1.68E-03	1.62E-03	1.82E-03	1.71E-03	4.23E-03	5.16E-02	3.49E-03	2.25E-03	1.56E-03	6.60E-04	5.13E-03
Water scarcity	m3 world-eq	1.43E+00	1.38E+00	1.61E+00	1.45E+00	5.15E+00	5.52E+00	1.34E+00	8.61E-01	5.97E-01	4.25E-01	3.58E+00

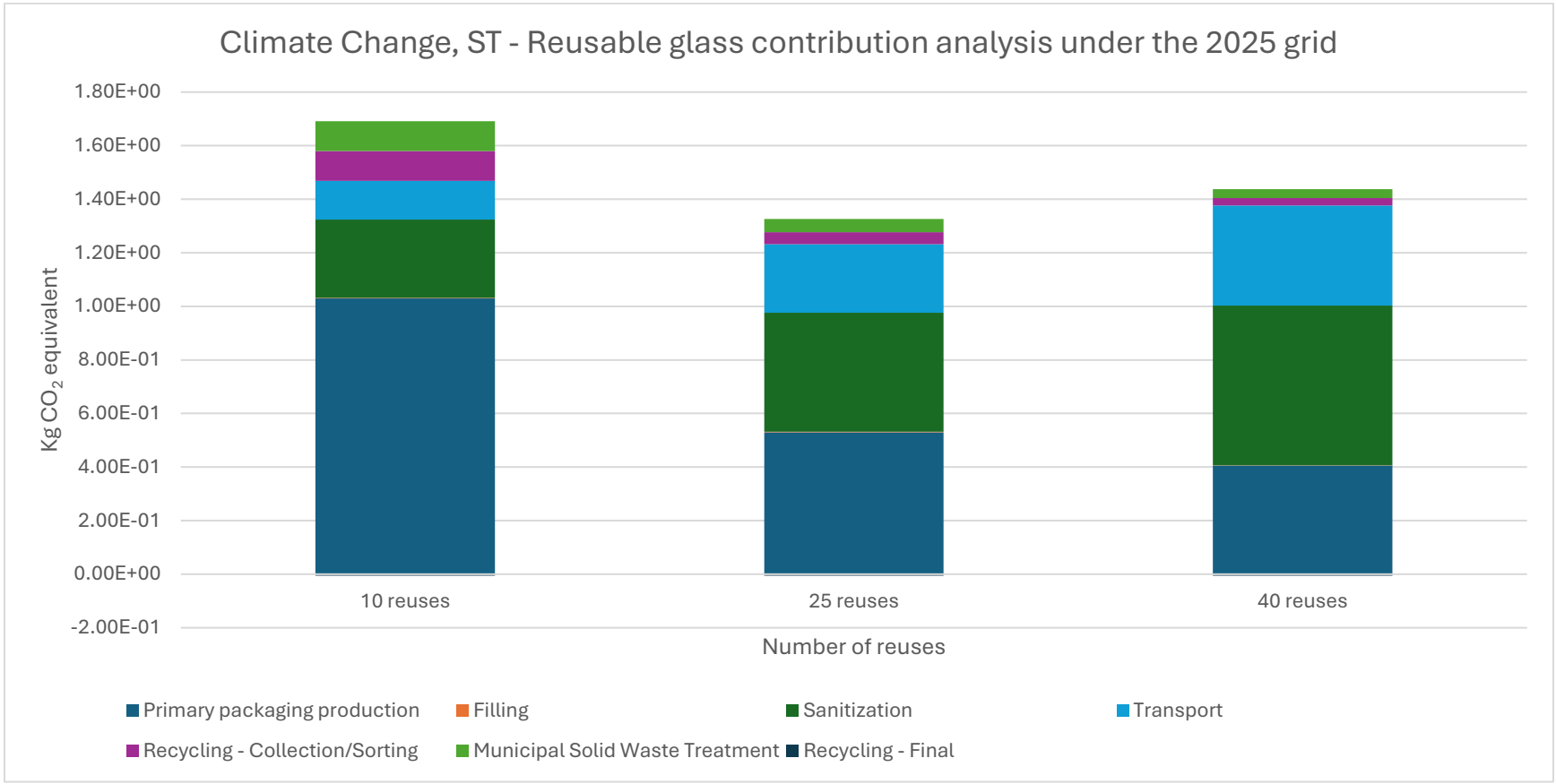
Appendix D - Baseline Reusable Packaging Results, 40 Reuses

Impact categories	Unit	Carton - 1L	Carton - 2L	Carton w/ Cap - 1L	Carton w/ Cap - 2L	Glass Bottle - 1L - Reusable	Glass Bottle - 1L - Single-use	HDPE Jug - 1L	HDPE Jug - 2L	HDPE Jug - 4L	Milk Pouch - 4L	PET Bottle - 1.5L
Climate change, long term	kg CO2 eq (long)	4.17E-01	4.01E-01	4.85E-01	4.52E-01	1.31E+00	9.53E+00	1.08E+00	6.95E-01	4.82E-01	1.96E-01	1.60E+00
Climate change, short term	kg CO2 eq (short)	5.37E-01	5.17E-01	6.21E-01	5.79E-01	1.43E+00	1.10E+01	1.32E+00	8.46E-01	5.87E-01	2.54E-01	1.86E+00
Fossil and nuclear energy use	MJ deprived	1.05E+01	1.02E+01	1.36E+01	1.24E+01	3.06E+01	1.57E+02	3.98E+01	2.56E+01	1.77E+01	6.54E+00	4.49E+01
Freshwater acidification	kg SO2 eq	1.58E-03	1.52E-03	1.72E-03	1.60E-03	3.90E-03	4.92E-02	3.34E-03	2.14E-03	1.49E-03	6.30E-04	4.89E-03
Freshwater ecotoxicity	CTUe	9.89E+01	9.53E+01	9.37E+01	9.64E+01	1.91E+02	1.82E+03	4.89E+01	3.15E+01	2.18E+01	3.76E+01	5.52E+01
Freshwater eutrophication	kg PO4 P-lim eq	1.20E-04	1.20E-04	6.15E-05	7.44E-05	-1.40E-04	1.70E-04	-1.03E-03	-6.60E-04	-4.60E-04	-2.09E-06	3.29E-05
Human toxicity cancer	CTUh	8.30E-09	8.00E-09	8.79E-09	8.36E-09	1.90E-08	1.34E-07	1.47E-08	9.48E-09	6.58E-09	2.49E-09	2.74E-08
Human toxicity non-cancer	CTUh	4.13E-08	3.98E-08	4.49E-08	4.18E-08	1.07E-07	9.47E-07	6.64E-08	4.27E-08	2.96E-08	1.34E-08	1.86E-07
Ionizing radiations	Bq C-14 eq	4.11E+00	3.97E+00	7.00E+00	6.31E+00	1.09E+02	1.11E+02	1.31E+01	8.43E+00	5.84E+00	2.92E+00	4.97E+01
Land occupation, biodiversity	m2 arable land eq .yr	5.40E-01	5.20E-01	5.57E-01	5.01E-01	8.24E-02	6.09E-01	8.80E-02	5.66E-02	3.93E-02	7.39E-03	6.84E-02
Land transformation, biodiversity	m2 arable land eq	3.50E-04	3.40E-04	3.60E-04	3.30E-04	1.60E-04	1.46E-03	1.10E-04	7.31E-05	5.07E-05	1.99E-05	1.70E-04
Marine eutrophication	kg N N-lim eq	2.50E-04	2.40E-04	2.70E-04	2.50E-04	1.70E-04	3.29E-03	3.20E-04	2.00E-04	1.40E-04	1.00E-04	4.00E-04
Mineral resources use	kg deprived	1.18E-02	1.14E-02	1.20E-02	1.15E-02	2.34E-02	2.91E-01	1.52E-02	9.78E-03	6.78E-03	4.09E-03	3.26E-02
Ozone layer depletion	kg CFC-11 eq	9.83E-09	9.47E-09	1.06E-08	9.81E-09	2.83E-08	1.17E-07	9.60E-09	6.17E-09	4.28E-09	2.34E-09	6.93E-06
Particulate matter formation	kg PM2.5 eq	3.90E-04	3.70E-04	4.00E-04	3.80E-04	6.70E-04	1.10E-02	5.60E-04	3.60E-04	2.50E-04	1.10E-04	8.00E-04
Photochemical ozone formation	kgNOxeq	1.65E-03	1.59E-03	1.65E-03	1.59E-03	2.72E-03	2.99E-02	2.75E-03	1.77E-03	1.22E-03	4.80E-04	3.79E-03
Terrestrial acidification	kg SO2 eq	1.68E-03	1.62E-03	1.82E-03	1.71E-03	4.07E-03	5.16E-02	3.49E-03	2.25E-03	1.56E-03	6.60E-04	5.13E-03
Water scarcity	m3 world-eq	1.43E+00	1.38E+00	1.61E+00	1.45E+00	6.70E+00	5.52E+00	1.34E+00	8.61E-01	5.97E-01	4.25E-01	3.58E+00

