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The future of polyethylene terephthalate bottles: Challenges and sustainability

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Abstract

Polyethylene terephthalate (PET) is the most widely used polymer for manufacturing plastic bottles appropriate for water and soft beverages usage. The advantages of PET, regarding its mechanical and barrier and permeation properties, convenience, safety as food contact material, and recyclability, are well documented during the past decades. However, the recent trends towards the adoption of circular economy and the EU Directives regarding the reduction of the impact of plastic products on the environment has raised significant concerns about the sustainability and future of PET plastics. The objective of the article is to demonstrate the advantages and drawbacks of PET for applications in the bottled water and soft beverages sectors and discuss the future of PET bottles, considering the current trends and sustainability issues.

KEYWORDS
bottled water, PET bottles, plastic packaging, polyethylene terephthalate, recycling

1 | INTRODUCTION

Polyethylene terephthalate (PET) is a polymer that, from a chemical point of view, is a polyester. Polyesters were initially produced in the 1930s, for applications as synthetic fibres. Several applications of PET have been focused on the production of fibres, either for industrial or clothing materials, often mixed with natural systems such as cotton and wool. Later on, in the early 1950s, PET applications expanded to packaging films and a PET bottle manufacturing process was introduced in 1970. PET bottles were initially used for soft drinks, but gradually their use for bottled water expanded.[1] PET is produced from terephthalic acid (TPA) and ethylene glycol (EG). The two substances react together to form long polymer chains, with water as a by-product (Figure 1). As in most processes of polymerization, a catalyst is used to speed up the reaction kinetics.[2] The PET repeating unit has a molecular weight (MW) of 176, resulting in a final MW of up to 27 000.[1]

Bottles for water, carbonated soft drinks and other beverages account for more than 80% of global PET demand. The market of bottled water is becoming the largest beverage category worldwide, with the annual consumption reaching high levels in the EU (more than 170 L/capita in Italy and Germany for 2019).[3] Gambino et al.[4] reported a consumer perception of poor quality of tap water in Southern Italy, which significantly affects the choice of consumers regarding the type of drinking water (bottled or tap). Due to the rapid increase of PET bottle consumption, we have to be conscious on several aspects. These include environmental burden, health concerns for scavengers (a means of active packaging technique which absorbs the dissolved gases, in most cases oxygen, into PET bottles, in order to retain food quality and extend shelf life) and low utilization efficiency for reclaimed PET bottles.[5] In light of growing concerns over environmental protection, resource conservation and the development of recovery technology, recycling has become a key factor in the supply chain of PET bottles. Research studies have indicated that for every pound of reclaimed flaked PET which is used, energy requirement is reduced by 84%, while greenhouse gas emissions (GHEs) decrease by 71%.[1,6]

There is an increasing trend of published articles focusing on topics relevant to PET bottles and packaging, including recycling and plastics, especially during the past 5 years. The historical trend of the number of published works involving keywords such as 'poly (ethylene terephthalate)', 'bottled water', 'plastic packaging', 'PET recycling', and 'PET bottles' within the period 1998–2021 is illustrated in Figure 2A,B.

The objective of the article is to demonstrate the advantages and drawbacks of PET for applications in the bottled water and soft beverages sectors and discuss the future of PET bottles, considering the current trends and sustainability issues.

