

Life Cycle Carbon Emissions and Emission Reduction Measures for Bottled Water

Jiaxing Li

*School of Engineering, Deakin University, Geelong, Australia
ingonc@qq.com*

Abstract. Bottled water is a widely consumed product around the world, but its potential impact on the environment can be caused by its packaging materials, production processes, transportation and end-of-life management. This review is based on several LCA studies in recent years and discussed life cycle carbon emissions and emission reduction measures for bottled water. The paper first summarises the LCA accounting framework for bottled water, including functional units, system boundaries, life cycle inventory and carbon footprint assessment. The review then identifies major carbon emission hotspots and discusses possible reduction measures and their trade-offs. Existing studies presented that PET resin production, bottle manufacturing, packaging-related inputs, electricity use, transportation and post-consumer treatment are likely to be the main sources of the carbon footprint from bottled water. While packaging optimisation and lightweighting can reduce material demand, it is also important to ensure the quality of product protection and transport performance. Recycled PET and bottle-to-bottle recycling can lower the demand on virgin PET, although the overall performance is determined by collection quality, sorting efficiency and food-grade recycling capacity. Transportation optimisation, renewable energy use and alternative packaging materials may also play an important role in emissions mitigation, but their actual results vary under different circumstances.

Keywords: Bottled water, Life Cycle Assessment, carbon footprint, emission reduction

1. Introduction

Nowadays, bottled water has become one of the most widely consumed packaged beverages around the world. This rapid growth of bottled water was potentially caused by several factors, including convenience, concerns about tap water quality, lifestyle changes and such. Recent studies also indicate that the trend of per-capita consumption of bottled water continues to rise, and this sector still has the fastest-growing rate compared to other products within the packaged beverage industry [1]. However, bottled water should not be simply understood as a drinking water product, because from a life cycle perspective, it is also closely associated with industrial practice, such as raw material extraction, plastic resin production, bottle manufacturing, water extraction or treatment, filling, packaging, transportation, retail distribution, and end-of-life management. Thus, the bottled water should also be considered as an industrial product. Due to the fact that most bottled water is sold in polyethylene terephthalate (PET) containers, the production and disposal of plastic

packaging may play a critical role in the outcomes of environmental impact [1]. In summary, the environmental burden of bottled water should be valued under a comprehensive life cycle perspective rather than only discussed as a plastic waste.

Compared with public tap water, bottled water generally shows much higher environmental impacts since it is often related to packaging materials, energy consumption, and distribution systems. A team from Barcelona conducted a modelling study and combined health impact assessment with life cycle assessment, in the end they managed to compare different drinking water consumption scenarios. The study found that a complete transition to bottled water would result in much higher ecosystem and resource impacts than a complete transition to tap water [2]. Although under some contexts, bottled water may be relatively beneficial because certain local health risks related to tap water contaminants were reduced, but when packaging, production, and waste treatment are considered, the total environmental burden is usually much larger. This highlights that it is necessary to assess bottled water from a full life cycle perspective when focusing only on a single stage of the system is often unreliable.

Life Cycle Assessment (LCA) has become an important method for evaluating the carbon emissions and environmental impacts of bottled water systems. Several recent studies evaluated bottled water from different LCA perspectives. Misopoulos et al. [3] identified plastic pallets, plastic cups and electricity use as important greenhouse gas emission hotspots in bottled water supply chains. Hu et al. [4] analysed the carbon footprint of 550-mL bottled water produced by ultrafiltration and reverse osmosis, and as a result, processes such as packaging, transportation, electricity consumption and post-consumer plastic recycling can strongly influence the overall result. Go et al. [5] conducted a meta-analysis of previous PET water bottle LCA studies and found that material production, bottle production and distribution or transportation are key stages affecting global warming potential.

Taken together, these studies show that bottled water carbon emissions are highly relevant with material production, packaging, transportation, energy use and end-of-life management. Meanwhile, the comparison for different LCA studies remains challenging. This is because different studies were generally based on different functional units, system boundaries, geographical contexts, recycling scenarios and allocation methods. Consequently, emission reduction measures may also involve trade-offs. For example, reducing packaging material, increasing recycled PET content or replacing PET with alternative materials may not always lead to lower emissions, especially when product protection, transport distance, recycling quality or end-of-life treatment are not properly considered. Therefore, a systematic review is needed to summarise existing LCA findings and evaluate emission reduction options from a life cycle perspective.

This review aims to examine life cycle carbon emissions and emission reduction measures for bottled water based on recent LCA-related studies. It will first introduce the LCA framework used in bottled water assessment. Then the reviews will summarize the major carbon emission sources identified in previous studies. Afterwards, a discussion around existing emission reduction measures will be presented. Moreover, the review would also discuss key emission reduction strategies related to packaging, recycling, transportation, and energy use, as well as their benefits and limitations.

