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Spatiotemporal carbon footprint analysis of bottled water production by ultrafiltration and reverse osmosis

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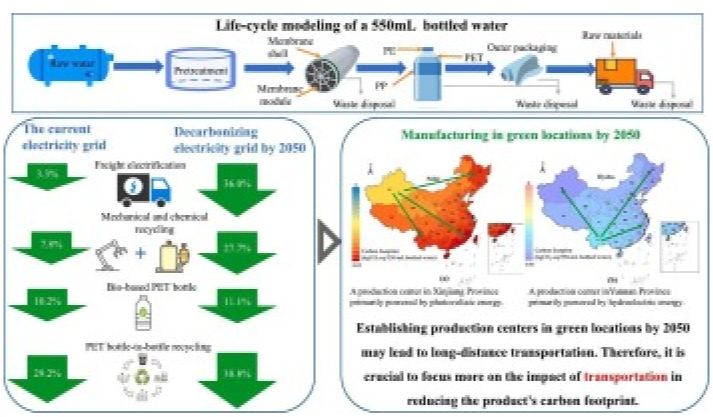
Highlights

- Carbon footprint analysis of bottled water by various production patterns.
- Higher contribution of transport by UF production in high-quality water sources.
- Reduce packaging carbon footprint through upstream decarbonization and recycling.
- Scenario analysis shows potential for significant decarbonization by 64.45%.
- Low-carbon bottled water supply needs to match production and consumption locations.

Abstract

The sustainable engineering of water treatment processes is critical for reducing the environmental impact of the bottled water industry, a sector experiencing growth parallel to rising standards of living. This study focuses on the environmental footprint of two membrane processes—ultrafiltration (UF) and reverse osmosis (RO)—used in the production of bottled drinking water. By employing life cycle assessment (LCA), we compare the carbon footprints of mineral water production via UF from high-quality sources against purified water production using RO technology. Initial findings indicate minor differences in the carbon footprints for one 550-mL bottled water produced by each method. However, the incorporation of green manufacturing practices reveals a significant reduction in the carbon footprint. Specifically, our analysis shows that with the deep decarbonization of the power grid and freight electrification, the carbon footprint of mineral water can be reduced by 36.04%. Additionally, through the adoption of renewable energy and the recycling of plastic packaging after consumption, the carbon footprint of mineral water could be lowered to 0.0295 kg CO_2-eq per 550-mL bottled water, demonstrating that mineral water offers low-carbon potential. This study further explores the roles of production location, transportation, and the adoption of various decarbonization strategies in optimizing the environmental footprint of bottled water. Our findings reveal the quantitative decarbonization potential of membrane processes, coupled with sustainable practices, for bottled drinking water production, supporting the industry's shift towards greater environmental sustainability.

Graphical abstract



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Introduction

The ongoing acceleration of industrialization has led to climate change being recognized as a formidable challenge in the 21st century, primarily due to escalating greenhouse gas (GHG) emissions in the atmosphere [1]. The surge in GHG emissions threatens to bring about irreversible consequences, including global warming and extreme weather events [2]. To avert the most severe impacts of climate change, it is imperative that anthropogenic CO_2 emissions are reduced by at least 50% by 2030, along with significant reductions in other GHGs, to retain a 50% probability of circumventing the most catastrophic outcomes [3]. Consequently, numerous countries are pursuing effective measures to curb the progression of climate warming. In this endeavor, the 21st Conference of Parties (COP 21) in 2015 was a pivotal moment when 188 nations agreed to the Paris Agreement, marking a commitment to a sustainable, low-carbon future. China, as the nation with the largest share of global CO_2 emissions—28.7% in 2013—has made a substantial pledge [4]. In September 2020, the Chinese administration announced targets to reach peak CO_2 emissions by 2030 and to attain carbon neutrality by 2060. These "dual carbon" objectives necessitate the establishment of a modern economic system that embraces green, low-carbon, and circular development principles. With the introduction of the Carbon Border Adjustment Mechanism (CBAM) by the European Union and the formal enactment of the "New Battery Law," [5], GHG emission management is gradually shifting from the organizational level to the product level. This shift mandates that all manufacturing sectors must actively engage in lowering the nation's GHG emissions. Therefore, implementing product life cycle management in the manufacturing industry is not only a key way to solve the emission reduction problem in the industrial value chain, but also a responsible manufacturing for enterprises. A crucial strategy to address emission reductions throughout the supply chain is the migration of production to green locations.

Green locations are defined as the migration of manufacturing production centers to areas abundant in renewable energy (e.g. solar and wind) and resources (such as biomass and fresh water), presenting a strategic response to regional policy variations. To narrow the gap between regions, China has formulated a series of national strategies, such as "Western Development" and "Central Rise" to stimulate the economy in underdeveloped regions. These provinces have more relaxed energy and emission policies [6]. As increasingly strict regulations and rising labor costs in eastern China continue to drive the migration of energy-intensive industries to western provinces [7], transferring the industrial chain to green locations may lead to more environmentally friendly and low-carbon production processes, However, due to consumption and exports being concentrated in eastern coastal cities, this may result in considerable GHG emissions in the transportation sector. Therefore, we will conduct a specific analysis of green locations to determine whether they have lower emission reduction benefits. The bottled water industry has been steadily growing for decades, with global annual productivity reaching almost 100 billion gallons in 2017 [8]. With the increasing demand for higher water quality in daily life, more and more people are choosing to drink bottled water at home instead of tap water [9]. This huge demand has compelled the manufacturing industry to increase the production of bottled water. Therefore, this study focuses on the green and low-carbon production of bottled water, using it as a case study to analyze the GHG emissions from the production, transportation, and disposal processes. The aim is to determine whether the entire life cycle of bottled water aligns with green and low-carbon development and to develop reasonable carbon reduction plans to mitigate global climate change.

