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Implementation of Effective Packaging Principles Using rPET Bottles in Bottled Water: A Review

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Abstract
This literature review evaluates the use of recycled polyethylene terephthalate (rPET) in bottled drinking water packaging as a strategy to achieve effective and sustainable packaging. Based on a narrative synthesis of scientific literature, industry reports, and case studies, the review finds that rPET can reduce greenhouse gas emissions by up to ~79% and energy consumption by ~76% compared to virgin PET, while significantly decreasing reliance on fossil resources. These benefits are primarily driven by closed-loop bottle-to-bottle recycling systems, which contribute to circular economy implementation. Functionally, the findings indicate that food-grade rPET is capable of maintaining adequate mechanical strength, thermal stability, and barrier properties, making it suitable for beverage packaging without compromising safety standards. However, the review also identifies key constraints, including material degradation during repeated recycling cycles, inconsistencies in feedstock quality, and persistent negative consumer perceptions, which limit full-scale adoption. Industrial case studies, such as PMKN in Indonesia, demonstrate that partial to full integration of rPET, combined with innovations such as label-free bottle design, can enhance recyclability and operational feasibility. Despite these advancements, the study highlights that technological improvements and efficient waste management systems remain critical to optimizing rPET performance.

Keywords:
bottled drinking water, circular economy, effective packaging, rPET, sustainable packaging

1. Introduction

Packaging is an important element in the food industry supply chain because it plays a role in protecting products, ensuring food safety, and conveying important information to consumers. In the context of the food industry, sustainable food packaging is defined as an optimized, quantitatively measured, and validated solution that considers the balance between social, economic, ecological, and safety implementations within the circular value chain based on the entire life cycle history of the product-packaging unit. In order for packaging to be considered effective in this industry, it must be able to perform its fundamental function, which is to protect food products from physical, chemical, or microbiological damage in order to maintain or extend the product's shelf life [1]. Polyethylene terephthalate (PET) has become the primary choice in the mineral water packaging industry due to its excellent combination of physicochemical properties, including high mechanical strength and chemical resistance. The optical versatility of PET, both in transparent and translucent forms, is highly valued because it allows consumers to see the clarity of the product inside the packaging. Additionally, PET is lightweight compared to glass, is resistant to impact, and can maintain its elasticity during the production process. Technically, PET is very suitable for processing using the injection stretch blow molding method, which is the dominant technique in producing mineral water bottles efficiently and massively [2].

The massive use of conventional plastic packaging has led to a significant increase in packaging waste volume, with statistics showing a burden of around 177 kg of waste per capita in the European Union in 2020. The widespread use of conventional plastic packaging has significantly increased waste volumes, while low recycling efficiency largely stems from industrial decisions that prioritize economic considerations and machinery costs over ecological sustainability. Additionally, the lack of application of data-based evaluation tools such as Life Cycle Assessment (LCA) in the material selection process often results in the real impact of plastic waste on the environment being systematically unmeasured [1]. The use of post-consumer recycled PET (PET-PCR) or rPET offers significant potential as a more environmentally friendly packaging solution due to its ability to mitigate the ecological impact of fossil-based plastic consumption through systematic waste reduction. Through validated reverse logistics strategies and decontamination processes, rPET enables the creation of a circular economy where used packaging can be reintroduced into the production chain. The effectiveness of this solution is reflected in data from Brazil, which shows that the growth in PET recycling rates has been able to surpass the increase in virgin resin consumption, with a recovery rate reaching 56.4% in 2021. Moreover, future technological advancements, including the expansion of chemical recycling methods and the use of enzymes for hydrolysis, are predicted to enhance the quality of rPET to match the performance of virgin material, thereby strengthening the sustainability of the packaging industry by efficiently extending the lifespan of resources [2].

Recycled Polyethylene Terephthalate (rPET) is a material produced from the recycling process of PET plastic waste to be transformed into a new sustainable resource. The production process of rPET is broadly divided into two main pathways, namely mechanical and chemical recycling. Mechanical recycling is the most commonly used method due to its cost efficiency, where plastic waste is physically processed through stages of sorting, deep washing, shredding into flakes, and melt extrusion. On the other hand, chemical recycling works by breaking down the PET polymer chain (depolymerization) back into its basic components or original monomers using breaking agents. The monomers resulting from this chemical process are then purified and repolymerized to produce rPET plastic with a quality equivalent to that of pure material [3].

