University of Algarve
Erasmus Mundus master's in chemical Innovation and Regulation

Module: E02 Environmental risk of plastic materials

Comparative Analysis of Environmental Sustainability of Plastic (PET) Bottles and Alternatives for Drinking Water: A minireview

Samuel John Amali
30th April 2023

Abstract: There have been a growing production and application of plastics which have huge potential impact to the environment, this mini-review compares the environmental impacts of plastic (PET), bioplastic (PLA), and refillable aluminum bottles for drinking water based on a life cycle analysis (LCA). The study found that PET bottles have the lowest environmental impacts compared to PLA and aluminum bottles, which are burdened by agricultural and washing phases, respectively. The study also highlights the alarming increase in contamination levels when refillable bottles are washed with hot water only.

1. Introduction

The increasing concern about the environmental impact of plastic waste has led to the exploration of alternative materials for packaging, bioplastics and refillable aluminum bottles have presented potential alternatives to petroleum-based plastics (Chen et al., 2016a). When the term 'bioplastics' is used, it typically refers to either a polymer that is produced from renewable resources, or a plastic that can biodegrade or compost at the end of its life (Gironi & Piemonte, 2011). Bioplastics, made from renewable resources, have been proposed as a more sustainable alternative to traditional plastic packaging. However, the sustainability of bioplastics has been subject to debate due to the energy-intensive production process and limited end-of-life options(Rezvani Ghomi et al., 2021; Shen et al., 2012). Refillable aluminum bottles have also gained attention as a potential sustainable option, as they can be reused multiple times before being recycled(Tamburini et al., 2021a).

One of the key issues that need to be addressed in choosing an alternative to petroleum-based plastics, particularly polyethylene terephthalate (PET) is its environmental impact throughout its life cycle. Therefore, a comparative life-cycle assessment (LCA) analysis has been conducted to assess the environmental sustainability of different packaging options for drinking water(Tamburini et al., 2021c). The life cycle assessment (LCA) has become the primary tool for assessing the environmental impact of both bioplastics and petroleum-based plastics (conventional plastics) in today's world. Broadly speaking, the LCA enables the evaluation of a product or service's interactions with the environment, encompassing the entire life cycle that includes raw material extraction and production, manufacturing, distribution, usage (including maintenance and reuse), recycling, and ultimate disposal. By utilizing the LCA, the aim is to assess the impact of a product on the environment and determine the direct or indirect environmental effects caused by its usage, thereby noting the most sustainable option (Rezvani Ghomi et al., 2021; Wolfson et al., 2019).

This mini-review aims to provide an overview of the comparative LCA analysis of PET, bioplastics (polylactic acid or PLA), and refillable aluminum bottles for drinking water.
Using the LCA method, the study evaluates the environmental sustainability of producing and using PET, PLA, and aluminum bottles for drinking water over a hypothetical one-year period. The analysis considers the environmental impacts of production from raw materials, as well as annual consumption and end-of-life options such as open and closed loop recycling for PET bottles, composting for PLA bottles, and incineration and landfill for plastic bottles. In addition, the study considers the impact of washing aluminum bottles with tap water and soap daily. The study also assesses the microbiological quality of water associated with each packaging material in different usage scenarios. The findings of the LCA analysis will provide insights into the sustainability of different packaging options for drinking water and help consumers and manufacturers make informed decisions about the most sustainable choice. The study will also be useful for policymakers in formulating regulations and guidelines on sustainable packaging practices.

2. Case study

A study titled Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles – What is the most sustainable choice for drinking water? A life cycle (LCA) analysis by (Tamburini et al., 2021b). The study is aimed at the examination of the environmental impact of production, use and end-of-life of PET and PLA bottles in comparison to aluminium bottle, in a time-frame of 1 year by the application of the LCA methodology.

3. Processes involved in life cycle assessment (LCA)

The Life Cycle Assessment (LCA) methodology is a widely used approach to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle. The LCA methodology is based on the principles and requirements provided by the ISO 14040 and ISO 14044 standards.

ISO 14040 provides the general principles and framework for conducting an LCA, while ISO 14044 provides the specific requirements for conducting an LCA study. The LCA methodology includes four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation(Chen et al., 2016b).

3.1 Goal and scope definition

The goal and scope definition phase defines the goals and boundaries of the LCA study, including the system boundaries, functional unit, and the intended application of the results. The functional unit is the quantified performance of the product, process or service that is being assessed (Nessi et at., 2018). The system boundaries define the stages of the life cycle that will be included in the study. A ''cradle-to-grave'' LCA, mainly covers all relevant process steps from raw material production to the final waste treatment or recycling.