2 | PET PROPERTIES AS FOOD PACKAGING MATERIAL

PET is a linear, transparent thermoplastic polymer with a melting temperature (T_m) of 267°C and a glass transition temperature (T_g) between 67°C and 80°C. It has the capacity to crystallize under certain controlled conditions. It is strong, stiff, ductile and tough in the glassy state ($T < T_g$) and can be oriented by stretching during moulding and extrusion, further increasing its strength and stiffness. PET bottles and films are largely amorphous (APET) with small crystallites and excellent transparency. However, crystalline PET (CPET) containers have a higher degree of crystallinity, larger crystallites and are an opaque white. PET films are most often used in the biaxially oriented, heat stabilized form. The material in its unoriented form has limited applicability because, if crystalline, it is extremely brittle and opaque, and if amorphous, it is clear but not tough. PET film's properties as a food packaging material include its great tensile strength, excellent chemical resistance, light weight, elasticity and stability over a wide range of temperatures (−60°C to 220°C), expanding its applicability to a wide range of temperatures, from frozen food to ready-to-cook (boil-in-the-bag) products.[1] APET has similar thermoforming characteristics with polystyrene (PS) and has been reported as a potential replacement for polyvinyl chloride (PVC). The properties of unoriented APET are similar to those of semicrystalline-oriented PET, with the exceptions of strength and stiffness which are enhanced by orientation.[1,7] Typical applications of PET, as food packaging material, based on its physical state and corresponding properties, are summarized in Table 1.

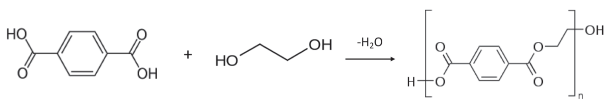

FIGURE 1 Chemical structure of PET

PET bottles are colourless, lightweight but very strong containers. The enhanced strength and lightweight of PET is significantly important in the case of beverage packaging, as it enables safe transportation.[2] PET bottles are stretch blow moulded. The stretching or biaxial orientation is necessary in order to get maximum tensile strength and

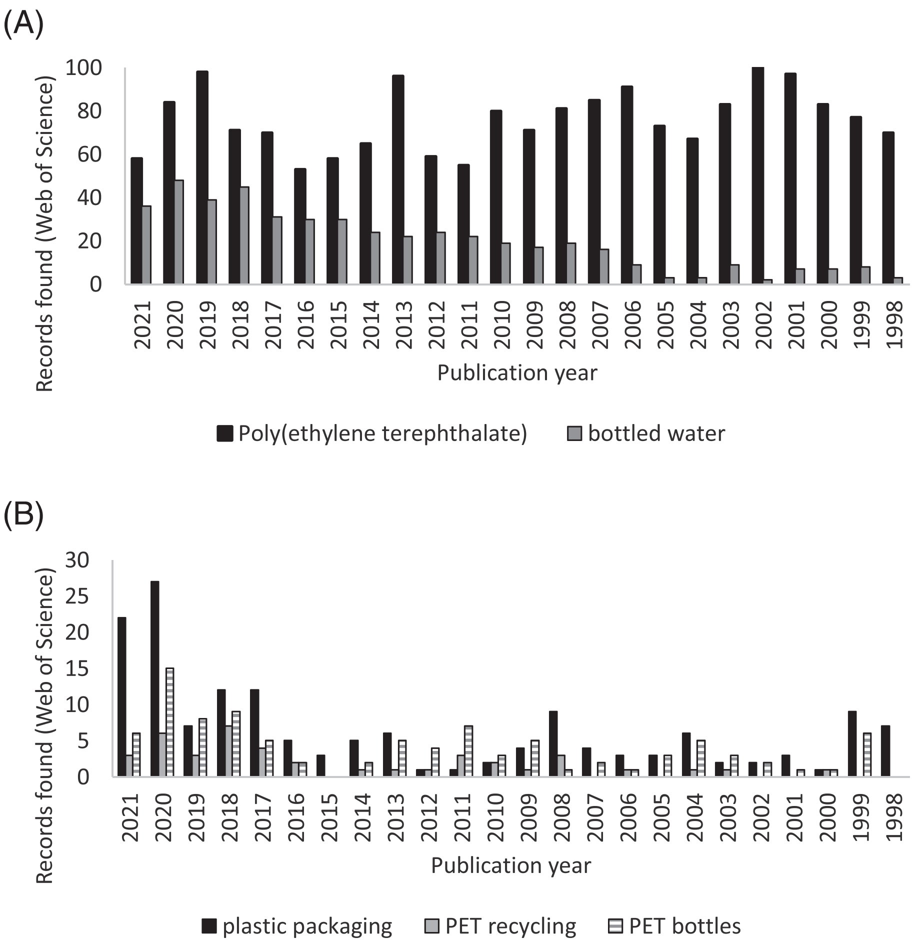

FIGURE 2 Historical trend in keywords (A) 'Poly (ethylene terephthalate)', 'bottled water' and (B) 'plastic packaging', 'PET recycling', and 'PET bottles' in publications within the period 1998–2021 (Source: Web of Science, 5/11/2021)