The use of recycled polyethylene terephthalate (rPET) offers significant environmental advantages compared to virgin PET, particularly in its ability to drastically reduce ecological impact. Based on life cycle analysis (LCA), replacing virgin material with rPET can reduce the level of danger to human health and ecosystems by more than 80%. However, rPET has real technical limitations, such as the unstable quality of secondary raw materials and the complex recycling process. rPET material often requires improvements in mechanical properties and barrier properties to be suitable for reuse in the packaging industry, and the high energy demand in the recycling process remains a major obstacle in achieving maximum efficiency compared to virgin PET [4].

In the context of the mineral water industry, the application of recycled polyethylene terephthalate (rPET) has begun to be implemented by several bottled water producers who integrate rPET into their bottle packaging as part of the company's sustainability strategy. This implementation impacts the sustainability performance of the product, particularly in the aspects of life cycle assessment (LCA), carbon emission reduction, and the decrease in the potential generation of plastic waste post-consumption.

2. Methods

This study was conducted using a Narrative Review design by collecting and descriptively examining various literature sources regarding the use of recycled polyethylene terephthalate (rPET) as a raw material for plastic bottles in bottled mineral water packaging (AMDK), this approach aligns with Principle 7: Effective Packaging, one of the 10 principles of food industry sustainability as outlined by Cheryl Baldwin (2015) in The 10 Principles of Food Industry Sustainability [5]. This design was chosen because it allows for the collection, comparison, and synthesis of previous research findings related to rPET, including technological developments in its application, environmental impacts, economic aspects, and its implementation in the bottled mineral water industry. Through this approach, the literature was analyzed according to specific discussion topics to obtain a comprehensive understanding of the potential and challenges of rPET as a sustainable packaging solution. Therefore, this method was considered the most appropriate for providing an integrated understanding within the given context by considering various scientific perspectives as well as industrial practices.

The research procedure was carried out in several stages. The first stage involved a literature search conducted through several scientific and industry-based databases with recognized credibility, such as ScienceDirect, Google Scholar, Scopus, PubMed, and company industry reports. The keywords used in the search process included “rPET packaging,” “recycled PET bottle industry,” “sustainable packaging food industry,” “AMDK rPET,” as well as other relevant keyword combinations. The literature was selected through a specific, flexible, yet focused search process based on topic relevance and source quality. The sampling technique used was purposive sampling, meaning that literature was selected based on its clear relevance to the focus of discussion and alignment with the established criteria. Therefore, literature that was not relevant, lacked credible sources, or did not specifically discuss PET/rPET was excluded from the sample. The included publications were limited to those published within the last 10 years (2016-2026) with a sum of 10 reviewed articles. The second stage involved an initial screening process through reading titles and abstracts to ensure relevance. The third stage consisted of further selection by reading the full text to understand the content and assess its suitability. The fourth stage involved conducting a synthesis and comparative analysis of various literature findings to identify similarities and differences. This was followed by integrating concepts from multiple sources into a coherent and logical narrative. The synthesis stage aimed to build a comprehensive understanding aligned with the concepts of effective packaging and sustainability. In addition, a specific analysis was conducted on examples of rPET implementation in the bottled mineral water industry by searching for references based on publicly available information such as sustainability reports, official company news, and other relevant supporting publications. Through these analytical stages, the discussion provides not only descriptive explanations but also a critical review and evaluation of the development of rPET usage in the food packaging industry.