3.2 Life cycle inventory analysis (LCIA)

The inventory analysis phase involves the collection and quantification of all inputs and outputs of the system being assessed. This includes raw materials, energy, water, emissions, and waste generated throughout the life cycle. The data collected is organized into a life cycle inventory (LCI).

3.3 Life cycle Impact assessment

The impact assessment phase evaluates the potential environmental impacts associated with the Life cycle inventory (LCI) data. This involves identifying the potential environmental effects of the inputs and outputs and characterizing the magnitude and significance of these effects. The impact assessment results are reported as impact categories, which can include climate change, human health, and ecosystem quality.

Table 1. Life cycle assessment (LCA) results in producing one bottle each of PET, PLA, and aluminum bottles. Daily scenarios were also calculated based on the average consumption of three single-use PET and PLA bottles for drinking water. The LCA impact of the aluminum bottle was calculated over its hypothesized average durability of 2.5 years (930 days), with daily use corresponding to the 930th part of the total impact resulting from its production. (Tamburini et al., 2021a).

Impact category	1 PET bottle	3 PET bottles (daily cons.)	1 PLA bottle	3 PLA bottles (daily cons.)	1 aluminum bottle	1 aluminum bottle (daily use)	Unit
Climate change (GWP)	0.134	0.403	0.616	1.847	11.921	0.01307	kgCO_2 eq.
Eutrophication (EP)	$2.28 \cdot 10^{-5}$	$6.85 \cdot 10^{-5}$	$5.90 \cdot 10^{-4}$	$17.70 \cdot 10^{-4}$	0.011	$1.12 \cdot 10^{-5}$	kgPO_4 eq.
Photochemical oxidant formation (POFP)	$3.10 \cdot 10^{-4}$	$9.30 \cdot 10^{-4}$	$25.20 \cdot 10^{-4}$	$75.60 \cdot 10^{-4}$	0.0279	$3.06 \cdot 10^{-5}$	kgNMVOC[a]
Ozone layer depletion (OLDP)	$9.82 \cdot 10^{-6}$	$29.40 \cdot 10^{-6}$	$9.17 \cdot 10^{-8}$	$27.5 \cdot 10^{-8}$	$5.19 \cdot 10^{-7}$	-	kgCFC-11[b] eq.
Acidification (AP)	$5.20 \cdot 10^{-4}$	$15.60 \cdot 10^{-4}$	$27.5 \cdot 10^{-4}$	$82.5 \cdot 10^{-4}$	0.054	$5.92 \cdot 10^{-5}$	kgSO_2 eq.
Fossil depletion (FD)	0.055	0.166	0.247	0.742	3.229	0.00354	kg oil eq.
Water depletion (WD)	6.99	20.97	8.92·	26.76	477.0	0.52303	liters
Human toxicity (HTP)	0.050	0.151	0.218	0.653	5.486	0.00602	kg 1,4-DB[c] eq.
Eco toxicity (ETP)	$2.15 \cdot 10^{-3}$	$6.45 \cdot 10^{-3}$	$9.86 \cdot 10^{-3}$	$29.58 \cdot 10^{-3}$	0.266	$2.92 \cdot 10^{-4}$	kg 1,4-DB eq.
Land occupation (LOP)	$2.01 \cdot 10^{-3}$	$6.03 \cdot 10^{-3}$	$32.28 \cdot 10^{-3}$	$96.84 \cdot 10^{-3}$	0.160	$1.75 \cdot 10^{-4}$	m^2
Particulate matter formation (PMFP)	$1.70 \cdot 10^{-4}$	$5.10 \cdot 10^{-4}$	$13.4 \cdot 10^{-4}$	$40.20 \cdot 10^{-4}$	$178.90 \cdot 10^{-4}$	$1.96 \cdot 10^{-5}$	kg PM10 eq.

[a] NMVOC = non methane volatile organic carbon.
[b] CFC-11 = Trichlorofluoromethane.
[c] 1,4-DB = 1,4 dichlorobenzene.

3.4 Interpretation phase

The interpretation phase involves analyzing the results of the impact assessment and drawing conclusions based on the goals and scope of the study. The results can be used to identify opportunities for improvement and to compare different products, processes, or services.

4. Summary of LCA findings

4.1 LCA of production and of daily use of PET, PLA, and aluminum bottles

Table 1 summarizes the LCA results for different bottle materials, which accounted for the varying capacities of PET, PLA, and aluminum bottles by calculating the impacts of three one-way PET/PLA bottles and one aluminum bottle refilled twice to cover the daily water consumption of 1.5 liters, with the impact categories units based on the reference substance for each category. The study shows the cumulative impacts for each impact category of a single aluminum bottle, with the average lifespan assumed to be 2.5 years (930 days) and the daily impact calculated by dividing the overall impact by 930 to account for daily usage of a single bottle, while noting that the environmental impact of producing an aluminum bottle is much higher than plastic bottles, but the daily impact is significantly reduced.