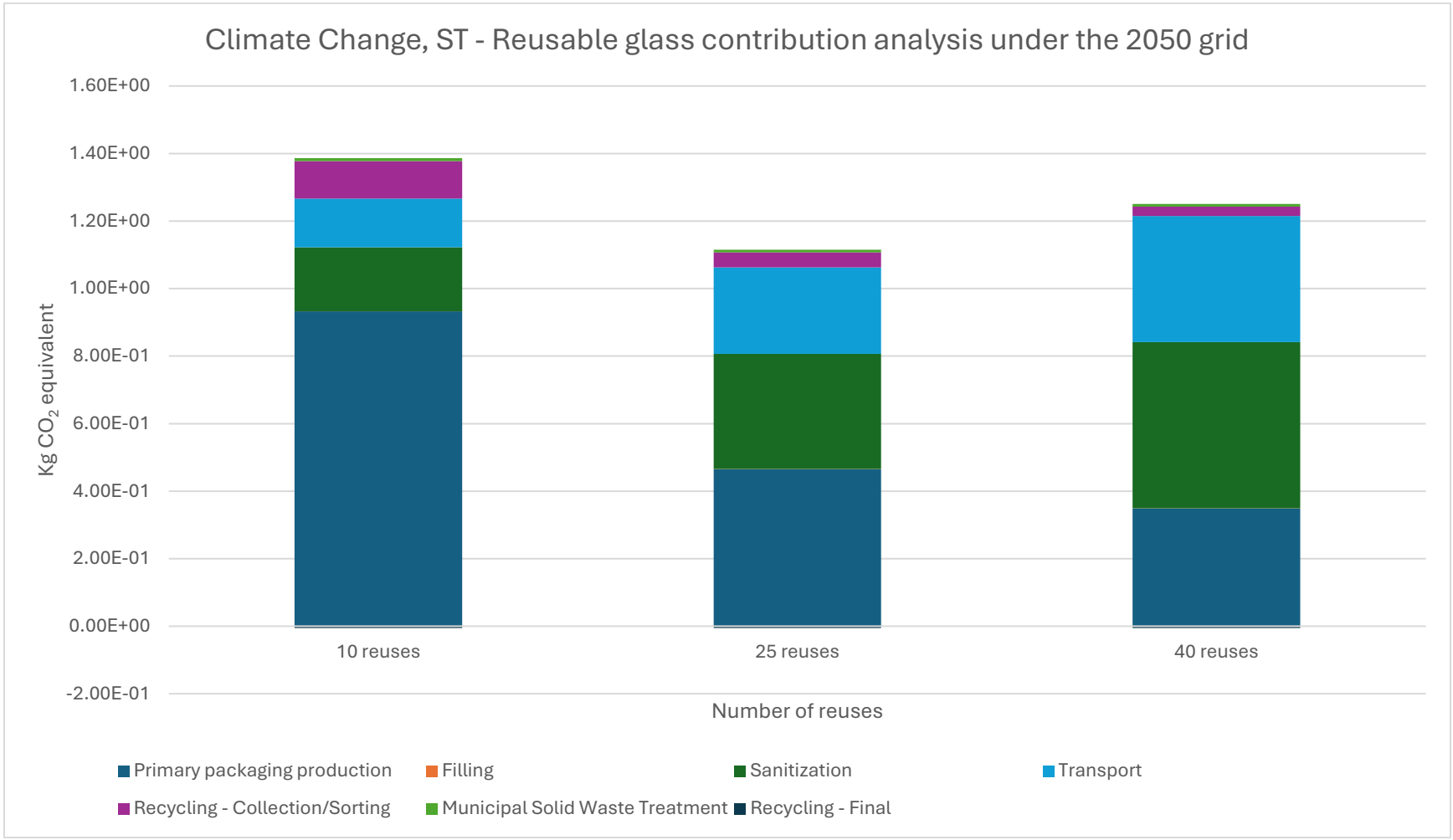
Appendix E – Equivalence between the reusable glass bottle at 25 reuses and single-use packaging types under the Canadian 2050 electricity grid

Impact categories	Unit	Carton – 1 L	Carton – 2 L	Carton w/ Cap – 1 L	Carton w/ Cap – 2 L	Glass Bottle – 1 L (single-use)	HDPE Jug –1 L	HDPE Jug – 2 L	HDPE Jug – 4 L	Milk Pouch – 4 L	PET Bottle - 1.5 L	
Climate change, long term	kg CO2 eq (long)					X						X
Climate change, short term	kg CO2 eq (short)					X	X					X
Fossil and nuclear energy use	MJ deprived					X	X					X
Freshwater acidification	kg SO2 eq					X						X
Freshwater ecotoxicity	CTUe					X						
Freshwater eutrophication	kg PO4 P-lim eq	X	X	X	X	X					X	X
Human toxicity cancer	CTUh					X						X
Human toxicity non-cancer	CTUh					X						X
Ionizing radiations	Bq C-14 eq					X						
Land occupation, biodiversity	m2 arable land eq .yr	X	X	X	X	X	X					X
Land transformation, biodiversity	m2 arable land eq	X	X	X	X	X						X
Marine eutrophication	kg N N-lim eq	X	X	X	X	X	X	X		X		X
Mineral resources use	kg deprived					X						X
Ozone layer depletion	kg CFC-11 eq					X						X
Particulate matter formation	kg PM2.5 eq					X						X
Photochemical ozone formation	kgNOxeq					X						X
Terrestrial acidification	kg SO2 eq					X						X
Water scarcity	m3 world-eq					X						X

Appendix F – Contribution analysis for reusable glass at 10, 25, and 40 reuses under the 2025 grid



Appendix G – Contribution analysis for reusable glass at 10, 25, and 40 reuses under the 2050 grid



Appendix H – Impact Category Inclusion Justifications

Impact category	Unit	Justification for inclusion
Climate change, short term	kg CO2 eq (short)	Climate change impacts common with fossil fuel-based feedstocks and to provide comparability within the literature.
Climate change, long term	kg CO2 eq (long)	Included for completeness and comparison with other studies but not examined due to LCA literature commonly using GWP100 (short) versus GTP100 (long).
Fossil and nuclear energy use	MJ deprived	Selected to capture non-renewable energy used in plastic production, glass melting, and transportation processes.
Freshwater acidification	kg SO2 eq	Selected to encompass acidifying emissions from combustion such as transport and glass melting processes involved in glass bottle production, among other packaging production processes.
Freshwater eutrophication	kg PO4 P-lim eq	Included to quantify eutrophication impacts to freshwater systems associated with pulp and paper production processes.
Marine eutrophication	kg N N-lim eq	Included for completeness and to quantify potential marine eutrophication impacts associated with effluents associated with pulp and paper production.
Freshwater ecotoxicity	CTUe	Selected to capture potential ecotoxicity impacts associated with raw material extraction such as mining and production processes associated with pulp and paper.
Terrestrial acidification	kg SO2 eq	Selected to quantify potential terrestrial acidification impacts associated with municipal solid waste treatment.
Human toxicity, non-cancer	CTUh	Selected to quantify non-cancer health effects associated with effluents from plastic and glass production, electricity generating sources, and waste treatment.
Human toxicity, cancer	CTUh	Selected to capture potential carcinogenic health impacts associated with emissions and effluent from packaging production, transportation, and waste treatment.
Ionizing radiation	Bq C-14 eq	Selected to account for potential ionizing radiation impacts associated linked to nuclear energy generation within the Canadian electricity grid.

Impact category	Unit	Justification for inclusion
Land occupation, biodiversity	m2 arable land eq .yr	Selected to capture the land occupation impacts associated with the forestry activities required to produce paper-based packaging.
Land transformation, biodiversity	m2 arable land eq	Selected to capture the land occupation impacts associated with raw material extraction such as mining, forestry, and oil and gas used in the packaging feedstocks.
Mineral resources use	kg deprived	Selected to account for the use and depletion of mineral resources in glass production.
Ozone layer depletion	kg CFC-11 eq	Selected to capture the emissions from ozone-depleting processes and products such as PET production and refrigerants used in transport.
Particulate matter formation	kg PM2.5 eq	Selected to quantify particulate matter formation driven by combustion-based processes such as glass melting and transportation.
Photochemical ozone formation	kgNOxeq	Selected to quantify particulate matter formation driven by combustion-based processes such as glass melting and transportation.
Water scarcity	m^3 world-eq	Selected to capture freshwater consumption use in pulp and paper production, and sanitization and washing processes which may exacerbate impacts in water-stressed areas.

Appendix I – Sensitivity Analysis

- Glass composition: As the raw material composition for the virgin glass was not provided by primary data sources, an average percent composition was used in absence of this data. Adjustments of between the range of -10% to +10% to the raw material composition of the virgin glass yielded marginal deviations for the total impact value across all of the impact categories, indicating negligible influence on the overall packaging rankings.
- Liquid packaging board production process: Within ecoinvent©, only two processes exist that produce liquid packaging board variants. Within this study, carton-based packaging was modelled using the solid bleached and unbleached carton board production process as this was deemed most comparable to Canadian systems. A sensitivity analysis was conducted and compared to use of both processes; no changes to intra-category rankings between packaging were observed.
- Transportation emission standards: ecoinvent© is a predominantly European-based life cycle database. As such, vehicle emissions are categorized by EURO standards. However, a sensitivity analysis was conducted to test this assumption against EURO5 standard vehicles which could potentially be in-service within certain fleets. When compared, a general increase in total impacts was observed for the EURO5 model; however, no changes to intracategory rankings were observed.
- Packaging converting at the dairy processor: Information regarding the location of converting for the HDPE jugs, PET bottles, and milk pouches within Canadian systems could not be sourced. As such, it is assumed that these are converted at the dairy processor based on U.S. systems detailed in Burek et al.'s (2018) study. A sensitivity analysis was conducted to compare this study against a model using assumed transportation distances between an initial converting plant to the dairy processor from Fry et al.'s (2010) study. No changes to intracategory rankings were observed when compared.
- Plastic production in Canada: Minimal information was available to confirm the location of the production of plastic granule feedstocks such as HDPE, LDPE, LLDPE, and PET. As such, this study assumes Rest of World production

processes. A sensitivity analysis was conducted to compare Canada-based versus Rest of World plastic feedstock production and noted no changes to intracategory packaging rankings.

- Secondary and transit packaging: Secondary packaging and transit packaging were excluded from the system boundaries due to a lack of information and data across all packaging types. The addition of estimated amounts of secondary and transit packaging was modelled, and total impact values were increased between 3% to 5% with no changes to intracategory packaging rankings.
- Cut-off approach: This study uses the avoided burdens approach which provides credits for recycling and energy-recovering in end-of-life processes. As highlighted within Raadal et al.'s (2025) study, different approaches to end-of-life modelling can produce significant changes in the comparison of glass packaging systems. The application of the cut-off approach to the existing models yielded minor increases between 3% to 5% to total values within each impact category due to the removal of credits. Relative rankings within each impact category did not change with the exception of freshwater eutrophication, within which the milk pouch became the least impactful above the rankings of plastic-based packaging such as the HDPE jug and PET. However, no changes between packaging materials occurred.
- Recycling rate: This study uses a national recycling rate for the different packaging materials under analysis. Canada's lowest and highest provincial recycling rates were selected for each packaging material from several provinces. The low recycling rate demonstrated moderate increases between 5% to 10% in total impact values. The high-recycling scenario demonstrated a significant reduction in impacts between 10-20% for HDPE and PET, in addition to reductions within the range of 10% for glass. Cartons and the milk pouch showed minimal changes; likely due to the limited spread between low, assumed, and high recycling rates. Similar to the changes observed in the cut-off approach analysis, the ranking of plastic-based packaging worsened with decreases in recycling rate within the freshwater eutrophication impact category. This can be attributed to a reduction in the environmental credit provided by recycling.

