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Cradle-to-grave life cycle assessment of single-use disposable and reusable cups

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Abstract

A cradle-to-grave life cycle assessment (LCA) of the reusable glass cup and the single-use disposable Polypropylene (PP) cup was conducted. The environmental impacts of both glass cup and PP cup were obtained and compared. In weighing the impacts, the break-even points from both environmental and economic viewpoints were investigated. Both impacts show that the glass cup has already outperformed the PP cup on the 5th day. Although the benefits are stark, consumer behavior will make a huge difference of whether using the reusable cups or disposable cups.

Keywords: Life Cycle Assessment (LCA); Glass Cup; PP Cup; Climate Change; Consumer Behavior; Break-even Point.

1. Introduction

In 1987, sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. In the present, the United Nations presents their 17 sustainable development goals, with Goal 12 about ensuring sustainable consumption and production patterns, which is key to sustaining the livelihoods of current and future generations. Reducing human waste, being thoughtful about human consumption, and choosing a sustainable option whenever possible are the main ways that a responsible consumer can contribute to sustainable development within their daily lives. The USA accounted for 37% of the good service disposable globally, with over 500 billion disposable cups were sent to landfills every year [2]. Using single-use disposable cup or reusable cup will make a substantial difference for both environmental and economic impacts [3].

Life cycle assessment (LCA) is a standardized methodology for evaluating the environmental impacts across the life cycle of a product. The results from these assessments will help the decision-makers (both the producer and the consumer) to identify the environmental impacts, improve the sustainability of the product, and make a meaningful decision toward a better, cleaner future [4-6].

In this paper, detailed LCA steps were presented, and then the detailed LCAs for the single-use cup and reusable cup were conducted. Environmental impacts were obtained, compared, and analyzed. The break-even points for both environmental and economic impacts were calculated and weighed. Finally, the results were summarized with recommendations.

2. LCA

The main international organization for standardization (ISO) standards for LCA are ISO 14040:2006, which defines the principles and framework for an LCA study, and ISO 14044:2006, which specifies the requirements and guidelines for conducting the four phases of an LCA. These ISO standards provide a systematic process for evaluating the environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to end-of-life.

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Based on ISO 14044, the LCA framework is shown in Figure 1 [4,7].

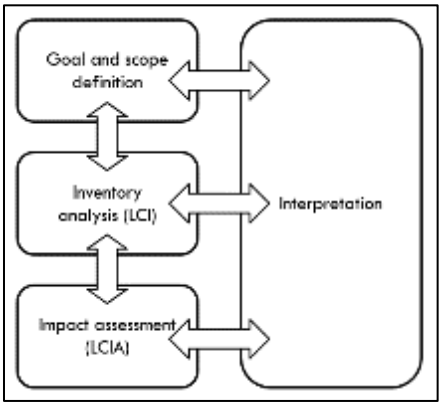

Figure 1 LCA framework

The key steps for the LCA are listed as follows

- Define the goals (i.e., identify the environmental impacts, support decision-making, improve resource efficiency, etc.) and scopes (i.e., expected product, boundary conditions, functional unit and assumption) of the assessment.
- Conduct a life cycle inventory (LCI) analysis by creating an inventory of flows from and to nature (i.e., inputs of raw materials, energy, natural resources, and releases to air, land, and water).
- Conduct a life cycle impact analysis (LCIA) to evaluate the significance of potential environmental impacts based on the above LCI analysis.
- Interpretate the data to identify, quantify, check and evaluate information from the LCI and LCIA results.

3. LCA of Single-use disposal and reusable cups

The goal of this study is to compare the environmental and economic impacts of these two types of cups. The manufacturing process, transportation, usage and/or cleaning process, and disposal are all included within the scope of this study. The functional unit is defined as 365*5*300cc beverages served. This assumes that the reusable cup has a 1-year (365 days) life span and is used 5 times/day for 300cc beverages each time.

There are too many variations (different sizes, different materials, different designs, etc.) for single-use disposal and reusable cups for them all to be considered within this study so the scope is limited to the two most common types. The commonly used 12oz single-use disposal cup made from Polypropylene (PP) and the 12oz reusable cup made from glass were selected for this LCA study. The average weight of a single-use PP cup is 6g while the average weight of the reusable glass is 360g [8].