Previous studies have also pointed out that an increase in bottled water consumption undoubtedly has a negative impact on the environment, particularly in terms of packaging [10,11]. However, the environmental impact generated by the water production process has not been considered. The water production process includes two major parts: energy consumption and material consumption. Since 1987, traditional drinking water treatment processes have been unable to effectively remove micro pollutants, including both natural and synthetic organic compounds. This limitation has prompted researchers to investigate membrane technologies for treating groundwater and surface water [12]. Today, membrane water treatment technologies are extensively employed in various industrial processes. In the context of potable water, the primary technologies are ultrafiltration (UF) and reverse osmosis (RO). Given that the RO membrane's pore size is significantly smaller than that of UF, it exhibits higher resistance and energy demands [13]. This characteristic also increases the RO membrane's susceptibility to contamination, necessitating frequent replacement of membrane components, which subsequently impacts the environment. Moreover, the deficiency of essential minerals in RO-treated water has been recognized as a drawback, with potential health implications due to nutritional deficiencies [14], while UF-treated water retains trace elements beneficial to human health. Typically, the pore size of UF is larger than that of dissolved metal ions in the form of hydrated ions or complexes with common ligands [15]. Therefore, a high-quality water source is needed, such as lakes and snowcapped mountains, which are far from the consumers. Compared with UF membranes, RO typically has performed better in removing heavy metal ions and desalination, resulting in greater flexibility in selecting water sources. The choice of water source directly affects the transportation distance for bottled water. Previous literature shows that the transportation process of bottled water accounts for approximately 25% of the GHG emissions throughout the entire life cycle of bottled water [16]. Therefore, based on the demand for water sources, it is crucial to determine the impact of UF and RO factory site selection on transportation distance and systematically estimate the environmental impact of transportation. In our previous studies, changes in background energy supply, such as the expansion of renewable energy [17], have significantly impacted the carbon footprint [18]. Therefore, we considered the carbon footprint assessment model for bottled water under different scenarios and systematically evaluated the environmental impact of the two types of water in various scenarios.

The demand for high-quality water sources has led to UF having lower pre-treatment requirements compared to RO. Due to the low pressure on the membrane, the service life of UF modules is also longer than that of RO modules. Previous research has developed a filtration decision-making tool at the unit operation level, focusing solely on the development of the membrane operation model and neglecting considerations related to the manufacturing and lifespan of the membrane [19]. The environmental merits of applying membrane water treatment instead of traditional processes have been previously proven [20,21]; however, the environmental impacts from the packaging and transportation of different aquatic products were not taken into account. Concurrently, Prézélus et al. [22] combined process modeling with life cycle assessment to provide input on raw materials and energy contributions. However, they did not consider the operation stage of the membrane module, failing to transition from 1 m^2 membrane manufacturing to 1 m^3 water membrane treatment. Therefore, throughout the entire life cycle of bottled water production, it is necessary to model the GHG emissions from the cradle to the grave of membrane components used in water production.

Thus, to investigate the potential benefits or impacts of producing in green locations, this case study considered two variants of bottled water produced using UF and RO technologies. Subsequently, a comparative life cycle assessment (LCA) was applied to assess the environmental performance, especially regarding the carbon footprint. Four scenario analyses were conducted to forecast the decarbonization pathways, including more sustainable packaging through bio-based plastic and recycling, adoption of electric trucks, and a cleaner grid dominated by renewable energy. A transport-focused sensitivity analysis examined how production location, supply coverage radius, and transportation method affect carbon footprints. Furthermore, the trade-off of product carbon footprint was deduced by simulating a ‘zero-carbon’ factory in typically green but remote provinces in China. The findings informed recommendations for decarbonization strategies for bottled water. The methodology can be expanded to evaluate the shift in manufacture from consumer-based locations to those with abundant green resources.

Section snippets

Methods

Following the guidelines of ISO 14040 and ISO 14044 [23,24], the LCA framework is comprised of four main components: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.…

Comparison of two types of bottled water

To evaluate the environmental benefits of producing bottled water in green locations, a quantitative evaluation and contribution analysis were conducted on two types of production modes. Based on the method described in Section 2, the carbon footprints of mineral water produced by UF (in limited manufacturing locations with high-quality water resources and long-distance transportation) and purified water produced by RO (flexible manufacturing locations with tap water supply and relatively short …

Discussion and suggestions

Regarding the water treatment process, the LCA model could include additional elements related to filtration membrane systems, such as transportation and pipeline infrastructure. The design of UF and RO modules (roll and frame), as well as the use of raw materials (membrane components, casings, etc.), varies depending on the manufacturer. Consequently, an investigation into the average inventory of UF and RO manufacturers, coupled with extensive upstream data surveys, would enhance data quality …

Conclusions

This study quantitatively evaluated the impact and feasibility of producing mineral water in green locations on its life-cycle GHG emissions, compared to purified water. The results consistently demonstrate that mineral water produced using UF membrane modules exhibits a lower carbon footprint than purified water produced with RO membrane modules. In the benchmark scenario, the bottle manufacturing process contributes 90.96% of the total carbon footprint, with the recycling of waste packaging…

CRediT authorship contribution statement

Wenqi Hu: Writing – original draft, Software, Investigation, Data curation. **Mengqi Han:** Writing – original draft, Software. **Dungang Gu:** Validation. **Robin Smith:** Writing – review

& editing. **Tingting Hu:** Validation. **Yuhang Lou:** Validation. **Yiran Sun:** Funding acquisition. **Guanghui Li:** Project administration, Funding acquisition. **Nan Zhang:** Writing – review & editing. **Jiaqi Lu:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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