Appendix J – Baseline Hotspot Figures

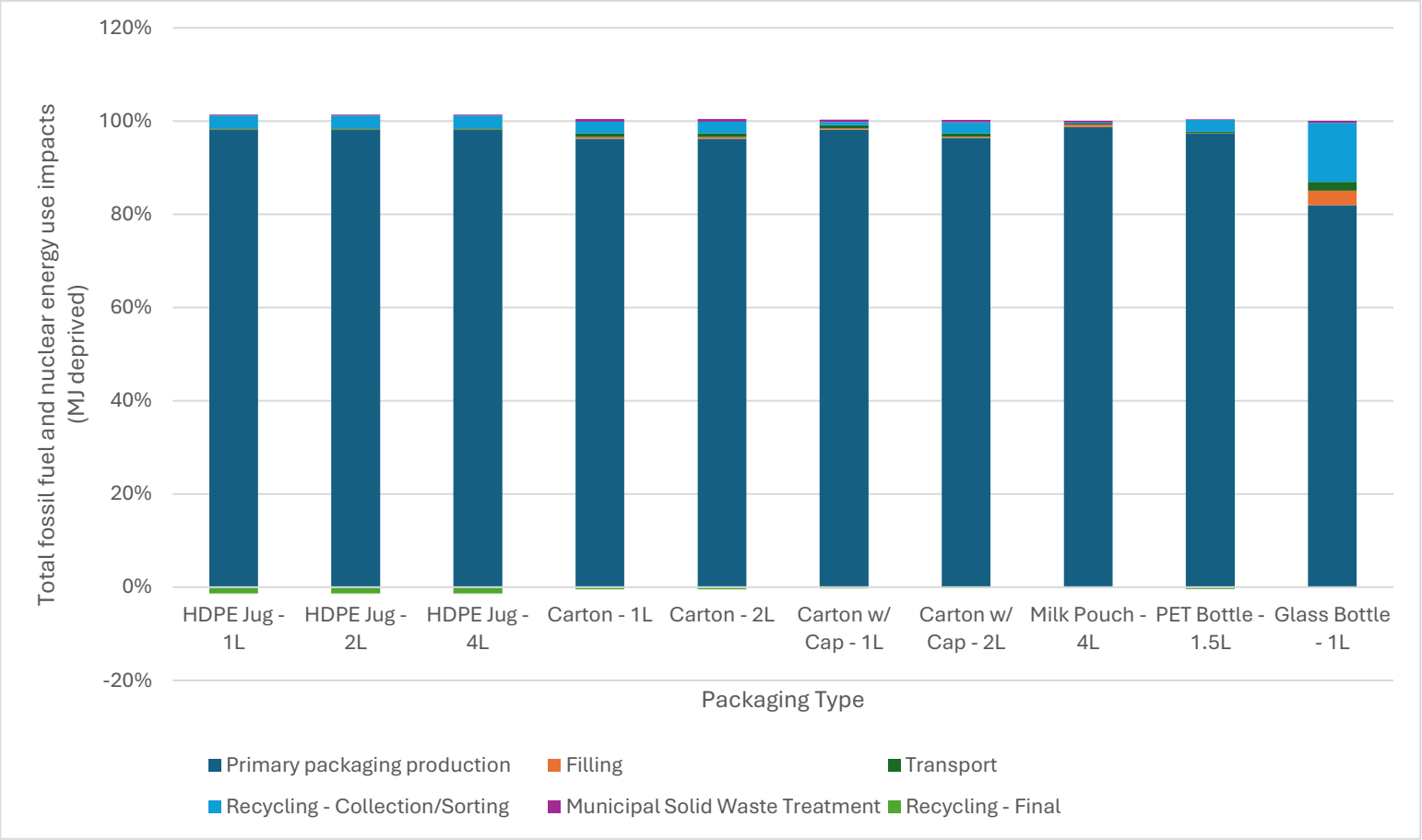


Figure 7 Fossil fuel and nuclear energy use contributions by stage

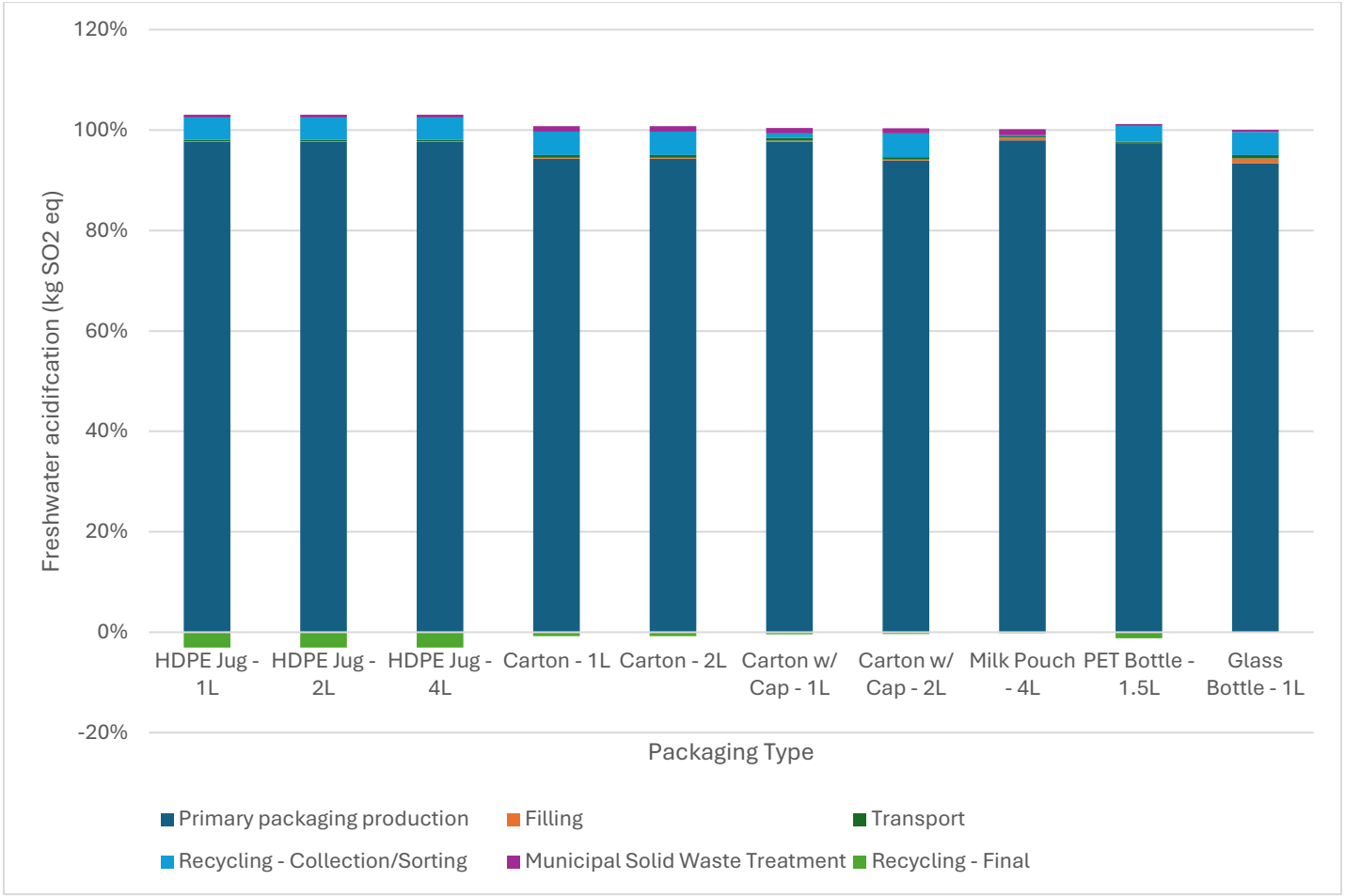


Figure 8 Freshwater acidification contributions by stage

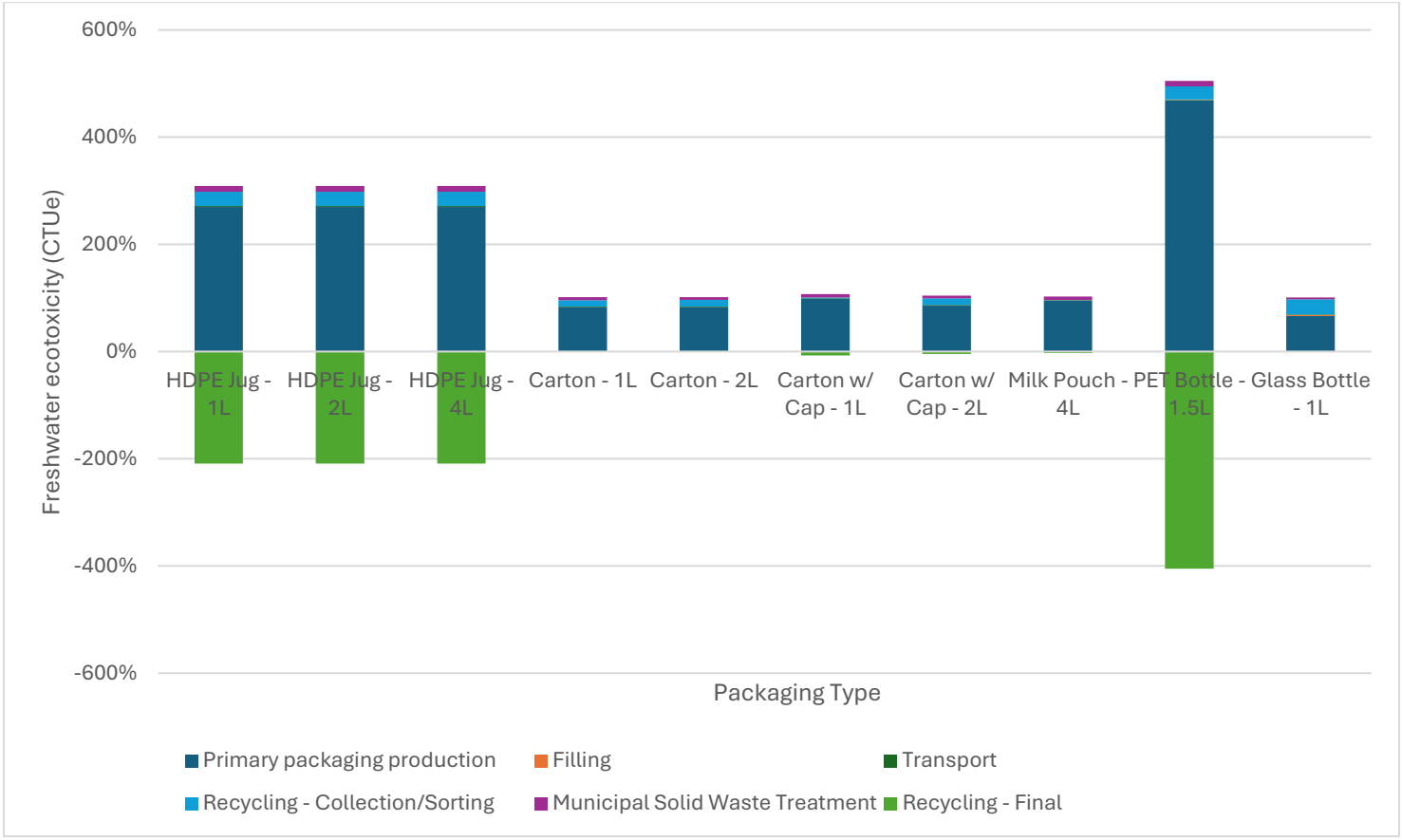