The life cycle of the glass cup is divided into six stages (i.e., production, transport, sale, use and wash, and disposal) as shown in Figure 2. Where that of the PP cup includes only five stages (i.e., production, transport, sale, use, and disposal) as shown in Figure 3.

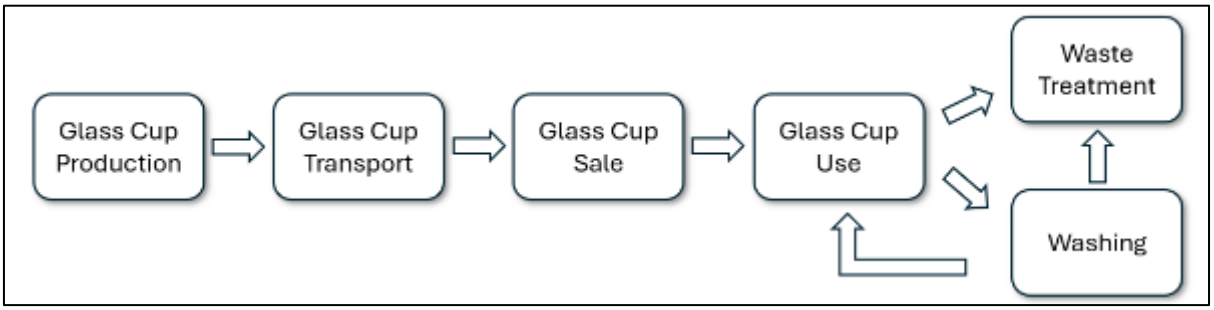

Figure 2 Glass cup life cycle

Figure 3 PP cup life cycle

To make a fair comparison of the LCA results of the PP and glass cup, the following assumptions were made:

- Both PP and glass cups are made in USA, with the average transportation distance by truck as around 800km [9,10].
- The glass cup will be hand washed 4 times followed by 1 time machine wash every day. This is based on the average household routine of using the washing machine once a day.
- The PP cup will be disposed after single use.
- The transportation distances for the disposal for both PP and glass cups are 100km.

The openLCA 2.4.0 with the ecoinvent v3.10 database is used for this study. And the tool for the reduction and assessment of chemical and other environmental impact (TRACI) V2.1 method is chosen, with the calculation type is set to Lazy/On-demand. The LCIA results of the entire life cycles of the Glass and PP cups are shown in Table 1, and relative performances are shown in Figure 4.

Table 1 Environmental impact of both glass cup and PP cup

Indicator	**Glass Cup**	**PP Cup**	**Unit**
Acidification	6.33E-02	1.91E-01	kg SO2-Eq
Climate change	2.14E+01	5.55E+01	kg CO2-Eq
Ecotoxicity: freshwater	6.27E+02	1.85E+03	CTUe
Eutrophication	1.21E+00	6.02E-01	kg N-Eq
Human toxicity: carcinogenic	5.94E-06	1.22E-05	CTUh
Human toxicity: non-carcinogenic	2.05E-05	3.07E-05	CTUh
Ozone depletion	2.63E-07	1.29E-06	kg CFC-11-Eq
Particulate matter formation	3.66E-02	4.28E-02	kg PM2.5-Eq
Photochemical oxidant formation	7.50E-01	2.79E+00	kg O3-Eq