TABLE 1 Typical applications of PET in food packaging[1]

Physical state	Property	Application
Amorphous	0%–5% crystallinity, heat stable to 67°C, clear	Blister packs
Oriented amorphous	5%–20% crystallinity, heat stable to 73°C, clear	Bottles
Crystalline	25%–35% crystallinity, heat stable to 127°C, opaque	Food trays
Oriented crystalline	35%–45% crystallinity, heat stable to 140–160°C, clear	Hot-fill containers, films

gas barrier, which in turn enables bottle low weight and cost effectiveness. The continuing trend for even larger containers for soft drinks has helped penetration of the PET bottle in the market. The 1-L glass bottle is considered being close to the limit of size and weight, above which it may become difficult to handle safely and with convenience. On the other hand, PET bottles up to 5 L in size are available, leading in considerable savings in bottle cost per unit volume.[1]

In general, the main advantages of PET, as a material for bottle manufacturing, include that it[8]

a. is colourless and may be transparent or translucent, which is an important aspect when the packed product should be visible to the end users;
b. is lightweight. Nowadays, each 1.5- and 0.5-L PET bottle weigh approximately 24 and 10.5–11.0 g, respectively, well below the 550- and 700-g weight of a 0.7- and 1.5-L glass water bottle, respectively. It should be mentioned that two decades ago, the respective weights for 1.5- and 0.5-L PET bottles ranged 38–40 and 16–18 g;
c. is safe. PET bottles are mode durable and breakage resistant as compared to their glass counterparts. This results in no fractures while filling, transporting and using, resulting in less injuries and losses.
d. is thermoplastic, robust, semi-rigid to rigid, mechanically resistant to impact, and stretchable during processing;
e. is flexible enough to be moulded into any shape and any shade of colour;
f. shows gas-barrier properties against moisture and CO_2;
g. is significantly inert compared to other plastics and free from plasticizers;
h. is recyclable;
i. can be blended with other polymers or surface modified;
j. can be copolymerized;
k. is cost-effective to produce and require less energy to transport;
l. is convenient. Since PET bottles are safe and lightweight, they are also convenient for on-the-go consumption.

Significant quality stability of packed food products has been reported with the use of PET as packaging material. The sorption of different aromatic compounds from strawberry syrup packed into PET and PVC containers during one-year storage has been investigated by Ducruet et al.[9] The results of the study showed that the absorbed aroma was four times higher in PVC compared to PET, indicating a better retention of the aroma in PET containers during long term storage. Recent technologies to enhance the gas barrier properties of PET bottles include coatings, multilayers, blending and oxygen scavengers, alone or in combined applications.[10]

PET bottles are usually fitted with either an aluminium roll-on closure or a pre-threaded plastic cap. The cap is often preferable in the case of PET bottles, as its main sealing surface is on the inside bore of the neck finish, which is precisely controlled with regard to diameter and smooth surface finish during injection moulding, while also having almost zero ovality.[1]

3 | PET FOR BOTTLED WATER AND SOFT BEVERAGES

PET bottles are the most widely used packaging system in the soft drink sector. Due to the functionalities and protective effect of PET as food packaging material, further applications of PET bottles are expected inside and beyond the water and soft drink segments.[10] In the case of bottled water, an important index of failure is microbial growth. The source of water contains sufficient trace nutrients for microbial growth.[11] The use of returnable containers for bottled water is common in several countries. Only a limited number of studies have been performed on the microbial contamination risk when conventional washing with commercial disinfectants is used for the returnable containers. It has been reported[12] that under optimal conditions, the following classification could be made in decreasing order of microbial rinsability: glass > PET > polycarbonate (PC) > polypropylene (PP) = PVC > high-density polyethylene (HDPE). Even at optimal rinsing conditions, it was not possible to totally remove all bacteria from the sides of the containers, leading to the recommendation that bottled water should be disinfected by ozonation.[12]

