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Comparative Life Cycle Assessment of Multiple Liquid Laundry Detergent Packaging Formats

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Abstract: The emerging packaging industry trend of focusing on packaging sustainability is also occurring in the laundry detergent industry. This study presents a cradle-to-grave comparative life cycle assessment (LCA) of three different packaging systems for liquid laundry detergent: the conventional pourable bottle, polyethylene terephthalate (PET) container with pods, and flexible pouch with pods. The scope of this study included material production, intermediate processes, transportation, and end-of-life phases of each packaging system. The results showed that the conventional pourable bottle made of high-density polyethylene (HDPE) has less environmental impact than the other two packaging systems in all impact categories, except ecotoxicity, due to the higher amount of packaging material required to produce the pods. The rigid PET container with pods impacted the environment in all categories more than the multi-layered flexible pouch containing pods, due primarily to the amount of material production, heavier weight, and intermediate processing using injection molding.

Keywords: packaging; sustainability; life cycle assessment; laundry detergent

1. Introduction

A notable current trend in the packaging industry is sustainability. Centobelli, Cerchione, and Esposito [1] suggested that the trend reflects the evolution of environmental awareness of both individual businesses and the supply chain resulting from the institution of major climate change agreements. While the current research trend focuses on sustainability, the environmental impact of the generation of packaging waste is significant [2]. Packaging waste from household products accounts for a substantial share of the total amount of municipal solid waste; 23–34% by weight [2,3]. In 2017, the category of containers and packaging waste constituted the largest percentage (29.9%) among municipal solid waste, composing 80 of 268 million total tons [4]. Furthermore, consumers, government, and non-governmental organizations are most concerned about environmental impacts that can be generated by the waste from packaging systems [5–8].

In Canada, the laundry detergent industry is the largest household product market, with USD 634 million annual sales [9]. Although this industry has recently demonstrated concern for packaging sustainability, they historically have been more sensitive to the sustainability of detergent formulations [10]. Many comparative life cycle assessment (LCA) studies have been conducted on new detergent formulations or ingredients [11–14]. The concern for packaging sustainability was borne out of increased pressure from consumers and regulations [5–10], and the industry began to focus on reducing primary packaging materials and including more recycled materials [10]. A few states in the USA have enacted laws that forced paper and plastic packaging to contain a specific proportion of recycled materials. For example, in 1991, California required the industry practice a 25% rate of recycling, reuse, or use of other methods to support the circular economy. Similarly, in 1991, Oregon passed a law that 25% of containers must be recycled or composed of 25% recycled material by 1995 [10]. In response to these laws, the laundry detergent industry started to reduce the amount of plastic and paperboard from its packaging. The Dial Corporation developed a bag-in-box style for liquid detergent products that reduced plastic waste by more than 75% from that of the conventional bottle type of container [10]. Lever Brothers and Procter & Gamble approached this issue by including up to 35% post-consumer recycled (PCR) plastic resins in their plastic bottle products [10]. In 2018, Canadian government also committed to reach at least 50% of the recycled content included in plastic products where applicable by 2030 during its G7 Presidency [15].

Liquid laundry detergent was conventionally contained in a pourable bottle made of high-density polyethylene (HDPE). The pourable bottle packaging system effectively provides containment and protection to preserve the characteristics of the product, which must remain in the same place for a long time before it is discarded. In 2001, a new type of liquid laundry detergent packaging method called pods was introduced into the UK, Irish, and French markets [16]. Liquid laundry detergent pods are small packets that consist of a water-soluble polyvinyl alcohol (PVA) film that holds a single dose of liquid detergent. This new type of detergent product was intended to improve customer experience and reduce the environmental burden of liquid laundry detergent overconsumption by eliminating manual metering and providing a single dosage in one packet [16,17]. Pods are commonly contained in two different packaging formats: the polyethylene terephthalate (PET) container or flexible pouch.

Although most LCA studies of the environmental impacts of laundry detergent have focused on the impact of new detergent ingredients or formulations [12,18], one recently published study expressly analyzed the impact of the different liquid detergent packaging systems. Nessi et al. [19] compared the environmental impact of two main types of packaging systems, the single-use container and the refillable container with a self-dispensing system. They found that using the refillable container system more than five times will lead to achieving the expected reduction in environmental burden compared to the single-use container [19]. Nevertheless, the environmental impact of three types of liquid detergent packaging increasing in consumer popularity—the conventional pourable bottle, PET container with pods, and flexible pouch with pods—has not been assessed. Such data gaps may mislead consumer perceptions of sustainable packaging by modeling bias. Without environmental impact data, the visual appearance of detergent packaging and verbal sustainability claims of detergent companies will influence consumer attitudes and purchasing [20]. In summary, there is an acute need for quantitative research using a numerical method that could objectively compare the environmental impacts of three popular detergent packaging types in the Canadian market using the LCA method.