Figure 9 Freshwater ecotoxicity contributions by stage

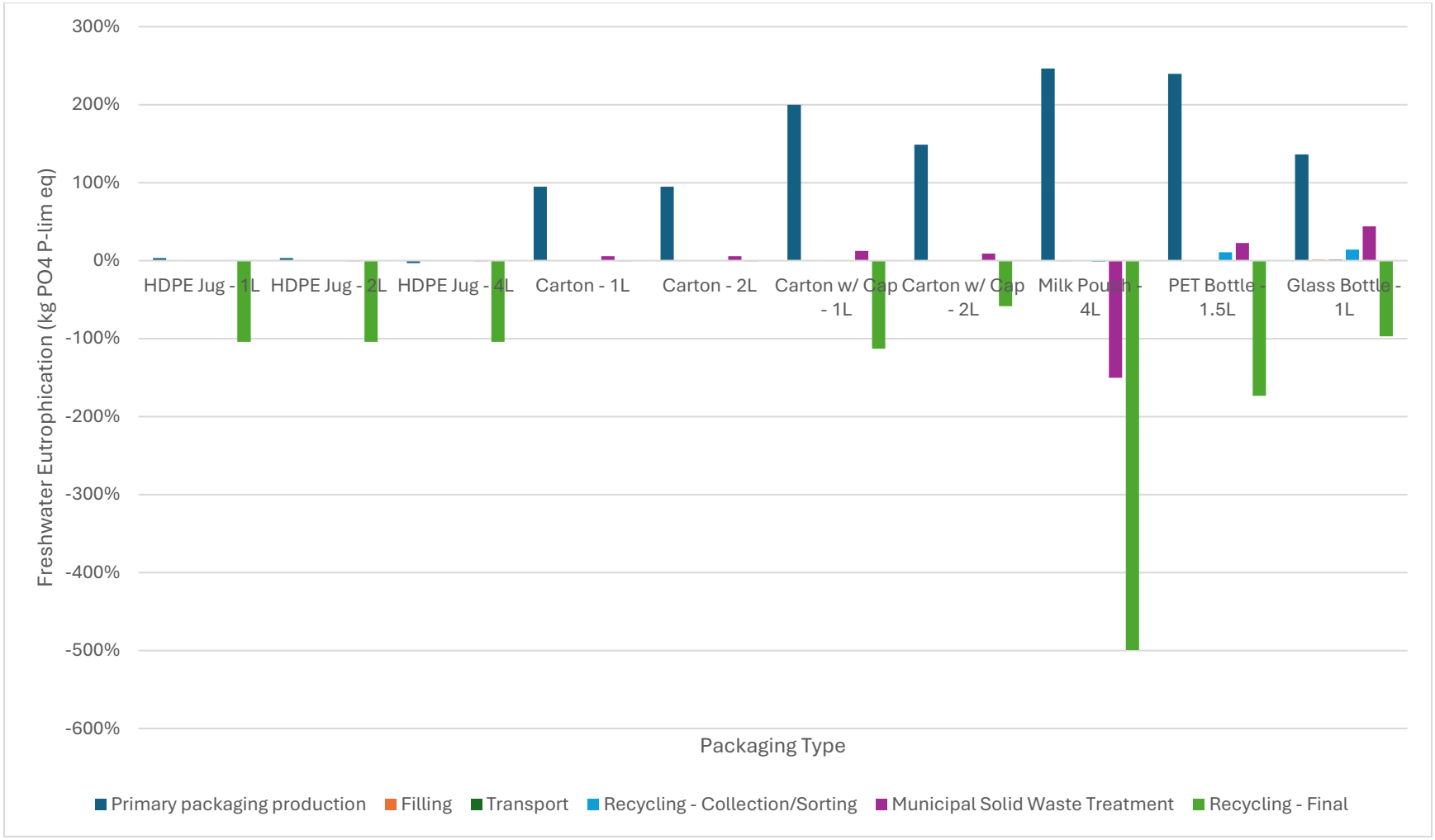


Figure 10 Freshwater eutrophication contributions by stage

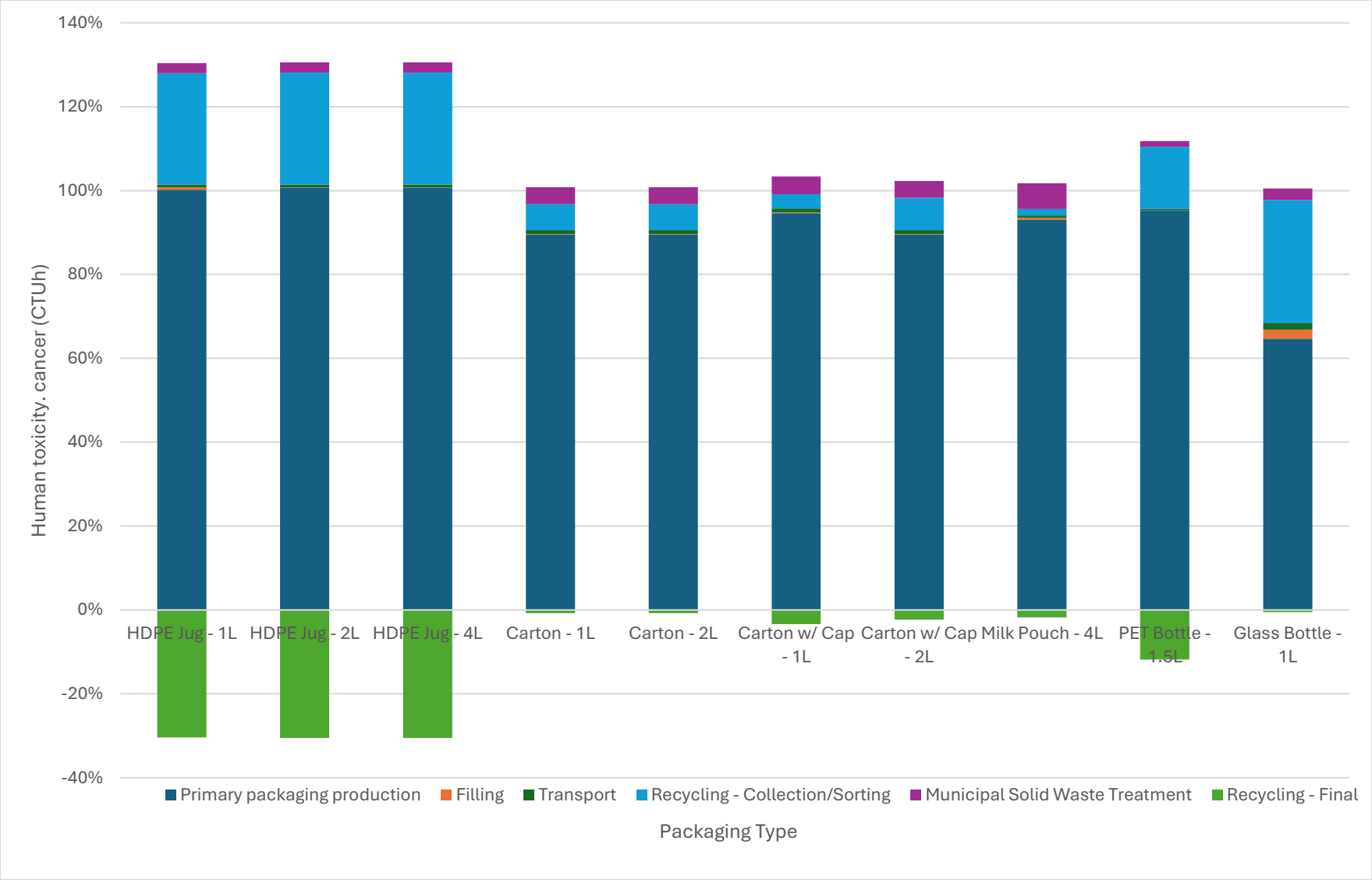


Figure 11 Human toxicity, cancer contributions by stage