The greatest contribution to almost all impact categories in PET bottle production is from PET resin production, specifically PTA production, followed by stretch blow molding; high temperature during stretch blow molding results in significant water depletion potential and influences other impact categories related to wastewater. PLA production is mainly burdened by resin production, contributing over 90% to impact categories (Bałdowska-Witos et al., 2020), except for water depletion potential (WDP); corn production for PLA resin contributes 91.08% of GHG emissions, and fertilizer use leads to high releases of nitrates and phosphates causing regional eutrophication; agriculture is the principal contributor to environmental impacts, including eutrophication and thinning of the ozone layer, which can lead to ecological imbalances and mutations(Gaur et al., 2018). The polymer synthesis step is the main contributor to the thinning of the ozone layer for PET and PLA, and overall, PLA bottle production has higher impacts than PET, with differences in environmental impacts of stretch blow moulding due to the different resin requirements, as reported by Bałdowska-Witos et al., 2020 & (Kiss et al., n.d.)

In the production of aluminum bottles, the main environmental impact comes from the manufacture of the bottle body, including the aluminum extraction process, which contributes 78.94% to the global warming potential (GWP) with 7.88 kg CO2 equivalent emissions, primarily due to the energy consumption of the processing plant and process itself, while the extraction process contributes 7.60% due to the required electrolysis processes and heat. The electricity consumption for bottle production has a significant impact.

4.2 LCA of annual use scenarios

The study compared the environmental impact of one-way PET and PLA bottles with that of aluminum bottles, considering their lifetime, refilling, and washing. They found that one-way PET and PLA bottles have a total of 1095 pieces each, while the aluminum bottle has a lifetime of 2.5 years, and the greatest impact on aluminum bottle production is due to the bottle body manufacturing process, including aluminum extraction. The study also derived an average of 3 liters of hot water for 1.2 minutes of bottle washing for the aluminum bottle, causing gas consumption which has high impact on the environment.

The use of a refillable aluminum bottle has lower environmental impact than 1095 one-way PET or PLA bottles per year, but the impact of washing the refillable bottle every day greatly increases the environmental impact. The waste reduction priority in a circular economy favors refillable bottles over disposable materials, but the severe annual impact of washing even a single bottle must be considered.

The end-of-life scenarios for PET and PLA bottles, as well as refillable aluminum bottles, for drinking water, differ significantly. PET and PLA bottles have a negative impact on the environment, especially when they are not properly disposed of and end up in landfills or oceans. Recycling can help to reduce this impact, but it also requires energy and resources (Ignatyev et al., 2014). On the other hand, aluminum refillable bottles have a much longer lifespan and can be used for many years, thus reducing waste generation. Additionally, aluminum can be recycled indefinitely without loss of quality, making it a more sustainable option. Therefore, when considering the end-of-life scenarios, refillable aluminum bottles are a more environmentally friendly option than single-use PET and PLA bottles.

4.3 Microbiological quality of water

The results from the microbiological analysis of water samples from PET and PLA bottles in Fig. 1 indicate that both bottles were microbiologically pure before use, with a low level of contamination occurring after 4 hours, possibly due to saliva on the bottle neck. However, after each use, empty bottles were discarded, and new ones were opened, resulting in each new bottle having microbiologically pure water. The final level of contamination did not exceed the log2 order of magnitude for both PET and PLA bottles.

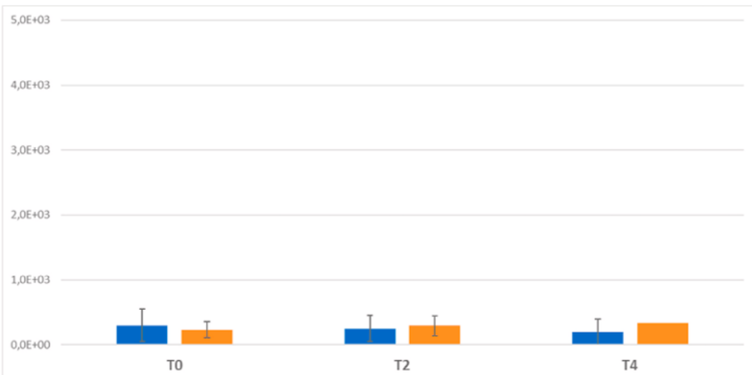

Fig. 1. Microbial contamination expressed in colony-forming units per milliliter (CFU/ml) within 0, 2, and 6 hours of opening a PET bottle (blue bars) and PLA bottle (orange bars) under a scenario of drinking every 30 minutes. The PreT0 sampling, which was taken immediately before opening and resulted in zero contamination in both bottles, is not included in the graph (Tamburini et al., 2021c).