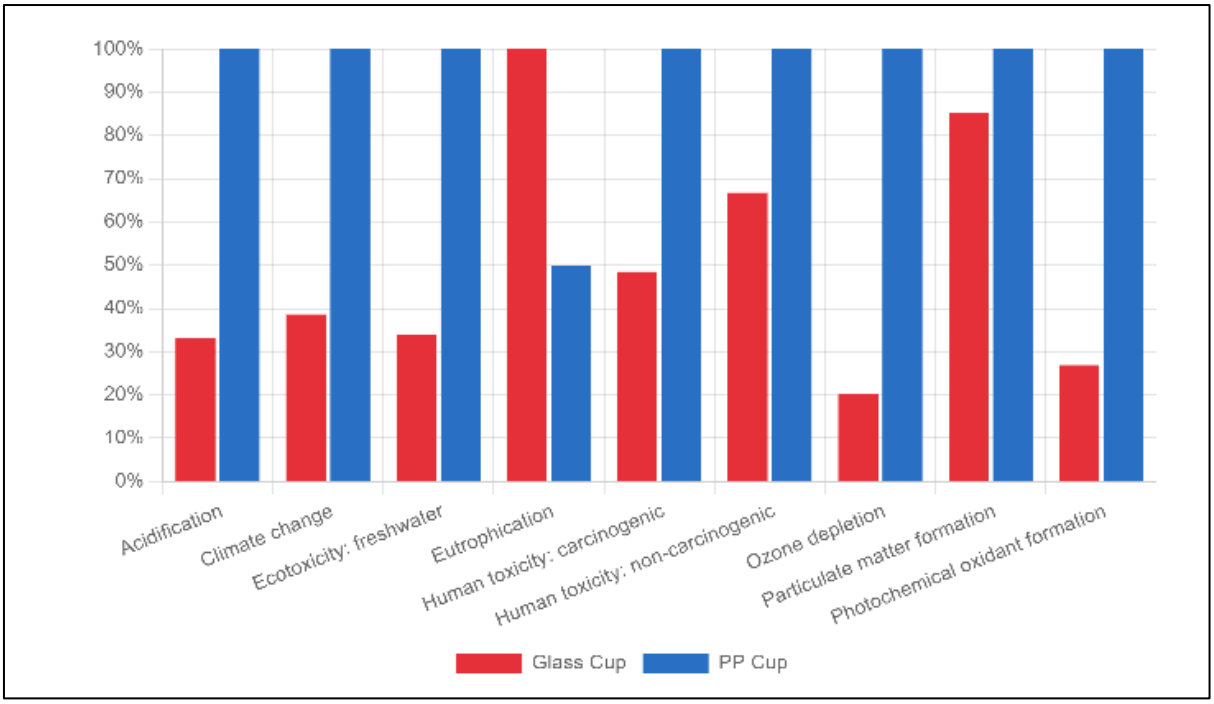

Figure 4 LCIA results for both glass cup and PP cup

From Table 1 and Figure 4, it can be found that the glass cup is better than PP cup in all key indicators except for eutrophication. Specifically for this study, the focus will be placed on the climate change indicator. The key contributors for the climate change indicator of different processes of both glass cup and PP cup are shown in Figure 5. It shows that the washing and production are the top two contributors for the glass cup, while the production and disposal are the top two contributors for the PP cup.

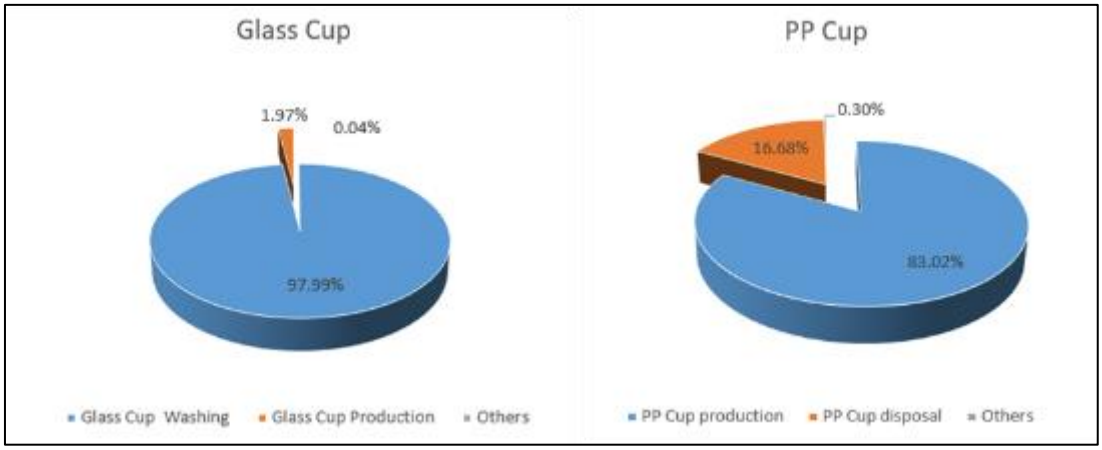

Figure 5 Key climate change process contributors for both glass cup and PP cup

While the glass cup offers a lower impact than the PP cup across most impact categories, this is contingent on the number of uses of the glass cup. As a result, consumer behavior plays a major role in determining the impact of a glass cup. Furthermore, consumer behavior in how the glass cup is washed is an important determinant of the degree to which glass cups is environmentally preferable to PP cups. Washing glass cups is the most significant contributor to the life cycle's environmental impacts, followed by production as shown in Figure 5.