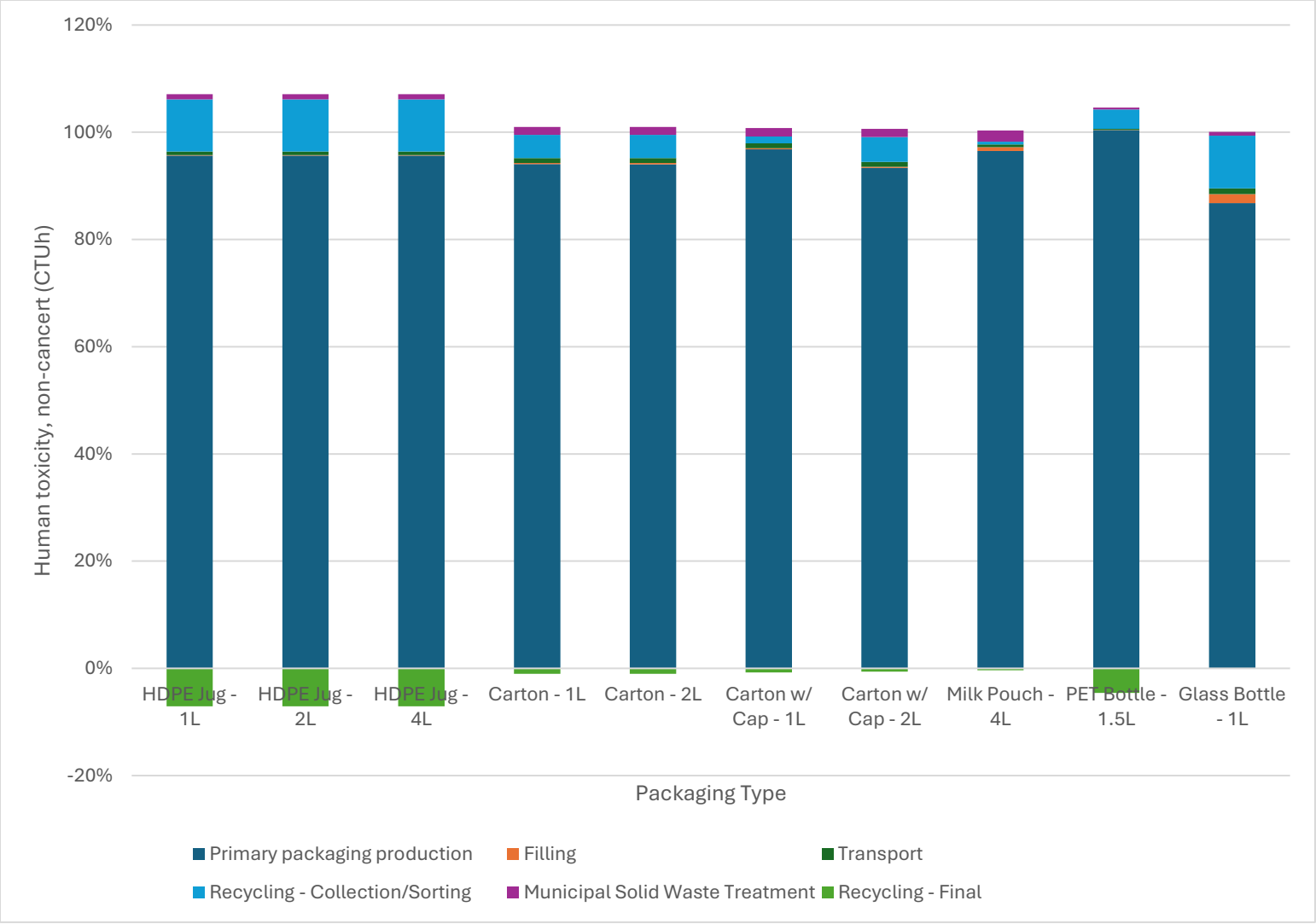


Figure 12 Human toxicity, non-cancer contributions by stage

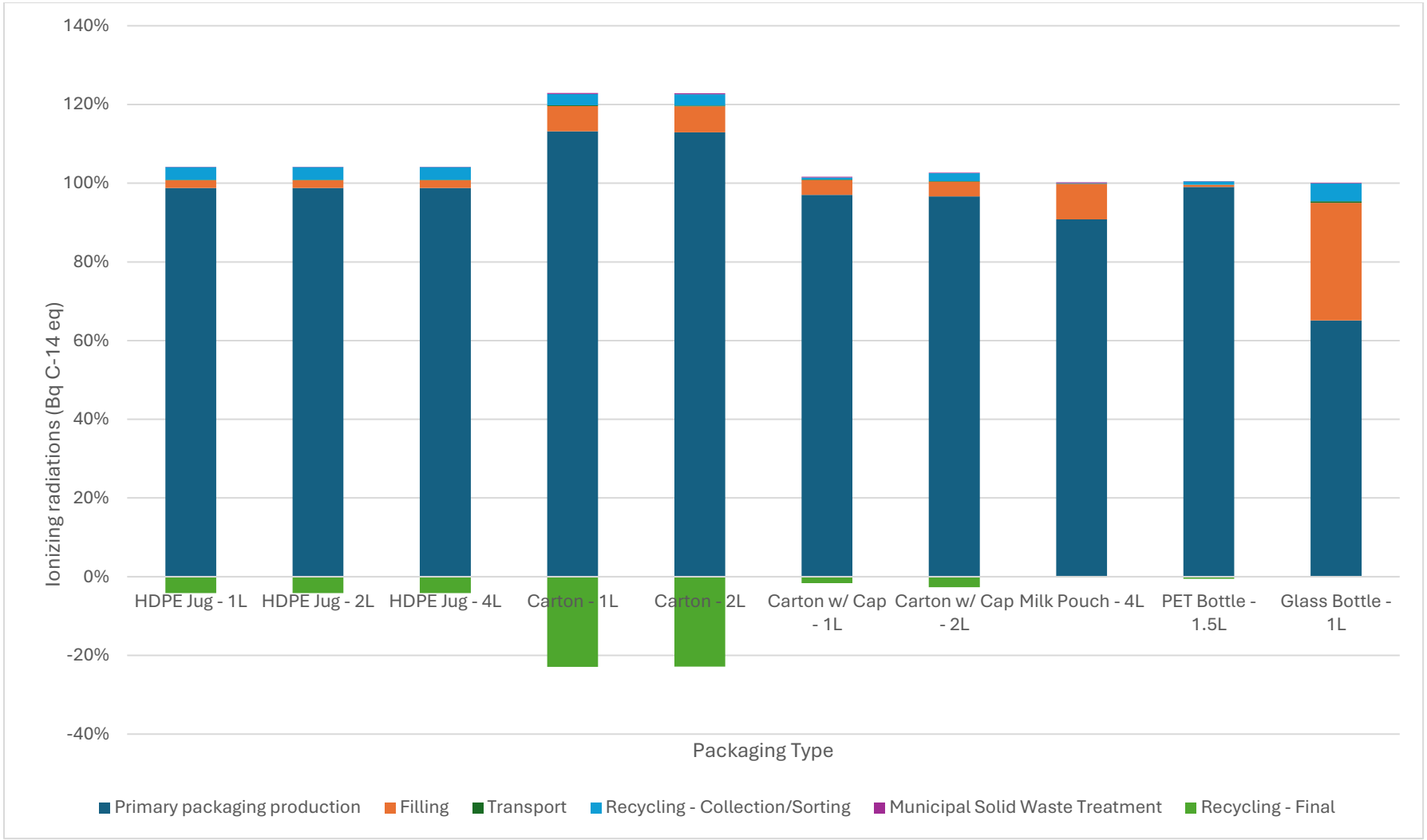


Figure 13 Ionizing radiations contributions by stage

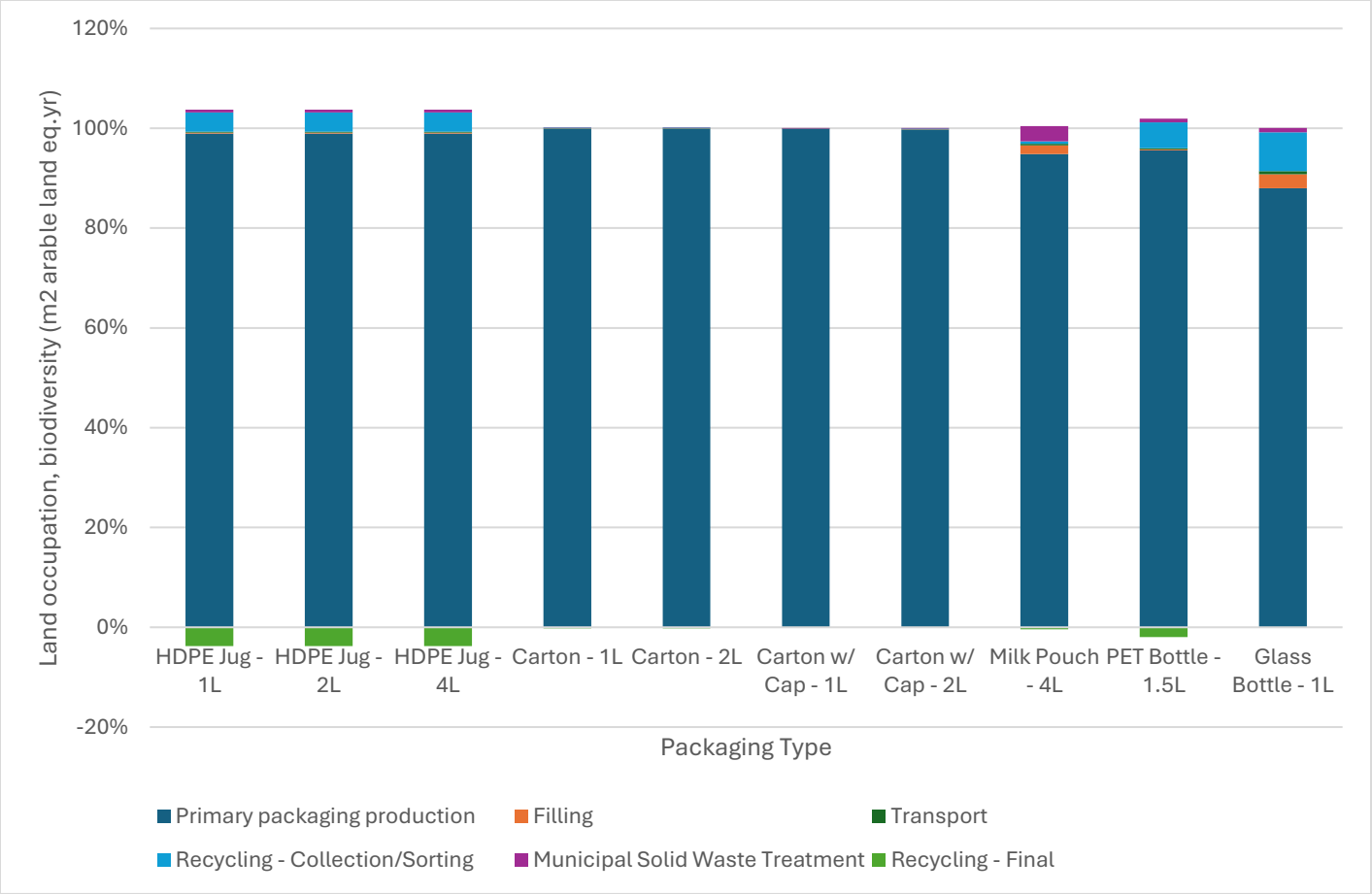


Figure 14 Land occupation, biodiversity contributions by stage