3. Results and Discussion

3.1 Recycled Polyethylene Terephthalate (rPET)

Polyethylene terephthalate (PET) is a strong thermoplastic polymer with high temperature resistance, chemical resistance, and good stability [6]. Recycled Polyethylene Terephthalate (rPET), or recycled PET, is material derived from post-consumer or post-industrial PET waste that is reprocessed into secondary raw materials for product applications. The recycling of PET is a crucial solution to reduce the accumulation of plastic waste. Conventional recycling methods include mechanical, chemical, and biological recycling. Mechanical recycling is the most common method used for PET products and involves collection, sorting, washing, separation, and extrusion. PET products are sorted based on color, shape, and quality, then washed and soaked in water or detergent to remove dirt and debris. The next stage involves shredding to reduce PET plastic into small pieces. The PET flakes are further washed to remove non-plastic contaminants, dried, and melted to form resin. In contrast, chemical recycling converts the long molecular chains of PET into monomers. This process includes depolymerization, purification, repolymerization, and reshaping [6]. Chemical recycling offers several advantages compared to mechanical recycling, including the potential to reduce greenhouse gas emissions and energy consumption by up to 50% compared to virgin PET production [7]. Additionally, biological recycling uses enzymes to break down long PET polymer chains into monomers. This process involves sorting, shredding, washing, enzymatic depolymerization, purification, and polymerization [6]. The results of biological recycling can address several limitations of mechanical and chemical recycling, including the production of high-quality rPET that is nearly equivalent to virgin PET [8]. However, its application in industry still requires further optimization and in-depth development.

3.2 Advantages of rPET Compared to Virgin PET

The use and application of rPET offer various advantages for industry, the environment, and the economy. A discussion of the benefits of rPET is presented in Table 1.

Table 1
Advantages of rPET Compared to Virgin PET

Advantages	Findings	References
Reduction in the use of fossil resources / energy consumption	LCA studies and technical reports (APR/industry LCA summaries) report lower life-cycle energy for rPET pellets compared to vPET.	[9]
Reduction of greenhouse gas emissions (GWP)	Several LCA studies report substantial GWP reductions. Meta-analysis and LCA studies have found GWP benefits for rPET. For example, Stefanini et al. (comparative packaging LCA) show that rPET has a lower global warming contribution compared to vPET.	[9]
Waste reduction & support for the circular economy	Using rPET diverts material from waste streams/landfills and closes the loop (bottle-to-bottle), supporting circular packaging strategies. LCA literature and policy reviews highlight the role of rPET in promoting circularity and reducing end-of-life (EoL) burdens.	[10]
Economic benefits /	Under certain market conditions, the use of rPET can lower raw	[11]

Advantages	Findings	References
potential raw material cost reduction	material costs (depending on oil prices, recycling capacity, and scale). Industry reports and hybrid LCC/LCA studies note that integrating rPET can reduce life-cycle costs in some scenarios.	
Reduction in the need for virgin raw materials (resource depletion)	Substituting virgin resin with rPET reduces the extraction of raw materials (petroleum feedstocks), thereby lowering resource scarcity indicators. LCA studies show lower resource depletion scores for rPET compared to vPET in many LCA cases. Stefanini et al. and Silva et al. (2024) highlight this.	[9]
Lower Carbon Footprint	Life Cycle Assessment (LCA) studies indicate that rPET bottle production reduces greenhouse gas (GHG) emissions by approximately 79% and energy consumption by about 76% compared to virgin PET.	[12], [13]
Lower Impact on Human Health & Ecosystems	LCA analyses demonstrate that rPET packaging significantly reduces environmental and human health impacts (over 80%) compared to virgin PET.	[4]
Reduced Natural Resource Depletion	rPET production substantially decreases reliance on virgin petroleum resources, reducing natural resource depletion by more than 90% in some cases.	[4]
Lower Overall Environmental Footprint	Implementation of rPET in bottled drinking water packaging shows reductions across multiple environmental impact categories, including climate change and ecotoxicity.	[4]
Plastic Waste Reduction	rPET utilizes post-consumer PET bottles as raw materials, contributing to plastic waste diversion from landfills and oceans.	[14]
Supports Circular Economy	rPET enables closed-loop recycling systems in the bottled water industry, supporting circular economy principles and sustainable packaging strategies.	[14]
Cost Efficiency	Recycled PET resin is generally more cost-effective than virgin PET resin, helping reduce raw material costs in bottled water production.	[15]
Food-Grade Safety Compliance	Advanced decontamination technologies allow food-grade rPET to comply with FDA and EFSA safety standards for food and beverage packaging.	[16]
Recyclability	PET is a mono-material polymer that can be mechanically recycled multiple times, making rPET suitable for new bottle production with proper processing.	[16]
Lower Production Energy Demand	Mechanical recycling processes require significantly less energy compared to virgin PET polymerization processes.	[17]
Conservation of Fossil Resources	rPET reduces dependency on fossil-based feedstocks, supporting long-term sustainability in the bottled water industry.	[17]