2. Materials and Methods

The LCA is an assessment and evaluation of the input and output data, and the potential environmental impacts of a product, system, or process throughout its life cycle [21]. This study complies with two ISO standards, 14040:2006 and 14044:2006, which require the definition of the goal and scope. These include definitions of the functional unit and the system boundary, the life cycle inventory analysis, the life cycle impact assessment, and the life cycle interpretation [21]. The analysis will include many environmental impacts that are easy to overlook, such as energy consumption and atmospheric emissions over the entire life cycle. The most appropriate life cycle inventory will be chosen and used to extrapolate accurate data from the LCA software, SimaPro v9.0.

2.1. Goal and Scope Definition

The goal of this study is to analyze the environmental impacts of the three types of liquid laundry detergent packaging. The LCA will investigate the detailed process of the laundry detergent packaging system from an environmental perspective. The functional unit used for this project was 10,000 loads of detergent, as the liquid detergent recommends a specific amount to use for a single load, and pods also mostly contain a precisely measured amount of liquid detergent for the single load.

The scope of this research includes the complete process of the packaging life cycle from raw material extraction to disposal options for each plastic material, which is the cradle-to-grave perspective. However, the system boundary excluded the production, package filling, and use stages of the liquid detergent. The geographical scope in this study is North America since the products are assumed to be manufactured in Ohio, USA, and consumed in Ontario, Canada.

2.2. Scenario Description

The life cycle scenarios of three packaging systems have been separated into four life cycle stages: material production, intermediate processes, transportation, and end of life. The material production stage includes plastic production and bleached paper label production processes. The intermediate process stage includes plastic formation processes, such as blow molding, lamination, plastic film extrusion, extrusion processing, injection molding, thermoforming, and supporting activities. The transportation stage covers the transportation of packaged products from the manufacturing site to the retail locations or end-users. The end-of-life phase includes waste management scenarios, such as landfilling, incineration, and recycling.

The materials used to produce the conventional pourable bottle were high-density polyethylene (HDPE) and polypropylene (PP). The body of the bottle was made by blow molding using an HDPE resin. Both cap and spout were made by the injection molding process using PP resin. According to an industry leading liquid detergent manufacturer, the HDPE bottle includes approximately 25% of post-consumer recycled plastics [21]. Therefore, it was assumed to be 75% primary HDPE (produced from new raw material) and 25% post-consumer recycled HDPE [21].

The rigid PET container holding the pods primarily consisted of four parts, including a body made of PET, a lid made of PP, neck made of PP, and a bleached paper label. The body, lid, and neck were produced through injection molding. The material used to form pods was polyvinyl alcohol (PVA), which is a synthetic polymer that has water soluble characteristics [22]. The pods were formed by thermoforming the PVA resin.

The flexible pouch with pods consisted of three different materials, such as a multi-layered film, a zipper, and a red slider. The multi-layered film consisted of linear low-density polyethylene, biaxially oriented nylon 6, and PET are laminated to hold the pods. The zipper and red slider are made of low-density polyethylene and PP, respectively, via injection molding. The pod products contained in this packaging were produced by the same process as the pods contained in the PET container.

After the completion of these processes, packaging materials travel to the liquid detergent manufacturing site for assembly and the product-filling process. The finished product travels to the retailers, and end-users dispose of it after the use stage. Lastly, the life cycle of liquid detergent packaging is completed at the end of life stage. Figures 1 and 2 show the system boundaries of the conventional pourable bottle and the two packaging systems that contain pods, respectively.

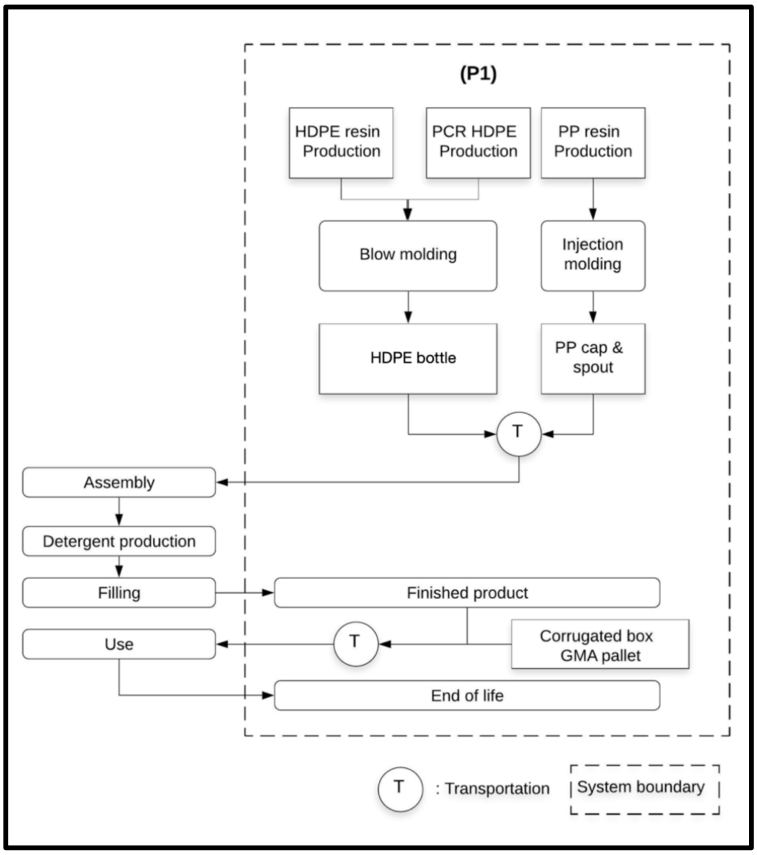

Figure 1. System boundary of the conventional pourable bottle packaging system. (P1) refers to the production process of the conventional pourable bottle packaging system.