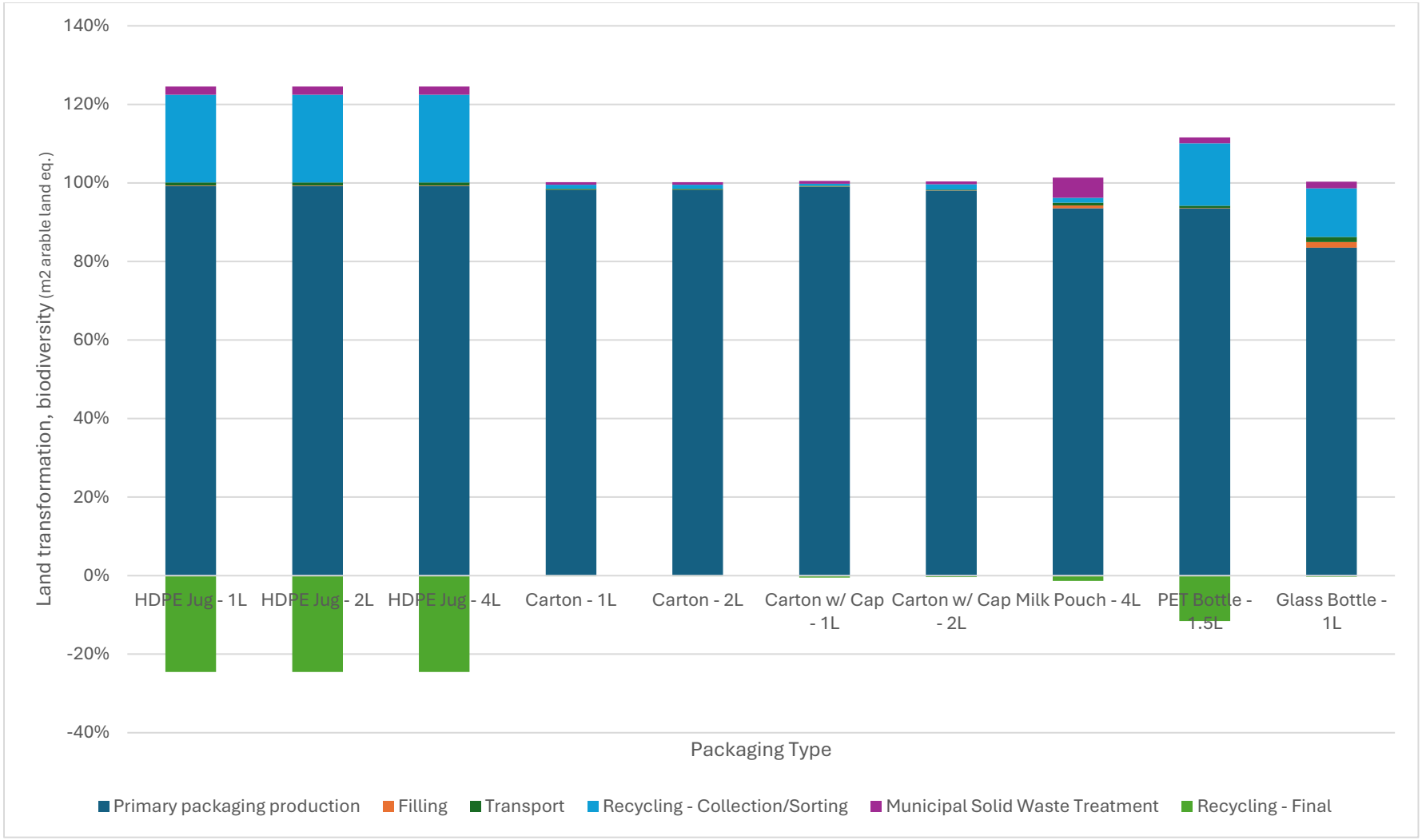


Figure 15 Land transformation, biodiversity contributions by stage

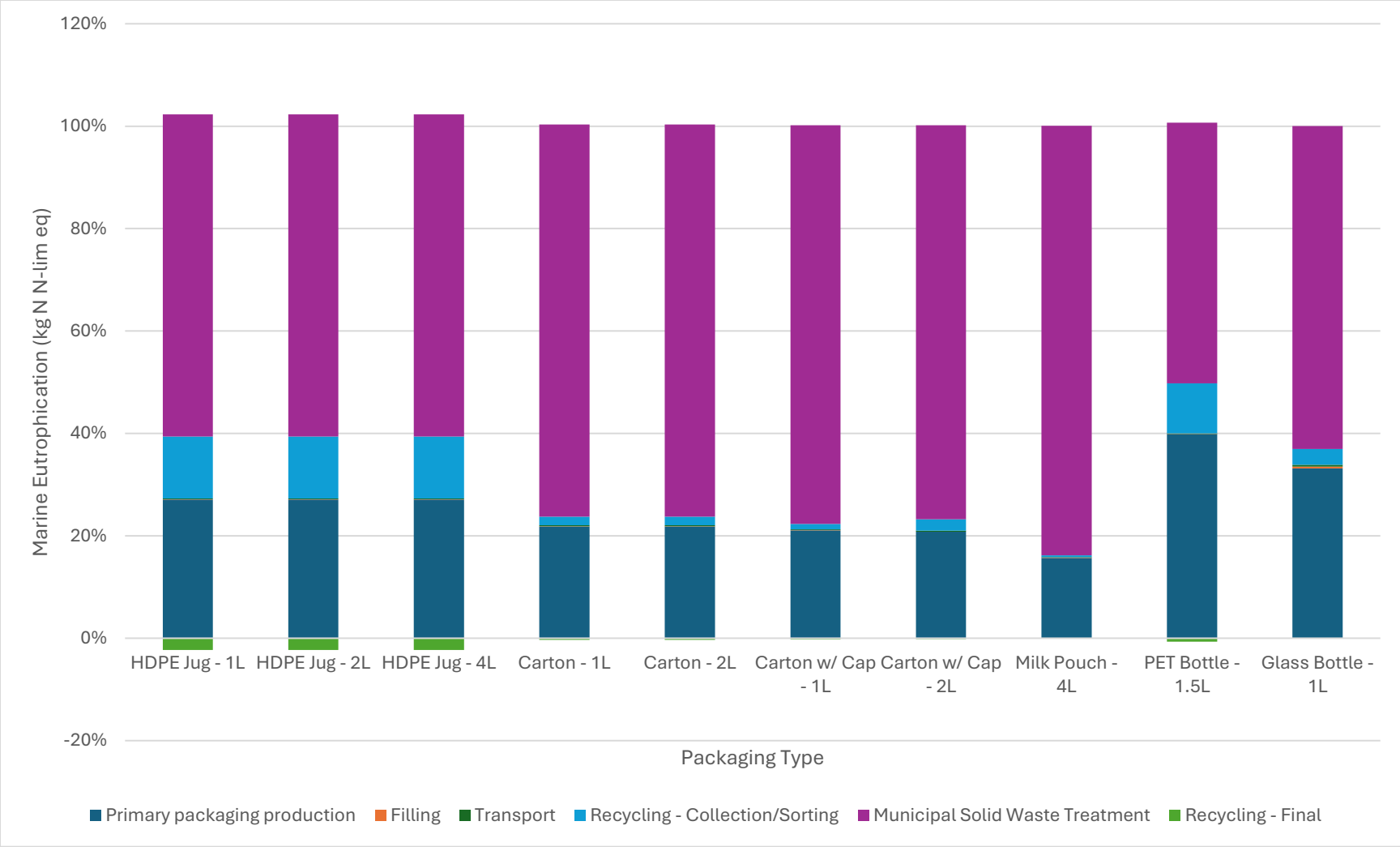


Figure 16 Marine eutrophication contributions by stage

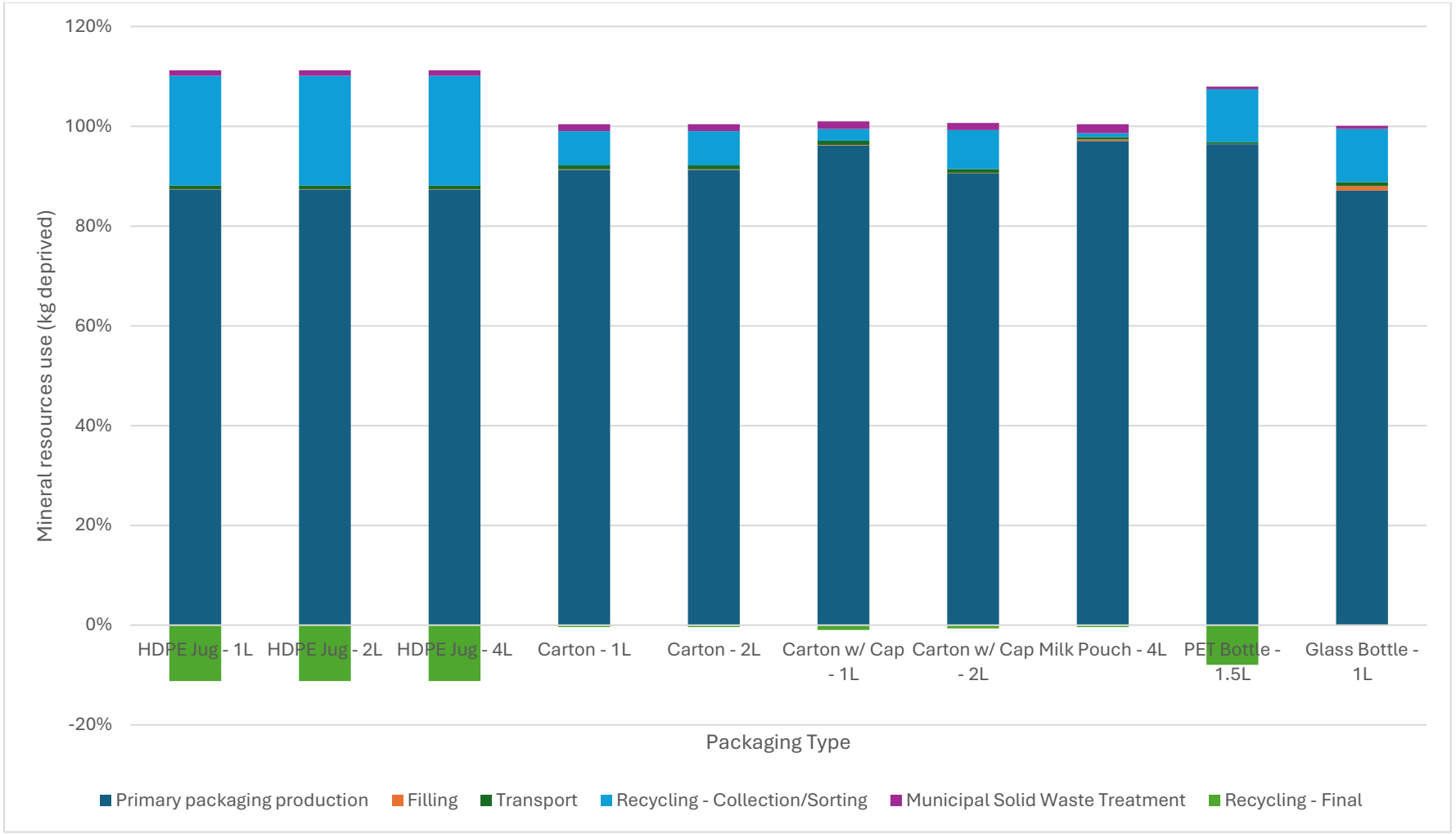