The results of Fig. 2 show interesting differences compared to PET and PLA bottles. The aluminium bottle showed a slight contamination in the pre-T0 sample, and in 4 hours it reached a contamination of 4.5·104 CFU/ml, which increased to 1.8·104.

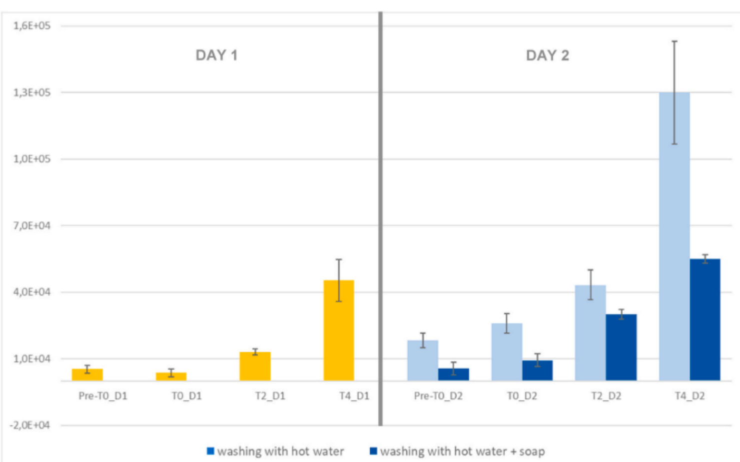

Figure 2. Microbial contamination expressed in colony-forming units per milliliter (CFU/ml) immediately after filling with tap water (Pre-T0) and within 0, 2, and 6 hours of opening an aluminum refillable bottle (yellow bars) under a scenario of drinking every 40 minutes on Day 1. The light blue bars represent a hypothetical Day 2 scenario of tap water bottle re-filling after washing with hot water only, while the dark

blue bars represent a Day 2 scenario of tap water bottle re-filling with tap water after washing with hot water and soap. (Tamburini et al., 2021c)

CFU/ml after washing with hot water at the end of Day 1. During Day 2, the microbial concentration increased to 1.5·105 CFU/ml and would likely increase further due to self-inoculation. However, washing the bottle with hot water and soap showed a positive effect on the overall microbial charge, although the contamination at the end of Day 2 was still higher than PET or PLA bottles.

Reusable drinking water bottles may be easily contaminated due to the humid environment and presence of microorganisms on the user's hands and mouth, leading to a potential risk of bacterial growth and foodborne illness, as indicated by various studies (Mills et al., 2018; Oliphant et al., 2002).

5. Conclusion

Consideration of preferred products or production process relies heavily on the thorough life cycle assessment of the product or process. This is very important to make an informed choice after thorough assessment of various aspects. There are several LCAs of PLA/plastics or comparative analysis between different plastics and PLA in terms of environmental impact, energy demand, and GHE. There are not much life studies on life cycle assessments on aluminium applied as packaging material, by exploiting the LCAs of aluminium, PLA and other plastics, we could have optimized products which are more environmentally friendly. The GHE attributed to the life cycle of PLA shows that the conversion of the bio-sources to lactic acid and then PLA is an energy-intensive process that releases a huge amount of CO_2 to the atmosphere. The environmental impact of bottles for drinking water, pointed out that a single bottle analysis can lead to misleading conclusions, and that a wider framework is necessary to understand the environmental consequences of plastic, bioplastic, or aluminium. The use of aluminium bottles is advantageous in the scenario of daily use and for a year's use, while considering the everyday washing with soap of the aluminum bottle could result in revised environmental impacts in favor of one-way plastic bottles due to water heating burdens.

The study indicates the use of one-way plastic/bioplastic bottles assure higher microbiological water quality compared to refillable bottles, but the availability of nutrients released by the contact with mouth and saliva is the principal determinant of microbial growth in drinking water. The study emphasizes the importance of proper hygiene practices around reusable water bottles and proper information about circular economy best practices for the recycling of traditional PET bottles to help consumers approach this fundamental issue for the future of the planet. From the circular economy point of view, refillable bottles are favoured since circular economy aligns strongly with waste reduction.