Note: rPET: recycled polyethylene terephthalate

The use of recycled polyethylene terephthalate (rPET) as a packaging material for bottled mineral water has been proven to provide environmental advantages compared to virgin PET. Various life cycle assessment (LCA) studies report that rPET generates lower greenhouse gas emissions, primarily due to the reduced need for producing new resin derived from fossil-based raw materials [9], [18]. This emission reduction makes rPET highly relevant in supporting the principle of effective packaging within the sustainable food industry. In addition to lowering carbon emissions, rPET also demonstrates more efficient energy consumption and reduced fossil resource use compared to virgin PET. The mechanical recycling process of rPET generally requires less energy than the synthesis of new PET, thereby providing advantages in terms of material life cycle efficiency [11], [19]. This is particularly significant considering the high production volume of bottled drinking water packaging in the industry.

From a waste management perspective, rPET plays an important role in reducing plastic waste accumulation and promoting a circular economy through bottle-to-bottle recycling systems. The literature emphasizes that the use of rPET can divert PET waste from landfills while extending the useful life of plastic materials [19]. Technically, food-grade rPET has been proven to meet the functional requirements of packaging, including mechanical strength and food safety standards. Although material property degradation may occur due to repeated recycling processes, studies indicate that these challenges can be minimized through proper process control and appropriate material formulation [19].

The use of recycled polyethylene terephthalate (rPET) as a substitute for virgin PET in bottled drinking water (AMDK) products offers clear advantages from both environmental and economic perspectives. From an environmental standpoint, rPET significantly reduces carbon footprint and energy consumption, with LCA studies showing a reduction in greenhouse gas emissions by up to 79% and energy use by 76% compared to virgin PET, while also lowering impacts on human health and ecosystems by more than 80%. This is largely because rPET utilizes post-consumer bottles as raw material, directly diverting plastic waste from landfills and oceans, while also reducing the extraction of virgin petroleum resources by more than 90%. Economically, rPET is more cost-effective due to the generally lower price of recycled resin and supports production efficiency through mechanical processes that require significantly less energy compared to virgin PET manufacturing. Additionally, with modern decontamination technologies, rPET can meet FDA and EFSA food safety standards, making it safe for use in beverage packaging. Another advantage is that PET, as a mono-material polymer, can be mechanically recycled multiple times, reinforcing circular economy principles in the bottled water industry. Although rPET does not completely eliminate energy demand and emissions, and bottle quality may degrade if recycled repeatedly without proper control, its use remains the most sustainable strategy currently available compared to virgin PET, especially for industries aiming to reduce environmental impacts and support a circular economy.

3.3 Limitations of rPET: Quality, Logistics Challenges, and Market Resistance

The thermal, mechanical, and oxidative degradation processes of rPET cause changes in color, chemical structure, molecular weight distribution, crystallinity, chain flexibility, and cross-linking. High temperatures during thermal degradation convert ester bonds into vinyl-terminated carboxylate and carboxyl-terminated units, which can affect the strength, flexibility, transparency, and color of the product [20]. As a result of these degradation processes, the optical transparency of rPET decreases, giving it a more grayish and yellowish appearance. Beyond optical differences, beverage companies have reported higher incidences of mechanical damage in bottles made with rPET due to environmental stress [21]. This is attributed to non-intentionally added substances (NIAS) that influence the optical and mechanical characteristics of rPET, thereby limiting its recycling applications in PET bottles.

The availability of high-quality rPET is also influenced by the collection, sorting, and washing systems for post-consumer PET waste. Materials contaminated with other substances or additives can reduce recycling process efficiency and the quality of the final product. In addition, suboptimal waste management in developing countries can hinder the large-scale industrial application of rPET. The use of PET and rPET is strictly regulated by health authorities in each country; however, the risks associated with rPET cannot be ignored. Arcega et al. examined the toxicity levels of virgin PET and rPET at various recycling stages using toxicity bioassays and high content screening (HCS) based on ToxPi scoring [22]. Beyond technical and regulatory challenges, market resistance is another limiting factor. A study by [23] found that food packaging labeled as "recycled" tends to be perceived by consumers as lower in quality, as they assume the product may be contaminated due to being made from recycled materials. This negatively affects the perceived quality of food packaged in rPET [23].