The theoretical significance of this review is that it combines existing LCA findings and clarifies the potential impact from these methodological choices, such as functional units, system boundaries and recycling assumptions. The practical significance is that it provides a life cycle-based understanding of emission reduction strategies for bottled water producers, packaging designers and waste management stakeholders. By comparing hotspots, mitigation measures and trade-offs, this

review can support more informed decisions on packaging optimisation, recycled PET use, transportation management and end-of-life treatment.

2. Life cycle assessment framework for bottled water

For the evaluation of the environmental impact of bottled water within the whole life cycle, Life Cycle Assessment (LCA) is considered a common method. In general, LCA consists of four main stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [6-8]. As for bottled water, the LCA is typically focused on the quantification of carbon emissions from production, distribution, and end-of-life treatment. In order to present comparable results from different studies, a clear functional unit is necessary. Common functional units generally include one litre of bottled water, one 550 mL bottle, one tonne of bottled water, and one kilogram of PET bottles [3-5].

Moreover, the definition of the system boundary is also critical as it would determine which life cycle stages are included in the assessment. The system boundary is commonly described using terms such as cradle-to-gate, cradle-to-market and cradle-to-grave [7, 8]. In this assessment, the boundary can vary from cradle-to-gate to cradle-to-market or cradle-to-grave. A cradle-to-gate boundary usually stands for raw material extraction, PET resin production, bottle manufacturing, water treatment, filling, and packaging. On the other hand, cradle-to-market studies usually include distribution and retail stages, while studies of cradle-to-grave further focus on post-consumer stages, such as collection, recycling, landfill, and incineration [3-5, 7, 8]. According to previous studies, different system boundaries are often used to align with their research aims. For example, the research of Misopoulos et al. [3] is concentrated on bottled water supply chains from raw materials to market distribution, while Hu et al. [4] viewed production, packaging, transportation, and waste recycling and treatment as critical parts in their carbon footprint assessment of bottled water. Additionally, Go et al. [5] separated the PET water bottle life cycle into multiple stages, including material production, bottle production, distribution and transportation, collection, waste management, and environmental benefits.

To conduct a life cycle inventory analysis, data of material collection, energy consumption as well as emissions from each stage are required [7, 8]. In bottled water systems, PET resin, bottle caps, labels, secondary packaging, electricity consumption, treatment chemicals, transport fuels, and end-of-life management routes are often regarded as key inventory items [3-5]. After the inventory data are collected, they would be converted into environmental impact results and used in life cycle impact assessment. This review mainly focuses on climate change impacts. Therefore, carbon footprint and global warming potential is the main impact indicator and commonly reported as kg CO₂-eq [4, 5].

Overall, the LCA accounting framework is significant in locating the stages of carbon emissions within the bottled water life cycle and supports the evaluation of emission reduction strategies.

3. Carbon emission hotspots in the bottled water life cycle

3.1. PET material production and bottle manufacturing

Based on the information from previous LCA studies, the carbon emissions of bottled water are often distributed across several life cycle stages, including material production, bottle manufacturing, packaging, transportation and end-of-life management. Among these 5 stages, PET material production and bottle manufacturing are frequently identified as major contributors to

global warming potential. According to the findings of Go et al. [5], after comparing and reviewing previous LCA studies on PET water bottles, it is found that material production, bottle production and distribution/transportation played a relatively important role in greenhouse gas emissions of PET water bottle systems. A reasonable explanation for this is that PET resin originates from fossil-based feedstocks, it also needs massive energy during the manufacturing processes before the preforms and bottles are presented. Moreover, Hu et al. [4] identified that packaging was the dominant contributor to the carbon footprint of bottled water production, which ties the environmental burden of bottled water closely to the production and use of PET packaging materials.

3.2. Packaging and supply chain inputs

Beyond the PET bottle itself, other packaging and supply chain inputs should also be taken into consideration. Misopoulos et al. [3] examined bottled water supply chains and came with a result that plastic pallets, plastic cups and electricity use were crucial greenhouse gas hotspots in the investigated companies. This suggests that the carbon footprint of bottled water should not be limited to the impact of the primary bottle alone, because the influence from secondary and tertiary packaging, storage, handling and production electricity may also alter the final result. Based on the further analysis conducted by Yudison et al. [10], bottled water product-packaging systems, packaging production and transportation are largely responsible for the overall environmental footprint across most midpoint indicators. Therefore, a hotspot analysis should consider the full product-packaging system in order to obtain reliable results.