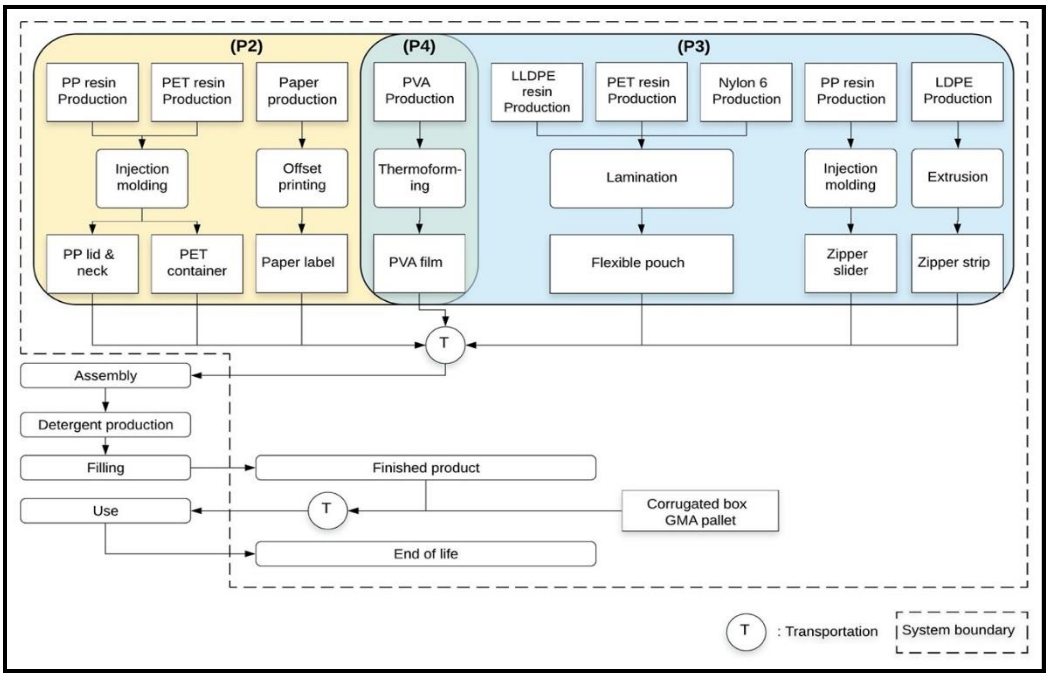

Figure 2. System boundary of two different packaging systems that contain pods. (P2) shows polyethylene terephthalate (PET) container production processes. (P3) shows flexible pouch production processes. (P4) shows polyvinyl alcohol (PVA) pods production stages shared by (P2) and (P3).

2.3. Life Cycle Inventory Analysis

The life cycle inventory analysis is the process of quantifying resource inputs, energy consumption, and environmental outputs that contribute to a product's life cycle by collecting and analyzing data [23]. Primary data includes the mass of packaging components obtained by direct measurement of the empty packaging samples. Life cycle inventory data for the inputs and outputs of PVA production were obtained from the literature [24]. For modeling unit processes of each type of packaging and calculation in this study, LCA software SimaPro v9.0 was used. Table 1 provides the life cycle inventory for modeling the production of each detergent packaging system based on the functional unit and weight applied for each inventory per functional unit.

Datasets available in SimaPro were used for secondary life cycle inventory (LCI) data. Three different LCI datasets, US-EI Version 2.2, US LCI version 1, and Ecoinvent version 2.2, are used depending on the items available from each dataset. The US-EI dataset is an admixed life cycle inventory, including newly created data, expanded US LCI data, and modified Ecoinvent Version 2.2 data [25]. It represents the North American industrial conditions by replacing energy data from the Ecoinvent dataset to U.S. energy data [25]. The US LCI database is also the life cycle inventory dataset that traditionally represents U.S. regional data of inputs and outputs from cradle-to-gate, gate-to-gate, and cradle-to-grave perspectives [26].

Transportation data used in this study were derived by assumptions, which are further explained below. The distance data were converted to ton-kilometer (tkm) for process modeling by multiplying distance (in km) and mass of material (in tons).

In this study, the final product manufacturing site is assumed to be located in Lima, Ohio, for packaging formation and filling. Manufactured laundry detergent products are transported from the manufacturing site in Lima, Ohio, to retailers and consumers in Toronto, Ontario (590 km). Raw material transportation data are already incorporated in each LCI dataset. Table 2 shows the transportation distances in tkm, the inventory dataset applied for process modeling, and the sources of each dataset.