Figure 17 Mineral resources use contributions by stage

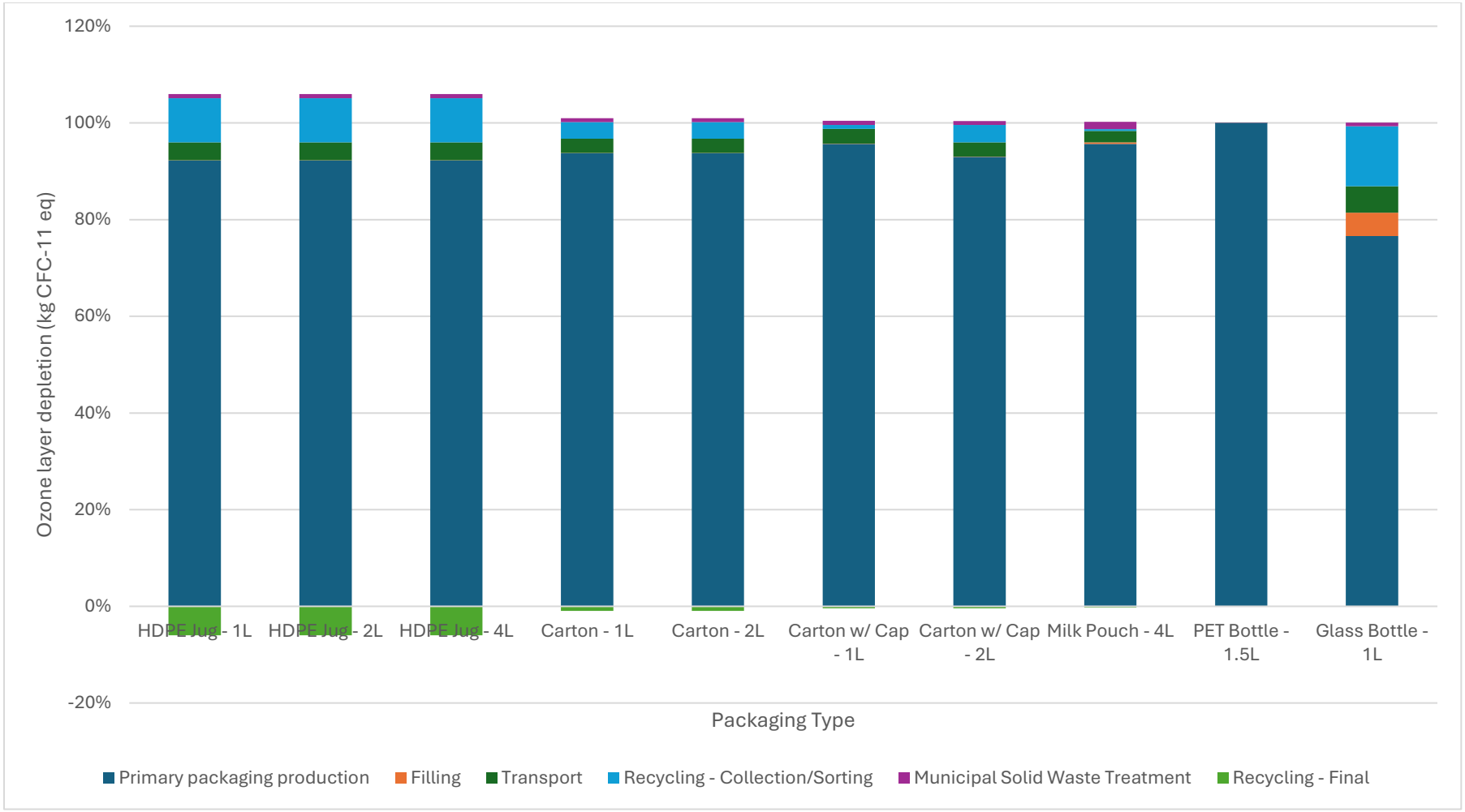


Figure 18 Ozone layer depletion contributions by stage

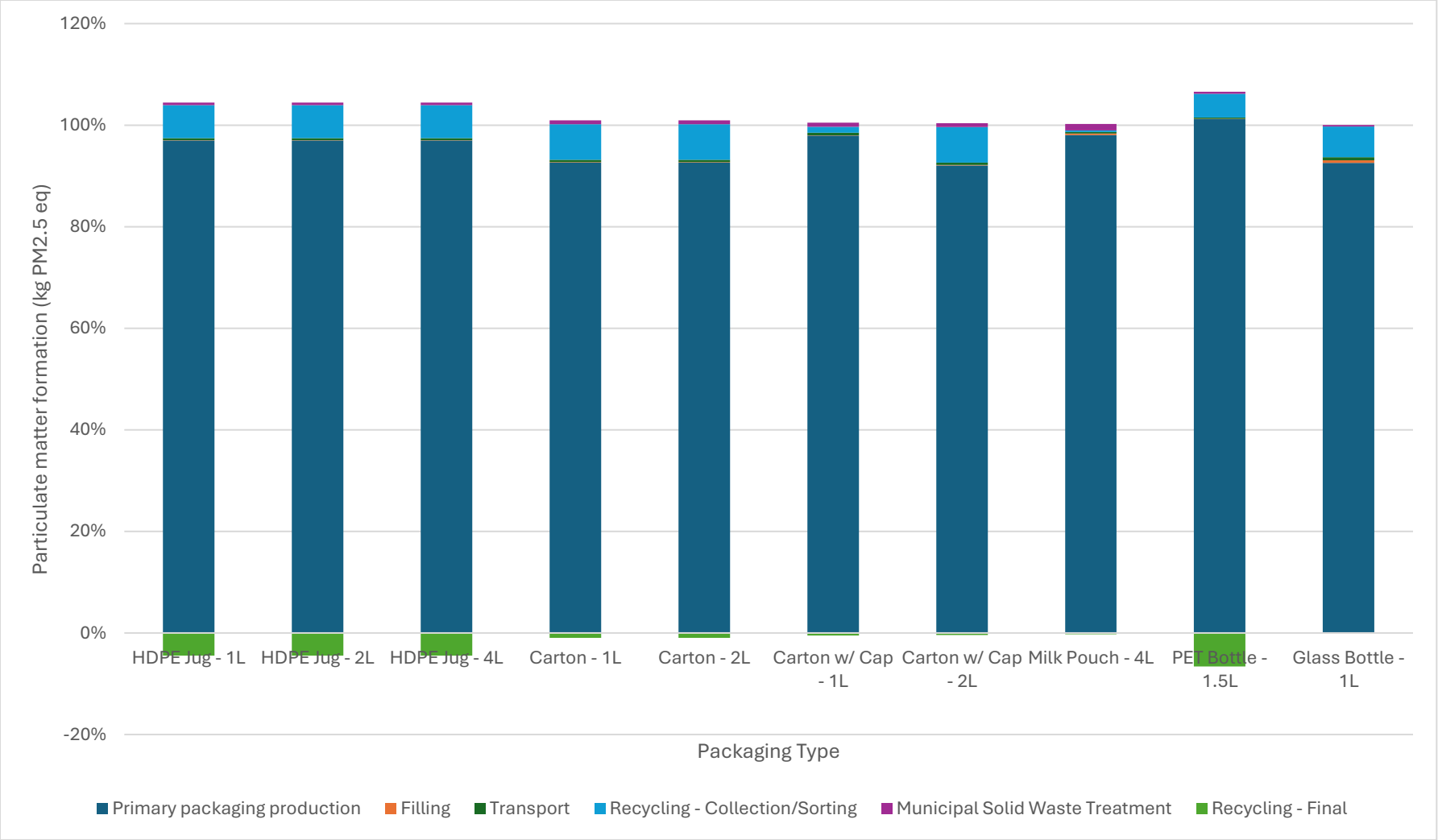


Figure 19 Particulate matter formation contributions by stage

