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Research paper
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LIFE CYCLE ASSESSMENT OF PACKAGING MATERIALS FOR DRINKING WATER

Abstract: *Packaging materials play a key role in sustainability, as their production and disposal affect the environment. This research examines the environmental impact of different materials used in the production of drinking water packaging: polyethylene terephthalate, white packaging glass, and green packaging glass. The assessment was carried out by applying two levels of environmental impact mechanism: midpoint and endpoint: ReCiPe Midpoint 2016 (H), and ReCiPe Endpoint 2016 (H). The results indicate that polyethylene terephthalate exhibits the lowest environmental impact across most categories, except for the "stratospheric ozone depletion" category. In contrast, white packaging glass demonstrates the highest overall impact.*

Keywords: *life cycle assessment, polyethylene terephthalate, packaging glass*

1. Introduction

The global population continues to consume growing quantities of goods, and an increasing number of these products are sold with packaging (Pasqualino et al., 2011). While packaging serves critical functions such as protection, transportation, and information provision, it also contributes significantly to environmental degradation. Plastic pollution, especially in marine environments, has become a major global concern, largely due to the extensive use of plastic packaging materials (Ferrara et al., 2021). Plastics are favoured in modern society due to their lightweight nature, durability, flexibility, resistance to moisture and gases, and low production cost (Kouloumpis et al., 2020, Stefanini et al., 2021). However, packaging is typically discarded shortly after use, prompting the need for environmentally responsible design, production, and disposal practices (Almeida et al., 2017).

The rise in plastic packaging, along with global population growth, has led to greater demand for glass packaging, especially in the food, beverage, and pharmaceutical sectors (Pradhan et al., 2015, Welle et al., 2011). Industries around the world have begun to adopt more sustainable practices and analytical tools to evaluate the environmental performance of packaging throughout its life cycle. One of the most widely used tools is Life Cycle Assessment (LCA).

Numerous studies have used LCA to assess beverage packaging sustainability. For example, Saleh (2016) compared polyethylene terephthalate (PET), aluminum, and glass in Palestine, finding PET had the lowest and glass the highest environmental impacts. Gress et al. (2024) analysed material type, reusability, and carbonation in mineral water bottles, showing PET as more cost and material efficient, but glass offers better shelf life. Noriega Beltran et al. (2024) similarly found that both PET and glass have significant environmental impacts, with glass

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performing slightly worse overall.

Bertolini et al. (2016) compared multilayer cartons, PET bottles, and high-density polyethylene (HDPE) bottles for shelf-stable milk packaging, concluding that multilayer cartons had the lowest environmental burden. Another study, Ustun Odabasi and Buyukgungor (2016) pointed out that the production phase plays the biggest role in the carbon footprint of PET bottles in Turkey. Simon et al. (2016) focused on post-consumer bottle collection systems, highlighting the positive impact of methods like kerbside bags and deposit-refund schemes on reducing emissions. Meanwhile, Boutros et al. (2021) found that environmental outcomes can shift based on local waste management practices, as returnable glass outperformed PET when open burning was considered in Lebanon.

Adding a broader perspective, Dolci et al. (2025) conducted a review of 53 LCA studies published between 2019 and 2023, comparing conventional plastics and alternative materials. The review emphasizes that sustainability performance depends not only on material type but also on factors such as packaging weight, reuse rates, and end-of-life treatment strategies.

The aim of the research is to evaluate the environmental impacts of different packaging materials used for drinking water, specifically PET, white packaging glass, and green packaging glass. The analysis is conducted using two levels of environmental impact mechanism: midpoint and endpoint: ReCiPe Midpoint 2016 (H), and ReCiPe Endpoint 2016 (H). The results will provide a comparative analysis of the sustainability performance of these materials and guide strategies for making more environmentally responsible packaging decisions in the beverage industry.

2. Metodology

A standardised LCA (ISO 14040 2006a; ISO 14044 2006b) was applied, the environmental impacts were calculated using the openLCA software (version 2.3) (GreenDelta, 2020).

2.1. Goal and scope

The goal of the LCA is to evaluate potential environmental impacts associated with the production of three packaging materials: PET, white packaging glass, and green packaging glass (Figure 1.) The functional unit is 0.75 l bottled drinking water. This research uses cradle to gate system boundaries. The geographic scope of this research is the Global (GLO) region, representing an average worldwide context for data.

Figure 1. Analysed bottles of PET, white packaging glass and green packaging glass

Assumptions:

- This research is focused only on materials needed for the production of packaging products.
- Standardized bottle designs and average global weights are assumed for the analysed bottles. Variations in bottle shape, wall thickness, and light weighting strategies across

different manufacturers or regions are not considered.