The three different packaging systems have unique end-of-life scenarios due to the variety of materials used. However, a specific recycling rate by resin type of plastic in the Canadian region was not available through current publicly available resources. Due to this limitation, end-of-life (EOL) scenarios of plastic waste have been estimated from the Canadian governmental report by Environment and Climate Change Canada [27] and applied to all three systems. In 2016, 3238 kilotons (kt) of plastic wastes were collected in Canada, and 9.48% of plastic wastes (307 kt) were separated to be mechanically and chemically recycled [27]. The waste streams remaining after separation were landfills (95.33%, 2794 kt), and incineration with energy recovery (4.67%, 137 kt) [27]. Packaging waste scenario 2015/US_U dataset from the US-EI 2.2 source was applied to the life cycle modeling after modification by the recycling rate described above.

Table 1. Life cycle inventory for modeling the production of 10,000 loads of each detergent packaging system.

Product	Component	Material	Dataset	Source	Weight per Functional Unit (g)	Pedigree Score
Conventional pourable bottle	Bottle	High-density polyethylene (HDPE)	High-density polyethylene resin, at plant/RNA	US LCI	16206.82	(1,3,1,2,2,3)
		Process	Blow molding/US-US-EI U	US-EI v2.2	16206.82	(2,3,1,3,2,5)
		Post-consumer recycled HDPE	Recycled post-consumer HDPE pellet/RNA	US LCI	5406.82	(2,3,2,2,2,5)
		Process	Blow molding/US-US-EI U	US-EI v2.2	5406.82	(2,3,1,3,2,5)
	Cap	Polypropylene (PP)	Polypropylene resin, at plant/RNA	US LCI	3361.36	(1,3,1,2,2,3)
		Process	Injection molding/US-US-EI U	US LCI	3361.36	(2,3,1,3,2,5)
	Spout	PP	Polypropylene resin, at plant/RNA	US LCI	3059.09	(1,3,1,2,2,3)
		Process	Injection molding/US-US-EI U	US LCI	3059.09	(2,3,1,3,2,5)
Polyethylene terephthalate (PET) container	Container	Polyethylene terephthalate (PET)	Polyethylene terephthalate (PET), granulate, bottle grade, at plant/US-US-EI U	US-EI v2.2	34937.50	(2,3,1,3,2,5)
		Process	Injection molding/US-US-EI U	US-EI v2.2	34937.50	(2,3,1,3,2,5)
	Lid	PP	Polypropylene resin, at plant/RNA	US LCI	5746.87	(1,3,1,2,2,3)
		Process	Injection molding/US-US-EI U	US LCI	5746.87	(2,3,1,3,2,5)
	Neck	PP	Polypropylene resin, at plant/RNA	US LCI	5609.37	(1,3,1,2,2,3)
		Process	Injection molding/US-US-EI U	US LCI	5609.37	(2,3,1,3,2,5)
	Label	Paper	Kraft paper, bleached, at plant/US-US-EI U	US-EI v2.2	840.63	(2,3,1,3,2,5)
Flexible pouch	Pouch	Linear low-density polyethylene (LLDPE)	Linear low-density polyethylene resin, at plant/RNA	US LCI	5106.28	(1,3,1,2,2,3)
		Nylon 6	Nylon 6, at plant/US-US-EI U	US-EI v2.2	1069.26	(2,3,1,3,2,5)
		PET	Polyethylene terephthalate resin, at plant/kg/RNA	US LCI	1098.36	(1,3,1,2,2,3)
		Process	Extrusion, co-extrusion {RoW}| of plastic sheets | Conseq, U	Ecoinvent 3	7273.91	(1,3,1,3,2,4)
	Strip	Low-density polyethylene (LDPE)	Low-density polyethylene resin, at plant/RNA	US LCI	617.39	(1,3,1,2,2,3)
		Process	Extrusion, plastic film/US-US-EI U	US-EI v2.2	617.39	(2,3,1,3,2,5)
	Slider	PP	Polypropylene resin, at plant/RNA	US LCI	352.17	(1,3,1,2,2,3)
		Process	Injection molding/US-US-EI U	US-EI v2.2	352.17	(2,3,1,3,2,5)
Pods	Pods	Polyvinyl Alcohol (PVA)	Polyvinyl Alcohol (PVA)_at Plant	[24]	16500.00	(2,3,4,3,2,5)
		Process	Thermoforming, with calendaring/US-US-EI U	US-EI v2.2	16500.00	(2,3,1,3,3,5)

Table 2. Transportation inventory dataset and distance in ton-kilometer (tkm) of each product.