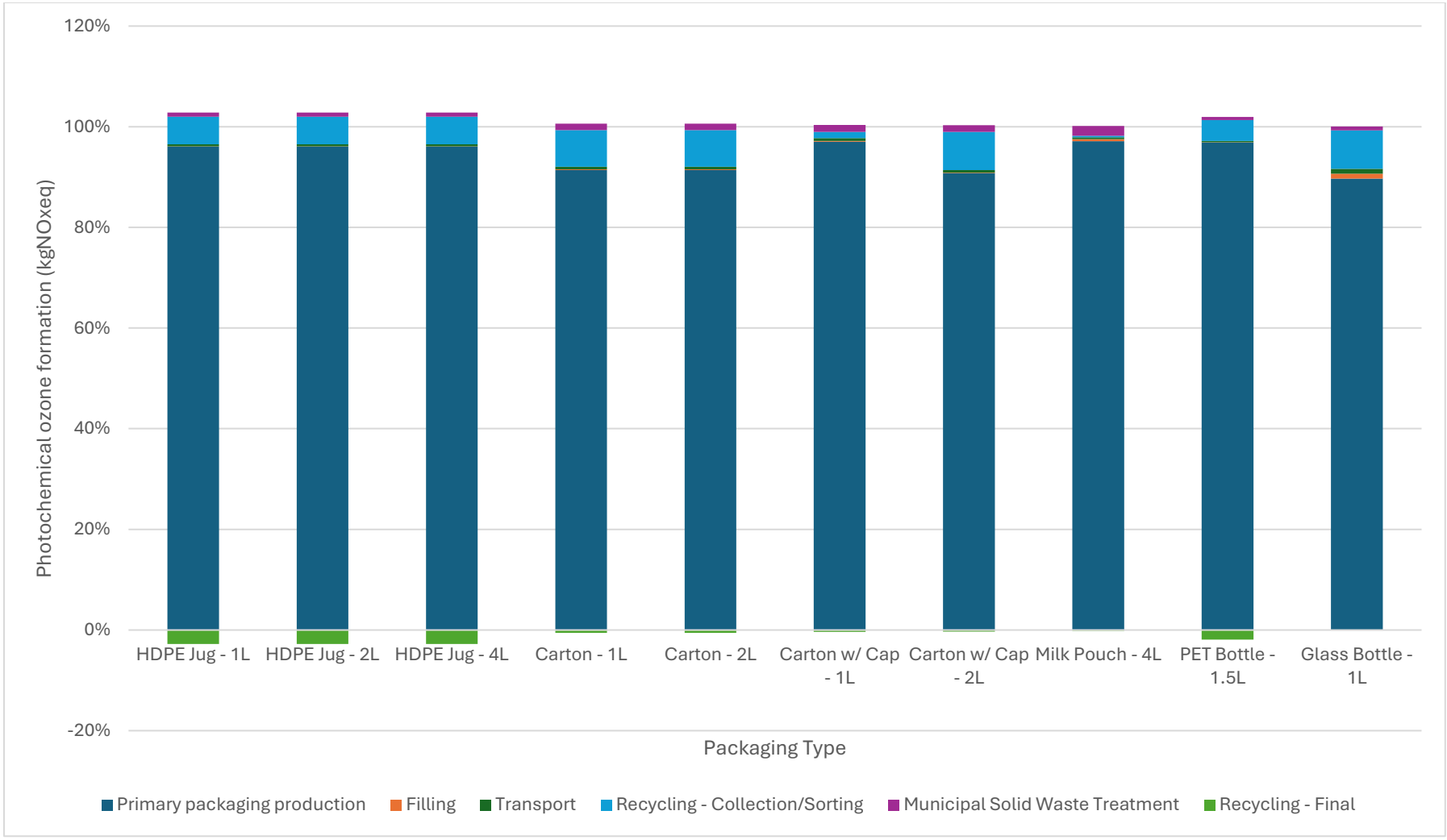


Figure 20 Photochemical ozone formation contributions by stage

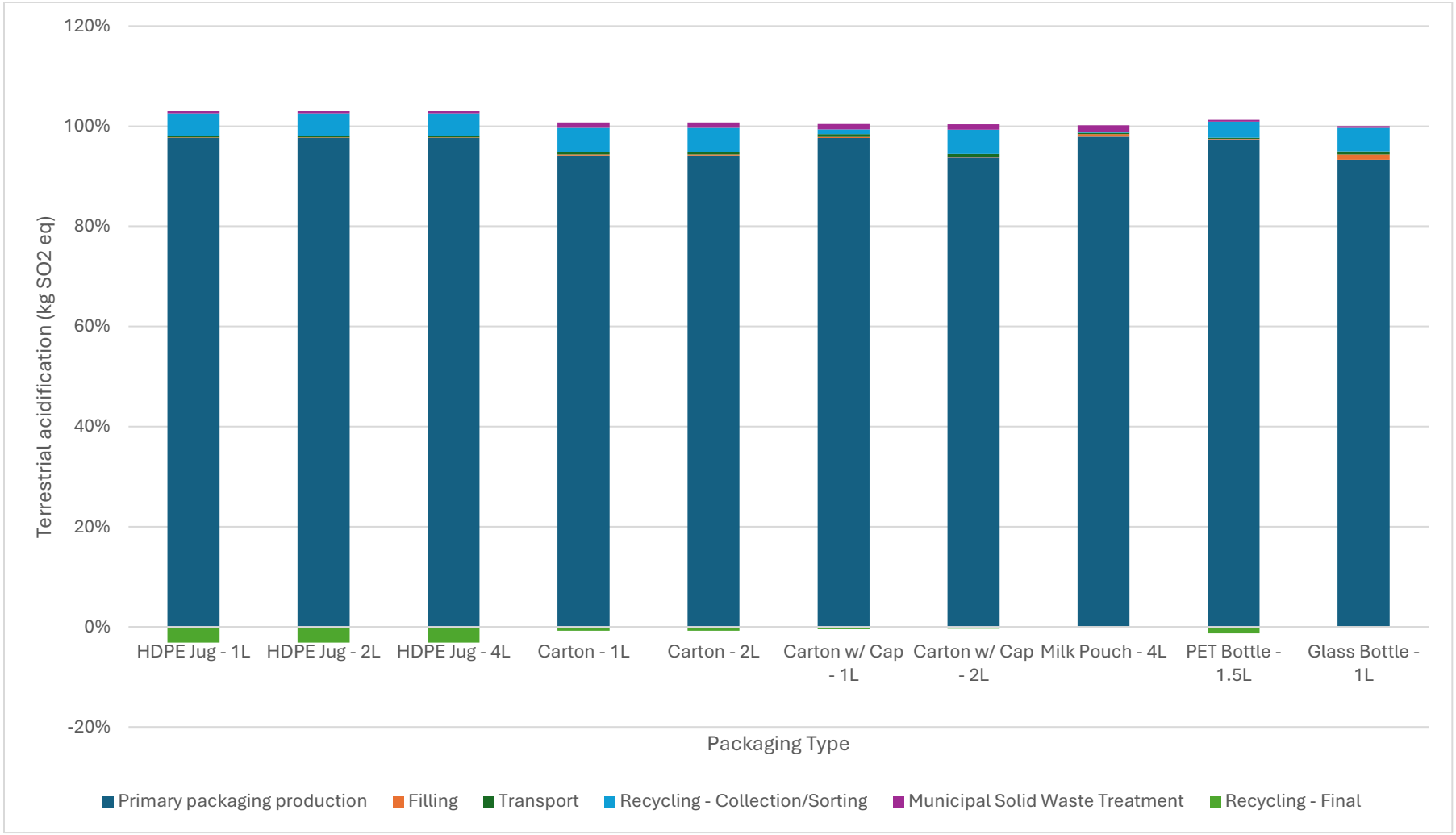


Figure 21 Terrestrial acidification contributions by stage

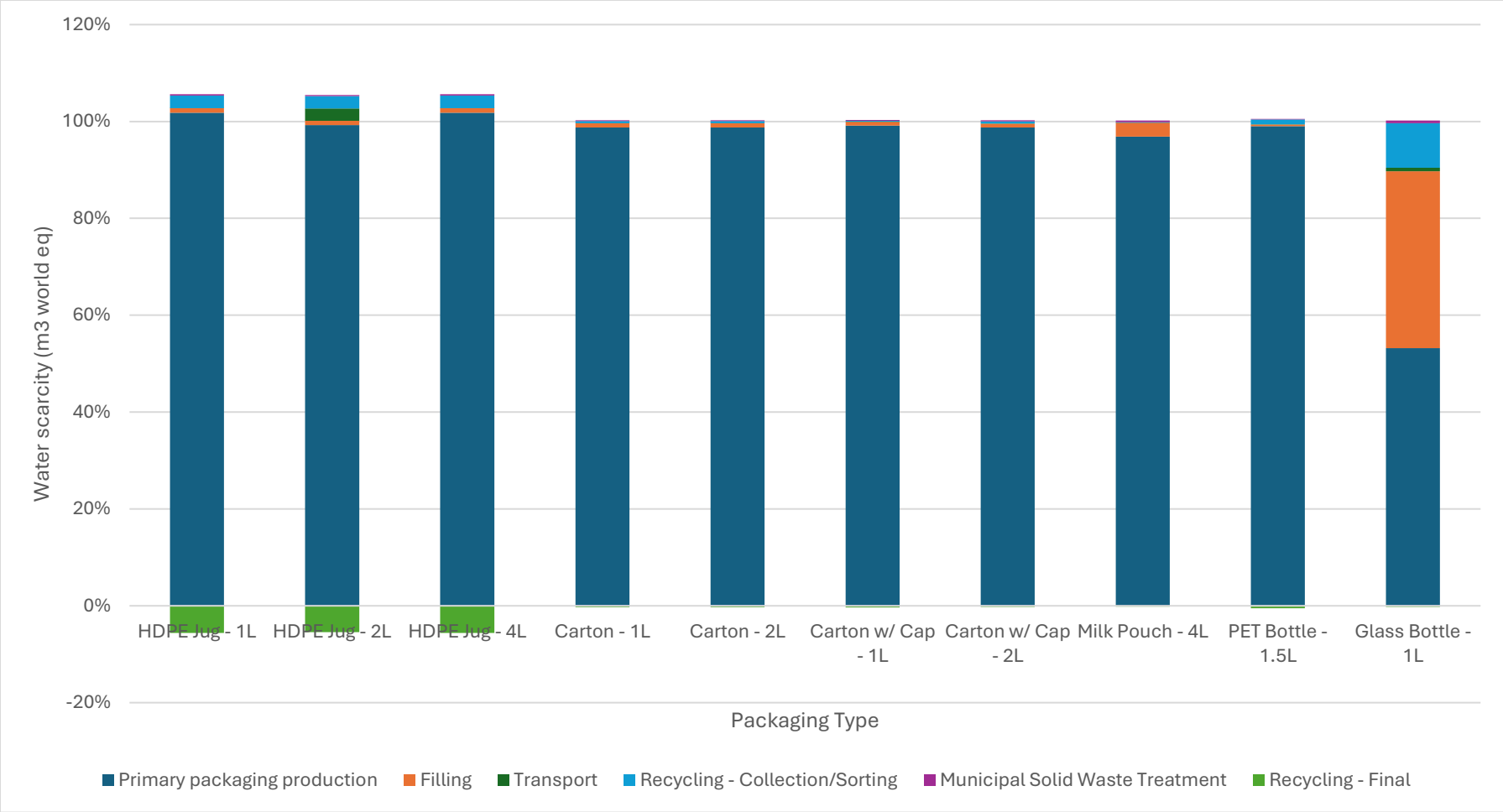


Figure 22 Water scarcity contributions by stage