3.4 Industrial Implementation: Case Study of a Bottled Drinking Water Company

The application of circular economy principles in the packaged beverage industry in Indonesia can be studied through the strategies implemented by the National Packaged Beverage Company (PMKN). As a market leader established in 1988, PMKN operates 32 factories and 381 distribution branches across Indonesia. In 2024, its production volume reached 1,915,822 kiloliters, highlighting the significant operational impact of the company on the national plastic packaging supply chain [24]. PMKN has adopted the use of recycled PET (rPET) as a core component of its sustainability commitment. This policy is implemented by diversifying the percentage of recycled content across different product lines to ensure both food safety and material sustainability. The implementation of rPET in PMKN's product lines can be observed in Table 2 below.

Table 2
Implementation of rPET in PMKN Product Lines [24]

Product Variant	Raw Material Composition	rPET Percentage
Eco Green 750 mL	100% rPET	100%
3D Mini Product 220 mL	Mix of rPET & PET	50%
Variants 330 mL, 550 mL, 1500 mL	Mix of rPET & PET	10%

Note: rPET: recycled polyethylene terephthalate; PET: polyethylene terephthalate

In addition to rPET integration, PMKN has innovated the physical structure of its bottles by launching a 1-liter label-free variant. Product information is embossed directly onto the bottle body, effectively eliminating the need for additional PVC plastic labels. This approach aligns with literature findings, which indicate that removing labels facilitates sorting in circular logistics systems and enhances the purity of the recycling stream [25].

3.5 Chemical Safety Analysis: NIAS and Substance Migration

The use of rPET by PMKN faces technical challenges due to the presence of Non-Intentionally Added Substances (NIAS), such as oligomers, benzene, and limonene [25]. Literature indicates that commercial rPET can contain benzene in the range of 30-410 µg/kg and limonene at 20-66 µg/kg [26]. To mitigate health risks, PMKN ensures decontamination through "super-clean" technology operated by a strategic partner (PT SOKA). According to global safety standards, the migration of hazardous substances into drinking water must remain below the threshold of 0.1 µg/L or comply with Cramer Class III criteria for low toxicological risk [26]. PMKN consistently conducts quality testing to ensure that products are free from Bisphenol-A (BPA) and bromate [24]. Implementation results show that although there is a risk of chemical migration, the use of rPET up to certain fractions, even if it contains minor amounts of non-food-grade plastic from waste streams does not significantly increase health risks when mechanical recycling processes are properly executed [27]. For PMKN, investment in rPET technology is not only about resource efficiency but also about mastering technology that provides a competitive advantage in the domestic market, which is increasingly attentive to environmental issues.

3.6 Evaluation of the Effectiveness of rPET as Mineral Water Packaging

rPET-based bottled water packaging is capable of performing the primary functions of food packaging: protecting the product from external contamination, maintaining product quality, and preserving shelf life. PET is known for its excellent barrier properties against gases and moisture, which helps maintain the stability of bottled drinking water. Studies show that rPET processed through proper recycling systems retains sufficient mechanical properties and thermal resistance for beverage packaging applications, although there may be a slight reduction in molecular weight due to repeated processing [16]. Furthermore, advances in rPET processing technology, such as improved temperature control and material purification, can reduce polymer structure degradation, allowing packaging performance to approach that of virgin PET. This demonstrates that rPET can be used as an alternative packaging material without significantly compromising technical functionality [28].

From a food safety perspective, the use of rPET in bottled water packaging must consider the potential migration of contaminants from recycled raw materials, particularly if the material originates from non-food packaging. Research indicates that post-consumer PET can contain organic compounds that may migrate into food products if not properly decontaminated [27]. Therefore, raw material quality and purification processes are critical factors in ensuring the safety of rPET. Super-clean recycling technology has been developed to remove contaminants from rPET, allowing it to meet international food safety standards. With stringent quality control systems, food-grade rPET has been proven safe for use in beverage packaging, including bottled water [16].