Final Products	Dataset	Source	Distance in tkm	Pedigree Score
HDPE bottle	Transport, single unit truck, long-haul, diesel powered, Central/tkm/RNA	USLCI	44.60	(1,3,1,1,2,3)
PET container with pods	Transport, single unit truck, long-haul, diesel powered, Central/tkm/RNA	USLCI	76.43	(1,3,1,1,2,3)
Multi-layered pouch with pods	Transport, single unit truck, long-haul, diesel powered, Central/tkm/RNA	USLCI	32.81	(1,3,1,1,2,3)

2.4. Limitations and Assumptions

Assumptions and limitations that could affect results in this study are identified as follows:

1. Data for secondary packaging (i.e., corrugated paperboard boxes) and tertiary packaging (i.e., pallets) rely on assumptions made based on the sizes of products and capacity of the secondary and tertiary packages. It is assumed that B-flute single-wall corrugated paperboard boxes with grammages of 161/127/161 are applied to distribute the primary packages. It is also assumed that the pallet type used to ship the packaged goods is the Grocery Manufacturers Association (GMA) style. The palletization and truck loading configuration and the quantity of secondary and tertiary packages were estimated through calculation by Esko Cape Pack v.18.1.1 packaging configuration simulation software.
2. The location of manufacturing site was assumed to be located in Ohio, USA. The transportation distances from the manufacturing site to the retailers were calculated based on assumed location data.
3. Since the end-of-life scenarios for each type of plastic resin in Ontario were not available from publicly accessible sources, common recycling, landfill, and incineration rates in Canada were applied for all kinds of plastic resin end-of-life scenarios.
4. The LCA did not include printing and die-cutting processes, because exact data regarding ink usage was not available.

2.5. Life Cycle Impact Analysis (LCIA)

Environmental impacts and life cycle impact categories were calculated from input and output data using a midpoint-oriented life-cycle impact assessment methodology called the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI 2.1). The TRACI 2.1 is geographically based on U.S. locations since it was created by the US Environmental Protection Agency [28]. TRACI 2.1 was applied in this study since it is geographically based in the U.S. and Ontario, which share similar environmental, geographical, and technological characteristics. TRACI 2.1 includes ten impact categories: ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion.

3. Results and Discussion

This chapter discusses the cradle-to-grave LCA results for the functional unit of 10,000 loads of each liquid laundry detergent packaging system. To interpret the characterization results of the life cycle impact assessment (LCIA), comparative analysis, contribution analysis, and uncertainty analysis were performed. Contribution analysis reports which packaging system has a higher environmental burden during its life cycle. Uncertainty analysis was conducted using a Monte Carlo simulation to define the uncertainty of each inventory datum. Tables 3–5 present the impact analysis values of the three different liquid laundry detergent packaging systems values for the impact indicators chosen. The values were obtained through computer simulations using SimaPro v9.0 with life cycle impact method of TRACI 2.1.

Table 3. Environmental impact of each phase for the conventional pourable detergent bottle.

Impact Indicator	Unit	Total	Material Production	Intermediate Process	Transportation	End-of-Life
Ozone depletion	kg CFC-11 eq	7.29×10^{-6}	9.80×10^{-7}	6.19×10^{-6}	7.34×10^{-10}	1.24×10^{-7}
Global warming	kg CO_2 eq	1.43×10^{2}	6.28×10	5.01×10	1.76×10	1.30×10
Smog	kg O_3 eq	9.83	3.31	1.95	4.33	2.31×10^{-1}
Acidification	kg SO_2 eq	7.95×10^{-1}	4.04×10^{-1}	2.12×10^{-1}	1.74×10^{-1}	5.69×10^{-3}
Eutrophication	kg N eq	5.13×10^{-1}	3.20×10^{-2}	1.15×10^{-1}	1.03×10^{-2}	3.56×10^{-1}
Carcinogenics	CTUh	4.00×10^{-6}	1.53×10^{-6}	2.10×10^{-6}	2.63×10^{-7}	1.09×10^{-7}
Non-carcinogenics	CTUh	2.91×10^{-5}	5.33×10^{-6}	6.96×10^{-6}	2.53×10^{-6}	1.42×10^{-5}
Respiratory effects	kg PM2.5 eq	4.64×10^{-2}	2.67×10^{-2}	1.32×10^{-2}	5.78×10^{-3}	7.12×10^{-4}
Ecotoxicity	CTUe	2.51×10^{3}	1.14×10^{2}	1.78×10^{2}	4.90×10	2.17×10^{3}
Fossil fuel depletion	MJ surplus	3.74×10^{2}	2.80×10^{2}	5.61×10	3.69×10	1.20

Table 4. Environmental impact of each phase for the PET container with pods.

Impact indicator	Unit	Total	Material Production	Intermediate Process	Transportation	End-of-Life
Ozone depletion	kg CFC-11 eq	4.67×10^{-5}	1.27×10^{-5}	3.38×10^{-5}	1.26×10^{-9}	1.73×10^{-7}
Global warming	kg CO_2 eq	4.83×10^{2}	3.28×10^{2}	9.07×10	3.01×10	3.51×10
Smog	kg O_3 eq	2.67×10	1.53×10	3.46	7.42	4.86×10^{-1}
Acidification	kg SO_2 eq	1.91	1.26	3.44×10^{-1}	2.98×10^{-1}	6.36×10^{-3}
Eutrophication	kg N eq	1.00	4.62×10^{-1}	1.65×10^{-1}	1.76×10^{-2}	3.60×10^{-1}
Carcinogenics	CTUh	2.46×10^{-5}	2.06×10^{-5}	3.36×10^{-6}	4.50×10^{-7}	1.41×10^{-7}
Non-carcinogenics	CTUh	8.98×10^{-5}	5.69×10^{-5}	1.05×10^{-5}	4.34×10^{-6}	1.81×10^{-5}
Respiratory effects	kg PM2.5 eq	1.32×10^{-1}	9.85×10^{-2}	2.28×10^{-2}	9.90×10^{-3}	7.90×10^{-4}
Ecotoxicity	CTUe	3.62×10^{3}	1.55×10^{3}	2.71×10^{2}	8.40×10	1.72×10^{3}
Fossil fuel depletion	MJ surplus	1.24×10^{3}	1.04×10^{3}	1.39×10^{2}	6.32×10	1.06

Table 5. Environmental impact of each phase for the flexible pouch with pods.