References:

Bałdowska-Witos, P., Kruszelnicka, W., Kasner, R., Tomporowski, A., Flizikowski, J., Kłos, Z., Piotrowska, K., & Markowska, K. (2020). Application of LCA Method for Assessment of Environmental Impacts of a Polylactide (PLA) Bottle Shaping. *Polymers*, *12*(2), 388. https://doi.org/10.3390/polym12020388

Chen, L., Pelton, R. E. O., & Smith, T. M. (2016a). Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *Journal of Cleaner Production*, *137*, 667–676. https://doi.org/10.1016/j.jclepro.2016.07.094

Chen, L., Pelton, R. E. O., & Smith, T. M. (2016b). Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *Journal of Cleaner Production*, *137*, 667–676. https://doi.org/10.1016/j.jclepro.2016.07.094

Gaur, N., Narasimhulu, K., & Y, P. (2018). Recent advances in the bio-remediation of persistent organic pollutants and its effect on environment. *Journal of Cleaner Production*, *198*, 1602–1631. https://doi.org/10.1016/j.jclepro.2018.07.076

Gironi, F., & Piemonte, V. (2011). Life cycle assessment of polylactic acid and polyethylene terephthalate bottles for drinking water. *Environmental Progress & Sustainable Energy*, *30*(3), 459–468. https://doi.org/10.1002/ep.10490

Ignatyev, I. A., Thielemans, W., & Vander Beke, B. (2014). Recycling of Polymers: A Review. *ChemSusChem*, *7*(6), 1579–1593. https://doi.org/10.1002/cssc.201300898

Kiss, F. E., Bukurov, M., Nikolić, S., Kiss, F., Mladenović, V., Bukurov, M., & Stanković, J. (n.d.). *Corn-based Polylactide vs. PET Bottles-Cradle-to-gate LCA and Implications Combine drying technology View project Research and Development of Ionic Bio Fluids View project Corn-based polylactide vs. PET bottles-Cradle-to-gate LCA and implications*. https://www.researchgate.net/publication/316418521

Mills, K., Golden, J., Bilinski, A., Beckman, A. L., McDaniel, K., Harding, A. S., France, A., Tobar, H. N., & Vecitis, C. (2018). Bacterial contamination of reusable bottled drinking water in Ecuador. *Journal of Water, Sanitation and Hygiene for Development*, *8*(1), 81–89. https://doi.org/10.2166/washdev.2017.064

Nessi, S., Bulgheroni, C., Konti, A., Sinkko, T., Tonini, D., Pant, R., 2018. Environmental sustainability assessment comparing through the means of lifecycle assessment the potential environmental impacts of the use of alternative feedstock (biomass, recycled plastics, CO2) for plastic articles in comparison to using current feedstock (oil and gas). JRC Technical Report, European Commission, 2018.

Oliphant, J. A., Ryan, M. C., & Chu, A. (2002). Bacterial Water Quality in the Personal Water Bottles of Elementary Students. *Canadian Journal of Public Health*, *93*(5), 366–367. https://doi.org/10.1007/BF03404571

Rezvani Ghomi, E. R., Khosravi, F., Saedi Ardahaei, A. S., Dai, Y., Neisiany, R. E., Foroughi, F., Wu, M., Das, O., & Ramakrishna, S. (2021). The Life Cycle Assessment for Polylactic Acid (PLA) to Make It a Low-Carbon Material. *Polymers*, *13*(11), 1854. https://doi.org/10.3390/polym13111854

Shen, L., Worrell, E., & Patel, M. K. (2012). Comparing life cycle energy and GHG emissions of bio-based PET, recycled PET, PLA, and man-made cellulosics. *Biofuels, Bioproducts and Biorefining*, *6*(6), 625–639. https://doi.org/10.1002/bbb.1368

Tamburini, E., Costa, S., Summa, D., Battistella, L., Fano, E. A., & Castaldelli, G. (2021a). Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles – What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis. *Environmental Research*, *196*, 110974. https://doi.org/10.1016/j.envres.2021.110974

Tamburini, E., Costa, S., Summa, D., Battistella, L., Fano, E. A., & Castaldelli, G. (2021b). Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles – What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis. *Environmental Research*, *196*, 110974. https://doi.org/10.1016/j.envres.2021.110974

Tamburini, E., Costa, S., Summa, D., Battistella, L., Fano, E. A., & Castaldelli, G. (2021c). Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles – What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis. *Environmental Research*, *196*, 110974. https://doi.org/10.1016/j.envres.2021.110974

Wolfson, A., Dominguez-Ramos, A., & Irabien, A. (2019). From Goods to Services: The Life Cycle Assessment Perspective. *Journal of Service Science Research*, *11*(1), 17–45. https://doi.org/10.1007/s12927-019-0002-9