- The functional unit of 0.75 l bottled drinking water is based on volume only, without considering differences in packaging usability, consumer preference, or durability.

Limitations:

- Manufacturing processes are not included in the analysis.
- The system boundary is limited to cradle-to-gate, meaning that use phase and end-of-life stages (recycling, disposal) are not considered, which may underrepresent the full environmental impact of packaging materials.
- The environmental impacts of secondary packaging (cartons, shrink wrap, pallets) and bottling infrastructure (caps, labels, machinery) are excluded.
- Recycled content or recycling rates are not considered, even though they may significantly affect the environmental impact of glass and PET.

To assess the environmental impacts two levels of environmental impact mechanism are used: ReCiPe Midpoint 2016 (H), and ReCiPe Endpoint 2016 (H). These are characterization models that represent different stages along the impact chain. The endpoint approach measures impact on areas of protection, such as human health, ecosystems, and resources. The midpoint approach evaluates impacts at an earlier stage, focusing on specific environmental problems like climate change or acidification, before they lead to final damage (Dong and Ng, 2014). The impact categories considered in this research for ReCiPe Midpoint 2016 (H) include: fine particulate matter formation (kg PM2.5 eq), fossil resource scarcity (kg oil eq), ecotoxicity (freshwater, marine and terrestrial (kg 1.4-DCB)), freshwater eutrophication (kg P eq), global warming (kg CO2 eq), human toxicity (carcinogenic and non-carcinogenic) (kg 1.4-DCB), ionizing radiation (kBq Co-60 eq), land use (m2a crop eq), marine eutrophication (kg N eq), mineral resource scarcity (kg Cu eq), ozone formation (human health and ecosystem) (kg NOx eq), stratospheric ozone depletion (kg CFC11 eq), terrestrial acidification (kg SO_2 eq) and water consumption (m^3). The midpoint impact categories in the ReCiPe method are grouped into three overarching endpoint categories: human health, ecosystem quality, and resource scarcity, to provide a more aggregated and interpretable view of the potential environmental damage. These methods were chosen to provide a comprehensive understanding of the environmental effects across multiple impact categories.

2.2. Inventory analysis

Data for used materials were extracted from the Ecoinvent 3.7 database with cut-off system model (Wernet et al., 2016), which provides life cycle inventory data on a wide range of materials and processes. Life cycle inventory for packaging materials is shown in Table 1.

Table 1. Life cycle inventory for packaging materials

Material/energy flow	Activity from Ecoinvent database	Location	Unit	Amount
PET	Market for polyethylene terephthalate, granulate, bottle grade	GLO	kg	0.023
White packaging glass	Market for packaging glass, white	GLO	kg	0.435
Green packaging glass	Market for packaging glass, green	GLO	kg	0.372

3. Results and discussion

Figure 2 presents the impacts of packaging materials for drinking water, the results were obtained using the ReCiPe 2016 Midpoint (H) method. Figure 3 presents the impacts of packaging materials for drinking water, the results were obtained using the ReCiPe 2016 Endpoint (H) method. Figure 3 shows the impacts of packaging materials for drinking water across three environmental categories (human health, ecosystem quality and resource depletion).