The environmental break-even point [11], which indicates how long until the glass cup's environmental impact is better than that of the PP cup, is shown in the following Figure 6.

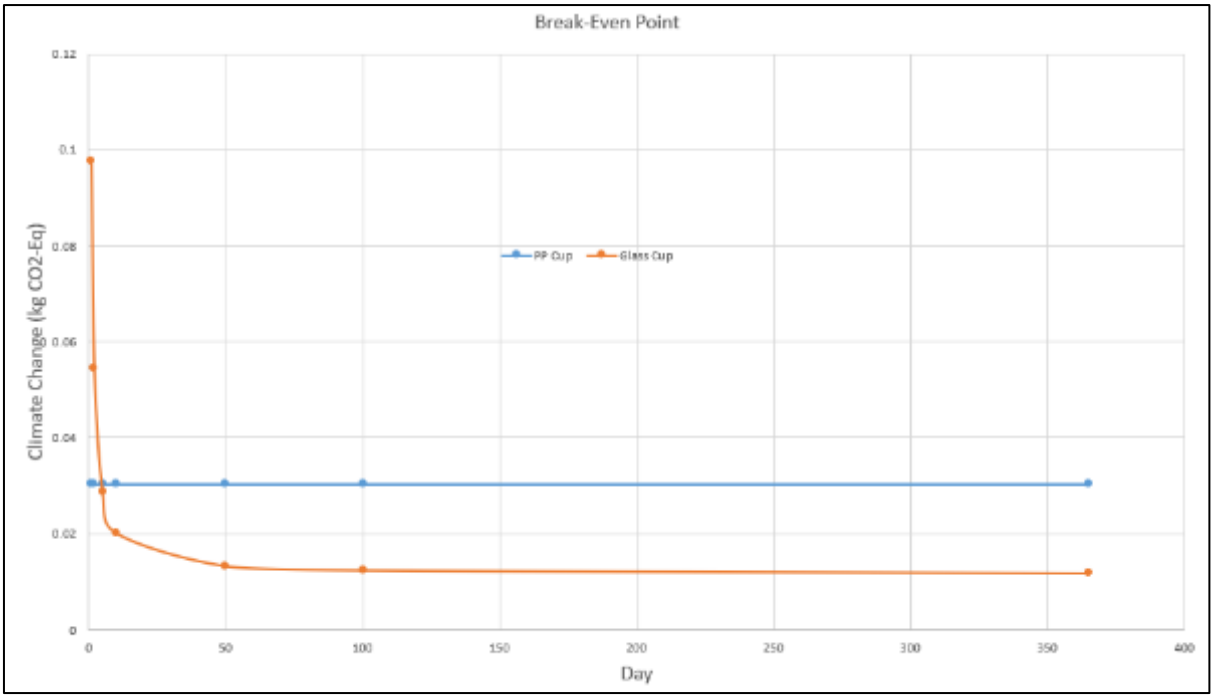

Figure 6 Break-even point of the glass cup for climate change category

On the 5th day (totally used 25 times), the glass cup had already outperformed the PP cup from the climate change perspective. These results remained within the same estimates of other studies, seeing that "most of the studies analyzed determine a breakeven point ranging from 10 to 670 uses depending on the materials compared, end-of-life assumptions and washing assumptions." [7].

Besides the above climate change break-even point, the economic break-even point analysis was conducted too. The typical unit prices for a 12oz glass cup and a PP cup are $2.54 (=$30.44/12) and $.12 (=11.69/100), respectively as shown in Figure 7. Considering the batch of 100, the average price for washing machines to wash a 12oz glass cup is around $0.003 (mainly due to the electricity usage).

Figure 7 Unit price of 12oz glass cup and 12oz PP cup

The economic break-even point, which indicates how long it takes until the cost/usage price of the glass cup is better than that of the PP cup, as shown in the following Figure 8.