Impact Indicator	Unit	Total	Material Production	Intermediate Process	Transportation	End-of-Life
Ozone depletion	kg CFC-11 eq	9.28×10^{-6}	7.95×10^{-6}	1.23×10^{-6}	5.40×10^{-10}	9.76×10^{-8}
Global warming	kg CO_2 eq	2.45×10^{2}	2.03×10^{2}	2.00×10	1.29×10	9.52
Smog	kg O_3 eq	1.38×10	9.60	8.50×10^{-1}	3.19	1.84×10^{-1}
Acidification	kg SO_2 eq	9.62×10^{-1}	7.48×10^{-1}	8.13×10^{-2}	1.28×10^{-1}	5.20×10^{-3}
Eutrophication	kg N eq	6.64×10^{-1}	2.68×10^{-1}	5.97×10^{-2}	7.58×10^{-3}	3.28×10^{-1}
Carcinogenics	CTUh	1.47×10^{-5}	1.34×10^{-5}	9.31×10^{-7}	1.93×10^{-7}	2.07×10^{-7}
Non-carcinogenics	CTUh	5.73×10^{-5}	3.37×10^{-5}	3.31×10^{-6}	1.86×10^{-6}	1.84×10^{-5}
Respiratory effects	kg PM2.5 eq	7.22×10^{-2}	5.55×10^{-2}	1.19×10^{-2}	4.25×10^{-3}	6.04×10^{-4}
Ecotoxicity	CTUe	2.26×10^{3}	9.28×10^{2}	1.11×10^{2}	3.60×10	1.18×10^{3}
Fossil fuel depletion	MJ surplus	6.75×10^{2}	6.22×10^{2}	2.54×10	2.71×10	1.04

Figure 3 shows the contribution analysis of each packaging system in four phases; material production, intermediate processes, transportation, and end-of-life.