3.3. Transportation and distribution

In addition, transportation and distribution are also impactful to carbon emissions in bottled water systems. For example, after the production process, the bottled water would be transported to distribution centres, retailers and consumers. During the transportation process, factors such as distance, vehicle type, fuel use, load efficiency and packaging weight could have substantial influence on the related emissions. This can be supported by Go et al. [5], who identified distribution and transportation as one of the important life cycle stages for PET water bottle systems. Similarly, Hu et al. [4] also consider transportation as a significant factor in their carbon footprint assessment of bottled water, showing that assumptions about transport are highly relevant to the overall results. The role of transportation is also important when comparing alternative packaging materials. Furthermore, Ferrara et al. [6] revealed that the environmental performance of glass and PET mineral water bottles depends strongly on reuse frequency and distribution distance. This indicates that heavier or reusable packaging doesn't always improve the emission performance, especially when long transport distance and low reuse efficiency are involved.

3.4. End-of-life management

End-of-life treatment is another important factor in bottled water LCA, although its influence depends strongly on the recycling scenario and allocation method. Go et al. [5] included collection, waste management and environmental benefits as part of the PET water bottle system, showing that post-consumer treatment can influence life cycle results. Chairat and Gheewala [9] discovered that, compared with virgin PET products, PET bottle recycling is more benefit to the reduction of environmental impacts, especially when recycled PET is used in bottle-to-bottle applications and

when collection rates and recycled content are increased. The same study also demonstrated that the applied allocation method for recycling systems may differ from each other, this would ultimately reflect in LCA results [9]. Table 1 summarises the main focus, key hotspots and possible reasons for variation across the reviewed bottled water LCA studies.

Table 1. Summary of carbon emission hotspots and reasons for variation in reviewed bottled water LCA studies

Study	Main focus	Key hotspots/drivers	Reason for variation
Misopoulos et al. [3]	Supply chain emissions	Plastic pallets, plastic cups, electricity	Company-level supply chain focus highlights secondary packaging and operational energy.
Hu et al. [4]	Product carbon footprint	Packaging, transport, electricity, recycling	Includes production, packaging, transport and waste treatment for a 550 mL bottle.
Go et al. [5]	PET bottle LCA meta-analysis	Material production, bottle production, transport	Summarises common hotspot patterns across previous PET bottle studies.
Ferrara et al. [6]	Glass vs PET comparison	Reuse frequency, distribution distance	Heavier reusable packaging depends strongly on transport and reuse assumptions.
Chairat and Gheewala [9]	PET recycling pathways	Bottle-to-bottle recycling, allocation method	Recycling benefits depend on collection, recycled content and methodological choices.
Yudison et al. [10]	Product-packaging system	Packaging, transport, end-of-life recovery	Integrated product-packaging assessment captures broader supply chain effects.

3.5. Summary of carbon emission hotspots

As summarised in Table 1, the main carbon emission hotspots of bottled water are concentrated in PET resin production, bottle manufacturing, packaging-related inputs, transportation and end-of-life management. These processes are critical mainly due to the fundamental characteristics of bottled water, which involve a great amount of packaging materials and transportation before reaching consumers. Meanwhile, due to the variations in applied parameters across studies, the relative importance of each hotspot is not exactly the same [3-6, 9, 10]. For this reason, even when measures such as using recycled PET, reducing packaging material, improving transport efficiency and increasing recycling rates are undertaken, the proper assessment should always aim for the whole life cycle.

4. Emission reduction measures and trade-offs

4.1. Material-level measures: lightweighting and packaging optimisation

As noted in previous sections, the packaging materials are repeatedly examined as crucial emission hotspot. For this reason, the ideal strategies for carbon footprint reduction should be targeted at lightweighting and packaging optimisation for bottled water. Based on the findings of Hu et al. [4]

and Go et al. [5], it is presented that within the bottled water system, stages such as packaging, material production, and bottle production are closely linked to the carbon footprint and global warming potential. Thus, reducing the amount of PET resin used in each bottle might be able to bring positive performances, as the emission from raw material production and bottle manufacturing would also decrease. Moreover, components such as caps, labels, secondary packaging and transport packaging are also part of packaging optimisation, because relevant studies have shown that plastic pallets, plastic cups and other packaging-related inputs can also create additional emission burdens [3]. Nonetheless, lightweighting is not only material use reduction. Packaging eco-design needs to consider the whole product-packaging system, including material use, product loss, distribution, and end-of-life performance [10]. If material use reduction ends up with low quality product protection or transportation disturbance, then using less PET may not meet the carbon reduction expectation because impacts in other life cycle stages may increase. Therefore, lightweighting and packaging optimisation are very suitable when material reduction can be achieved without undermining the product protection or transport stability of bottles. In contrast, if excessive material reduction results in product damage, transport losses or the need for additional secondary packaging, these measures may be less effective.