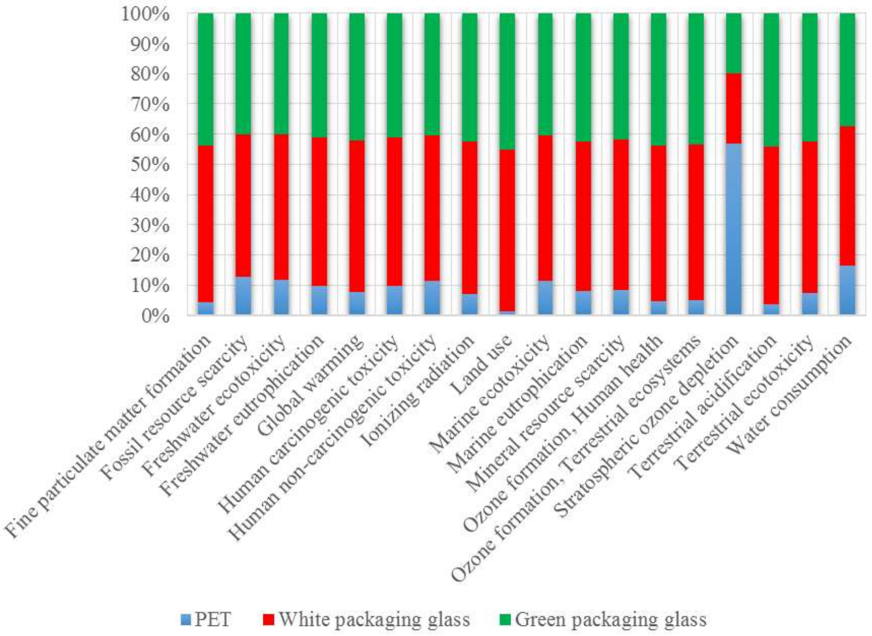

Figure 2. Impact of packaging materials on categories using the ReCiPe 2016 Midpoint (H) method

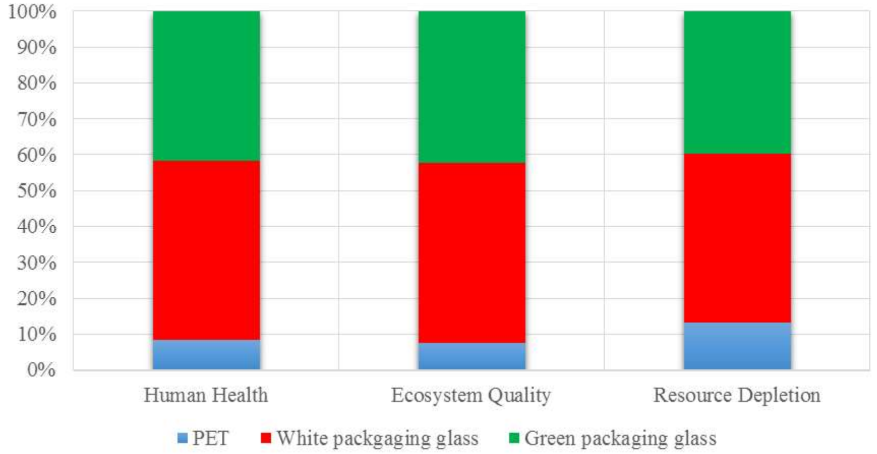

Figure 3. Impact of packaging materials on three environmental categories (human health, ecosystem quality and resource depletion) using the ReCiPe Endpoint 2016 (H) method

The results presented on Figures 2 and 3 indicate that white packaging glass consistently exhibits the highest contribution to environmental impacts across most categories, followed closely by green packaging glass, while PET packaging demonstrates the lowest impact in nearly all categories. This research only considers the materials used for packaging and does not include the manufacturing processes, which may affect the results. When comparing the results of this study with ones of Saleh (2016), both studies conclude that PET packaging has the lowest environmental impact, while glass has the highest. This study also found that PET performs better across most environmental categories. These consistent findings highlight the environmental advantages of PET packaging in various contexts.

In categories such as fine particulate matter formation, land use, and terrestrial acidification, the combined impact of white and green glass is greater than 85%, with PET contributing only marginally. Notably, PET shows a slightly higher share in stratospheric ozone depletion and water consumption. It can be assumed that white packaging glass has the greatest impact compared to PET due to its higher energy requirements during melting and forming stages, the heavier weight resulting in increased transportation emissions, and the lower recycling efficiency relative to PET. Additionally, the raw material extraction and processing for glass, particularly when not incorporating high rates of cullet (recycled glass), tend to be more resource-intensive.

4. Conclusion

The results indicate that white packaging glass has the highest environmental impact across most categories, particularly in energy consumption and emissions during production. This can likely be attributed to the energy-intensive manufacturing process of glass, which requires high temperatures for melting raw materials such as silica, soda ash, and limestone. Additionally, the heavy weight of glass packaging raises the carbon footprint during transportation, making its environmental impact even greater. On the other hand, PET packaging exhibits the lowest overall environmental impact in most categories. However, it should be noted that PET has a notably higher impact in the "stratospheric ozone depletion" category, likely due to the use of certain chemicals during its production, such as blowing agents and other volatile compounds, which can contribute to ozone layer depletion. It is important to note that this research did not involve manufacturing processes and focused only on the materials used for packaging, which could influence the results.

These findings suggest that while PET offers advantages in terms of lower energy use and emissions during production and transportation, its contribution to ozone depletion remains a significant environmental concern. The research highlights the need for a holistic approach when assessing the environmental performance of packaging materials.

Future efforts should focus on improving the sustainability of glass production processes and mitigating the environmental impact of PET, particularly in relation to ozone depletion, to strike a balance between performance, energy use, and environmental safety.

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