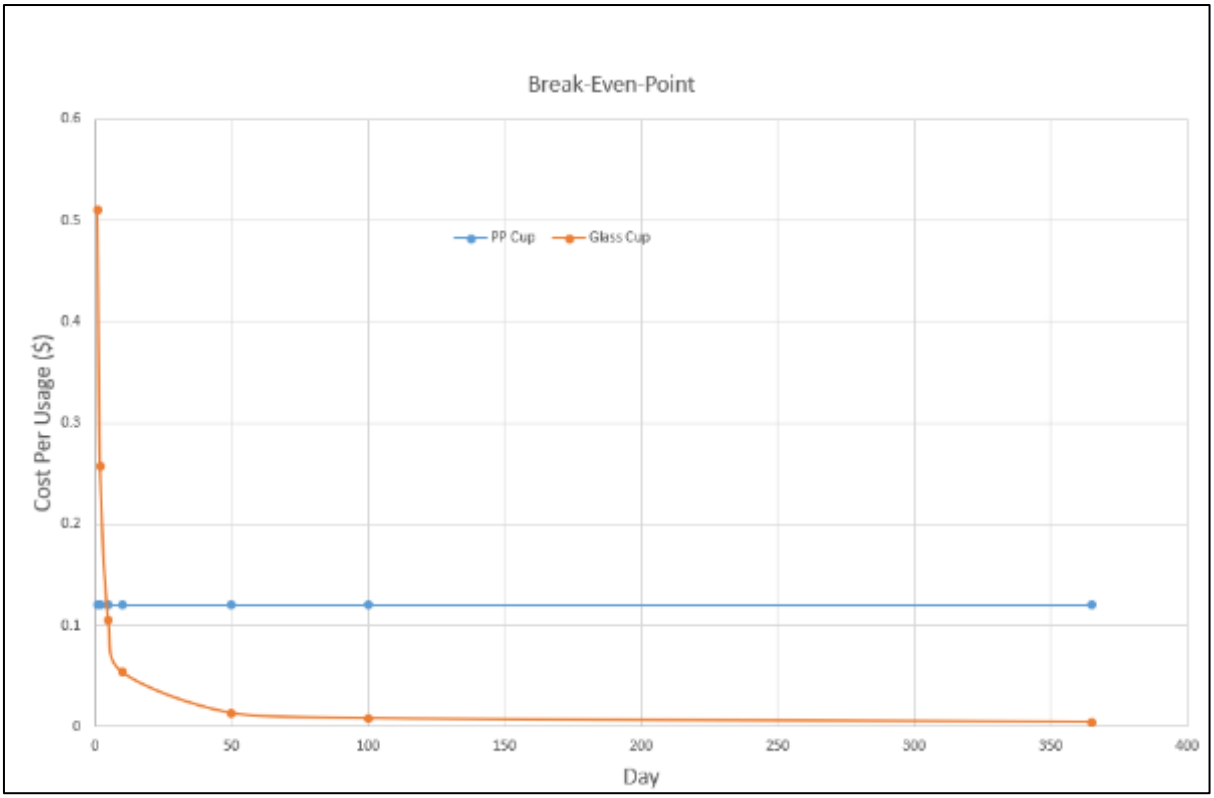

Figure 8 Break-even point of the glass cup for cost

The result shows that on the 5th day, the cost/usage of the glass cup is already lower than that of the PP cup. Although both environmental and economic break-even point analyses show that on the 5th day, the glass cup had already outperformed the pp cup, there are big differences in the long-term impacts. With increased time, the environmental impact of the glass cup becomes flat as it is mainly due to the impact affected by the washing process, while the economic impact of the glass cup continuously decreases.

Although the glass cup outperforms the PP cup from both environmental and economic viewpoints, from a consumer behavior perspective, the transition from single use to reusable cups faces significant challenges (i.e., convenience, habits, and perceived effort). To completely abandon the use of single-use cups is difficult in the short term, especially in applications with stringent hygiene requirements. Culture changes and policy incentives may be able to change this trend slowly; but this change is absolutely critical for the creation of a sustainable future.

4. Conclusions

The LCA results demonstrate that a glass reusable cup can deliver substantial environmental advantages over a single-use PP cup for most impact categories and achieve parity within about five days of regular use. However, realizing these advantages in practice depends critically on consumer behavior, especially washing frequency, mode, and temperature, which are the main drivers of glass-cup impacts. Despite the rapid environmental and economic break-even, short-term elimination of single-use cups is challenging due to convenience, habit, and perceived hygiene requirements. Therefore, effective transition strategies should combine design and policy levers, such as incentives or fees that shift the default away from disposables. Although these results are scenario-dependent, the key conclusion, under typical use, a multi-use glass cup quickly outperforms a single-use PP cup in both environmental impact and cost, stands.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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