4.2. Recycling-based measures: rPET and bottle-to-bottle recycling

Additionally, increasing the use of recycled PET (rPET) is another important strategy. According to the findings of Chairat and Gheewala [9], after the used PET bottles are efficiently recycled and reproduced into bottle-grade PET resin, the emission performance from the whole system would be improved compared with virgin PET products. They also highlight that this bottle-to-bottle recycling method is preferable as it can keep PET at a higher material value. Yudison et al. [10] also demonstrated that increasing post-consumer recycled content and improving end-of-life recovery can be very helpful to environmental footprint reductions. Nevertheless, the benefits from recycling are determined by the quality of collected PET, sorting efficiency, contamination control, recycling technology and allocation method. Furthermore, the findings from Chairat and Gheewala [9] showed that LCA results for recycling pathways are based on whether substitution, recycled content, or economic allocation methods are applied. Therefore, it can be concluded that rPET is actually a system-level issue involving collection infrastructure, food-grade recycling capacity and market demand for recycled resin. Therefore, rPET and bottle-to-bottle recycling are most applicable to mature sorting, collection and recycling systems. In such a context, the collection rates are typically high, contamination levels can be well controlled, and food-grade recycling capacity is available. Consequently, when the collected PET is highly contaminated or recycled PET cannot be used again in bottle-grade applications, the overall program may not be feasible.

4.3. Logistics and energy measures

In addition, the optimisation for transportation and using cleaner energy can further reduce life cycle emissions. Based on the research from Go et al. [5] and Hu et al. [4], distribution and transportation are identified as critical components in both PET water bottle systems and carbon footprint assessment. Misopoulos et al. [3] revealed that, the electricity use during the water bottle supply process is another factor for greenhouse gas emission. Therefore, energy management at production and packaging facilities would be necessary for emission mitigation. Consequently, the possible mitigation measures would prioritise choosing better production location where closer to target markets, improving route planning, increasing vehicle load efficiency and using lower-carbon

freight options [4, 10]. In addition, replacing fossil-based electricity with renewable energy would be beneficial to emissions from water treatment, bottling, packaging and recycling operations [3, 4]. More importantly, there are some drawbacks for these mentioned measures. Despite that regional production would bring better emission performance, this could also be troubled water source availability, production capacity or market structure. By the same token, even though renewable energy is able to mitigate operational emissions, but it does not remove emissions embodied in PET resin and packaging materials [4, 5]. Therefore, logistics and energy measures are most applicable when production can be located closer to target markets, transport routes can be optimised, vehicle load efficiency can be improved, and low-carbon electricity is accessible. Nonetheless, the actual water source location, production capacity, market structure and the emissions within the PET packaging materials may conflict with the ideal structure.

4.4. Alternative packaging materials

To cope with environmental impact of PET bottles, another reasonable solution is choosing alternative packaging material. Nonetheless, some LCA studies highlighted that material substitution would bring additional compromise. For instance, the findings of Ferrara et al. [6] and Tamburini et al. [11] suggested that environmental benefits of alternative packaging materials are conditional, the overall performances of these materials, such as glass, PLA, and refillable aluminium, are highly dependent on how they are used, transported, cleaned, and treated at the end of life. For this reason, alternative packaging materials are most appropriate under favourable conditions, where their functional performance can be maintained alongside frequent reuse, short transport distances, efficient washing systems, and appropriate end-of-life treatment. Otherwise, they may fail to reduce emissions if reusable packaging is transported over long distances or if it is reused multiple times.

5. Conclusion

Based on recent LCA-related studies, this review aims to examine life cycle carbon emissions and emission reduction measures for bottled water. The reviewed evidence shows that the carbon footprint of bottled water is closely associated with PET resin production, bottle manufacturing, packaging-related inputs, electricity use, transportation and end-of-life management. Among these stages, PET material production, bottle production, packaging and distribution are frequently identified as important carbon emission hotspots. These findings indicate that bottled water should be understood as a product-packaging system rather than only as a drinking water product or a plastic waste issue.

This review also has several limitations. First, the reviewed studies use different functional units, system boundaries, geographical contexts and allocation methods, which limit direct comparison between results. Second, this review mainly focuses on carbon emissions, while other environmental impacts such as water use, toxicity, land use and plastic pollution are not discussed in detail. Third, the conclusions are based on secondary literature rather than original LCA modelling, so the findings should be interpreted as a synthesis of existing evidence rather than a new quantitative assessment.

Future research should focus on improving the transparency and comparability of bottled water LCA studies. In particular, future studies should clearly define functional units, system boundaries, recycling scenarios and allocation methods, so that results from different studies can be more meaningfully compared. More region-specific and dynamic assessments are also needed, because electricity mix, transport distance, recycling infrastructure, recycled content and policy conditions

may change across locations and over time. In practical terms, future emission reduction should combine packaging optimisation, higher recycled content, bottle-to-bottle recycling, cleaner energy use and more efficient logistics. Alternative packaging materials should also be assessed under realistic use conditions, including reuse frequency, transport distance, washing requirements and end-of-life pathways. Overall, bottled water emission reduction should move from single-measure improvement toward integrated life cycle optimisation.

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