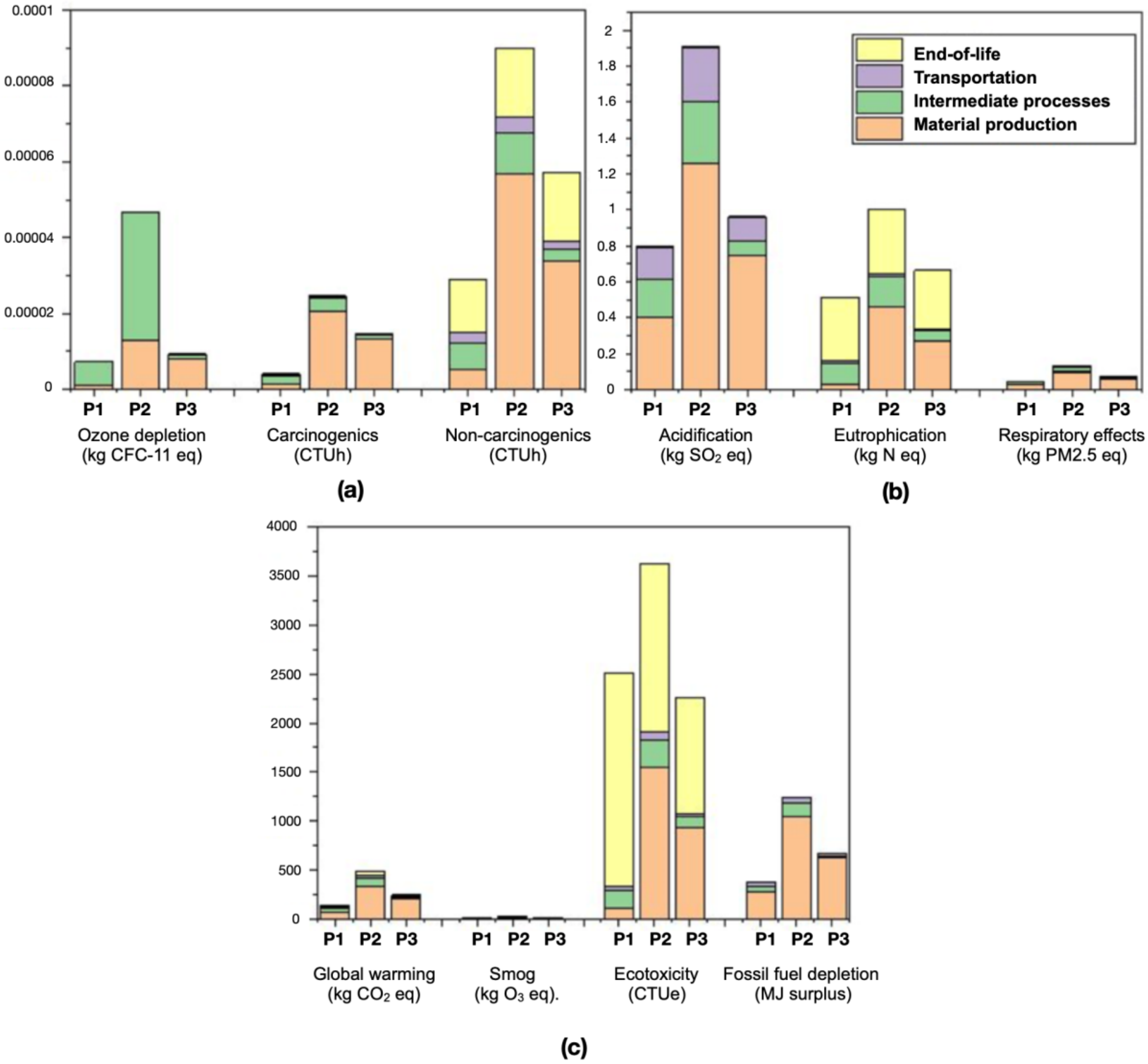

Figure 3. Results of impact categories from LCIA using TRACI 2.1. The letter at the bottom of each impact category column represents the different scenarios: (P1, Conventional pourable detergent bottle; P2, PET container with pods; P3, flexible pouch with pods). Each graph shows three to four categorical results. Graph (**a**) shows results of ozone depletion, carcinogenics, and non-carcinogenics impact categories. Graph (**b**) shows results of acidification, eutrophication, and respiratory effects impact categories. Graph (**c**) shows results of global warming, smog, ecotoxicity, and fossil fuel depletion impact categories.

The most significant contributor to ozone depletion from the PET container with pods and conventional pourable bottles was the intermediate processes phase, especially the injection molding process. Unlike the two previous packaging systems, the material production phase for a multi-layered pouch with pods, specifically the production of PVA at the plant, most contributed to ozone depletion. As seen in Tables 4 and 5, the results show that the PET container with pods contributes approximately 80.1% more ozone depletion than the multi-layered pouch with pods (with 100% certainty, based on the result of Monte Carlo simulations). The conventional pourable bottle contributed 4.3% less to ozone depletion than the multi-layered pouch packaging system. The primary reason found for the difference in the ozone depletion category was the different amounts of material used in the injection molding processes. As shown in Table 1, approximately 46.29 kg of materials for the PET container with pods required injection molding, while for the multi-layered pouch with pods, approximately 0.35 kg required injection molding. The conventional pourable bottle required approximately 6.42 kg of injection molding. The other reason was the use of different types and amounts of materials used. Packaging systems that contain pods required a relatively higher amount of packaging materials than the packaging systems that do not contain pods. For instance, 16.5 kg of the PVA film was required to package a single dose of liquid laundry detergent. The material production process of PVA produced at the plant was 7.32×10^{-6} kg CFC-11 eq, which is more than half of the material production phase emission for both PET containers with pods and multi-layered pouch with pods, mainly due to the production of crude oil for vinyl acetate.

For the carcinogenics and non-carcinogenics impact categories, the material production stage was the largest contributor to the PET container with pods and multi-layered pouch with pods. Specifically, the production of PET and PVA are the largest contributors for the PET container with pods and production of PVA for the multi-layered pouch with pods. The carcinogenics and non-carcinogenics results of the conventional pourable bottle were not similar to the results of the previous two types of packaging systems. For the conventional pourable bottle, the intermediate process phase, specifically the blow molding process, most contributed to the carcinogenics impact category and end-of-life phase, specifically landfilling, most contributed to the non-carcinogenics impact category. The PET container with pods had a 40.1% higher level of carcinogenics and a 36.2% higher level of non-carcinogenics than the multi-layered pouch with pods (96% certainty in Monte Carlo simulations). The multi-layered pouch with pods packaging system had a 43.6% higher level of carcinogenics and a 31.4% higher level of non-carcinogenics than the conventional pourable bottle. The main reason for the differences in carcinogenics and non-carcinogenics was the different amounts of material used. As mentioned in the previous paragraph, the use of additional material such as PVA film for pods significantly increases the total weight of the material. For instance, the production of PVA for the multi-layered pouch with pods produced 1.22×10^{-5} CTUh of carcinogenics, which is 80% of the total value of the carcinogenics impact category.

The largest contribution to the acidification, respiratory effects, global warming, and fossil fuel depletion for all three packaging systems compared in this study was also the material production phase. Specifically, the production of polyvinylchloride (PVC) for PVA film contributed the most for PET containers with pods and multi-layered pouch with pods and production of natural gas for ethylene production contributed the most for the conventional pourable bottle. The PET container with pods packaging system had 49.7% higher acidification values, 45.3% higher respiratory effects values, 49.2% higher global warming values, and 45.5% higher fossil fuel depletion values than the multi-layered pouch with pods (100% certainty in Monte Carlo simulations). The conventional pourable bottle showed the lowest value for all four impact categories among the three packaging systems compared. The differences in the acidification, respiratory effects, global warming, and fossil fuel depletion values are mainly due to the different types and amounts of material used. The reason is the same as that for the major differences in the carcinogenics and non-carcinogenics values. The second major reason for differences in these four impact categories varies from each impact category, but these reasons are not considered a significant factor because the main reason predominates (approximately 49% to 92%) in every category.