The use of rPET also offers economic efficiency opportunities by reducing the need for fossil-based raw materials and energy consumption during production. rPET production requires less energy compared to virgin PET synthesis, potentially lowering long-term production costs. This efficiency can enhance the competitiveness of beverage packaging industries that adopt recycled materials [29]. However, the costs associated with collecting, sorting, and purifying PET waste remain a challenge. The stability of recycled raw material supply heavily depends on effective waste management systems and a sufficiently large-scale recycling industry.

Based on multiple Life Cycle Assessment (LCA) studies, rPET has been shown to have a positive environmental impact compared to virgin PET. rPET production reduces greenhouse gas emissions, lowers energy consumption, and decreases fossil resource use. Closed-loop recycling systems that transform used bottles into new ones also improve material efficiency and reduce the amount of plastic waste ending up in the environment. Additionally, rPET supports the circular economy concept by enabling plastics to be reused within sustainable production cycles, reducing environmental pressure while increasing resource utilization efficiency [28].

The implementation of rPET in food packaging is also strongly influenced by international regulations and safety standards. Agencies such as the European Food Safety Authority (EFSA) and the Food and Drug Administration (FDA) impose strict requirements on PET recycling processes to ensure that materials used in food contact are safe. These regulations emphasize decontamination process validation, quality control, and traceability systems for recycled raw materials. Moreover, global environmental policies aimed at increasing the use of recycled plastics in beverage packaging further encourage the industry to raise the percentage of rPET use as part of a sustainable packaging strategy.

3.7 Implications and Future Trends

Technological advancements in PET recycling processes continue to progress, particularly through the application of advanced recycling or chemical recycling. This technology allows PET to be broken down into its constituent monomers, which can then be reprocessed into PET material with quality approaching that of virgin PET. This approach is considered capable of overcoming the limitations of mechanical recycling methods, which typically result in material quality degradation after multiple processing cycles. Additionally, innovations in material purification technology and improvements in the thermal stability of rPET are expected to expand its use in food and beverage packaging in the future, enhancing resource efficiency while supporting sustainability principles in the packaging industry [28].

The circular economy approach has now become a key strategy in plastic waste management, emphasizing the sustainable reuse of materials through recyclable packaging design and optimization of waste collection systems. To support this concept, Extended Producer Responsibility (EPR) policies require manufacturers to take responsibility for the entire life cycle of packaging, including post-consumer waste management. The implementation of EPR has proven to encourage the industry to increase the use of recycled materials and invest in the development of more efficient and integrated plastic waste management systems.

Beyond technological and regulatory developments, consumer behavior also plays a crucial role in increasing demand for recycled plastic materials. Growing public awareness of environmental issues makes consumers more likely to choose products with environmentally friendly packaging. This preference indirectly motivates producers to improve transparency in sustainability reporting, increase rPET usage, and develop innovative packaging designs that are more sustainable and add value to the product [30].

4. Conclusion

This literature review highlights the significant potential of recycled polyethylene terephthalate (rPET) as a sustainable alternative to virgin PET in bottled drinking water packaging. Across the reviewed studies, rPET consistently demonstrates substantial environmental advantages, particularly in reducing greenhouse gas emissions, energy consumption, and reliance on fossil-based resources, while supporting circular economy practices through closed-loop recycling systems. From a functional standpoint, properly processed rPET is capable of meeting essential mechanical, thermal, and barrier requirements, confirming its technical feasibility for food-grade packaging applications. Despite these benefits, several limitations remain, including material degradation during repeated recycling, variability in feedstock quality, and persistent negative consumer perceptions toward recycled materials. These challenges indicate that the broader adoption of rPET is influenced not only by technological constraints but also by systemic factors such as supply chain efficiency and market acceptance. This review is subject to limitations, including its narrative approach, reliance on a limited number of secondary sources, and variability in methodologies across the included studies. Future literature reviews should therefore adopt more systematic and comprehensive approaches, incorporating a wider range of sources, standardized evaluation methods, and cross-regional comparisons to enhance the robustness and generalizability of findings. Overall, rPET represents a viable and scalable pathway toward more sustainable food packaging systems. However, its long-term effectiveness will depend on continued advancements in recycling technologies, supportive regulatory frameworks, and increased consumer acceptance to fully realize its role within a circular economy.

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