For the ecotoxicity and eutrophication impact categories, the end-of-life phase most contributed in all three packaging systems, except for the eutrophication indicator in PET containers with pods, which was the most impacted category from the material production phase. The main processes of eutrophication for the PET container with pods and multi-layered pouch with pods packaging systems were the landfill of plastic mixtures and the spoil from coal in a surface landfill. The landfilling of polypropylene and the average incineration residue were the main contributors to ecotoxicity, respectively, for the PET container with pods and multi-layered pouch with pods. In the case of the conventional pourable bottle, the main process contributing to both eutrophication and ecotoxicity was the landfilling of polyethylene. The PET container with pods had a 33.9% higher contribution to eutrophication than the multi-layered pouch with pods and 30.7% higher contribution to ecotoxicity than the conventional pourable bottle (96% certainty during Monte Carlo simulations). Notably, in the ecotoxicity impact category, unlike other impact categories, the conventional pourable bottle showed a slightly greater impact than the multi-layered pouch with pods. This result was mainly due to the landfilling of polyethylene and polypropylene contributing more to ecotoxicity than the other disposal processes during the end-of-life phase of the multi-layered pouch with pods.

Transportation was found to be the main contributor to smog for the conventional pourable bottle, and material production was found to be the most significant contributor to smog for the PET container with pods and multi-layered pouch with pods. Specifically, the road transportation of the final product from the manufacturing site to retailers in Toronto, Ontario by long-haul diesel-powered single-unit truck was the largest contributor for the conventional pourable bottle packaging, whereas production of PVC for PVA film was the largest contributor for the PET container with pods and multi-layered pouch with pods. The PET container with pods contributed 48.2% more to the smog impact category than the multi-layered pouch with pods (with 100% certainty in Monte Carlo simulations).

The PET container with pods had the highest value in all impact categories, and the multi-layered pouch with pods had the second-highest value in most of the impact categories except for ecotoxicity. These results indicate that the PET container with pods packaging system releases comparably higher environmental impacts under all 10 considered impact categories than the other two packaging systems. The most considerable difference was shown in ozone depletion, in which the PET container with pods contributed 84.4% more than the conventional pourable bottle. The second greatest difference was carcinogenics generated by PET container with pods, with approximately 83.6% greater contribution than the conventional pourable bottle (with 100% certainty in Monte Carlo simulations). When comparing the conventional pourable bottle and multi-layered pouch with pods, the results show the conventional pourable bottle system performed better in most of the categories than the multi-layered pouch with pods, except for ecotoxicity. These results were mainly due to the heavier total weight of material used for packaging systems that contain pods. PVA film material production process for pods of the PET container with pods and multi-layered pouch with pods is primarily responsible for most of the impact categories, whereas the conventional pourable bottle shows relatively lower values in the material production phase for every impact category. The importance of light-weighting of packaging material was also shown from the difference of impact values between the PET container with pods and multi-layered pouch with pods. Comparing results between the two packaging systems containing pods showed that the multi-layered pouch with pods, which consists of the lighter weight of secondary packaging, has lower environmental impacts than the PET container with pods.

4. Conclusions

The results in this study showed that two packaging systems containing PVA pods (i.e., PET container with pods and flexible pouch with pods) have higher environmental burdens than the conventional pourable bottle primarily made of HDPE for all impact categories except ecotoxicity. The primary reason for these results was that more PVA film was required to produce the pods.

The flexible pouch with pods generates less environmental impacts than the PET container with pods. For most of the impact categories, it was mainly because the multi-layered flexible pouch consumed less material mass than the rigid PET container. The lighter weight of the flexible pouch also resulted in less environmental impacts than the rigid PET container for transportation. For the intermediate processes, moreover, the rigid PET container generated more environmental impacts than the flexible pouch for most of the impact categories because of the injection molding used for the PET container conversion.

This study did not consider any potential loss or overpouring of liquid detergent, which can occur when consumers use the conventional pourable bottle for washing. This was because there was no significant leak found from the conventional pourable bottle sample used in this study, and it provided instructions for the appropriate liquid detergent measurement instruction on its packaging.

But other types of conventional pourable bottles in the market could cause these types of issues if their packaging structures, especially their pourable necks, are not designed in this way. The pod packaging system can help consumers use the right amount of the liquid detergent, avoiding any leak or loss due to its premeasured and pre-packed formulation. The results of this LCA may be different if it counted any significant loss of liquid detergent or overfilling of the liquid detergent during the use of the conventional pourable bottle because of the potential environmental impacts generated from the liquid detergent itself. Therefore, a bottle design to prevent any leak during usage as well as to guide for using the appropriate amount of liquid detergent per use was important for the results of this study.

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