Glass bottles were long considered the container of choice for sparkling waters and carbonated soft drinks, but nowadays, PET bottles have gained a rising share of this segment. The majority of still waters and several sparkling waters are currently packed in plastic containers, and PET is the principal material.[1]

Water packed in PET is normally regarded as free from taints. The major volatile compound in PET is acetaldehyde (AA) which is present as a thermal degradation product formed during the melt condensation reaction and melt processing of PET material. AA possesses a distinct door and taste, generally described as sweet, plastic-like and fruity, and has a low sensory detection threshold that ranges from 20 to 40 ppt. Present manufacturing techniques have reduced residual AA levels in PET packaging to <1 ppm. AA scavengers are available to reduce AA formation in PET packaging by up to 80%; anthranilamide is particularly preferred because of its low cost, efficiency and ease of incorporation into PET.[1,13] Mutsuga et al.[14] analysed commercial samples of water bottled in PET from Japan, Europe and North America and reported that AA and formaldehyde (FA) migrated into water from PET bottles, with concentration ranging 5.0–25.7 ppb for AA and <0.5–3.0 ppb for FA. Antimony trioxide (Sb_2O_3) is used as a catalyst and initiator in the manufacture of 90% of the PET manufactured worldwide, at a maximum level of 350 ppm as Sb. Welle and Franz[15] reported a mean value of 224 ± 32 ppm Sb in 67 PET bottles from the European market. Although Sb is a potentially toxic trace element with no known physiological function, only a small fraction of the Sb contained in PET bottles migrates into water. All of the waters found to contain Sb in relevant studies, were at concentrations well below the guidelines commonly recommended for drinking water (i.e., World Health Organization 20 ppb, US EPA and Health Canada 6 ppb, German Federal Ministry of Environment 5 ppb and Japan 2 ppb). According to the EU Legislation 10/2011/EU and further amendments, the specific migration limits (SML) for Sb is 0.04-ppm Sb migration limit for empty bottles, and 5-ppb concentration limit in Natural Mineral Water final product (2003/40/EU) and 10 ppb in drinking water final product (98/83/EC and 2184/2020/EU). Shotyk et al.[16] reported that 12 brands of bottled natural waters from Canada contained 156 ± 86 ppt Sb, and 3 brands of deionized water contained 162 ± 30 ppt Sb. Comparison of three German brands of water available in both glass bottles and PET containers showed that waters bottled in PET contained up to 30 times more Sb, with a range of 253–546 ppt Sb. One German brand of water in PET bottles had 626 ± 15 ppt Sb 6 months after bottling. The median concentration of Sb in 35 brands of water bottled in PET from 11 other European countries was 343 ppt. Cheng et al.[17] reported Sb leaching into water packed in PET bottles after treatments, such as cooling with frozen water, heating with boiling water, microwaving, incubating with low pH water, outdoor sunlight irradiation and in-car storage. After heating and microwaving concentrations exceeded the value of 6 ppb, while for all other treatments the Sb levels remained well below the acceptability limits.

The continuous trend for larger containers for soft drinks has enabled the penetration of the PET bottle. The 1-L glass bottle is considered to be near the limit of size and weight, above which it becomes non-convenient, especially for children. In contrast, PET bottles up to 5 L in volume are nowadays available, leading to significant savings in container cost per unit volume. In addition, the larger the bottle, the more CO_2 is retained per unit of time because of a smaller surface area to volume ratio (i.e., a reduced area for permeation).[1]

4 | PET AND SUSTAINABILITY

Plastic packaging is lightweight (approximately 24 and 10.5–11.0 g for each 1.5- and 0.5-L PET bottle, respectively) and functional and has thus replaced several conventional packaging materials, such as glass and metal. Despite the widespread application of plastic films, mainly the rigid plastic packaging materials are currently recycled, with PET providing the greatest volumes, followed by HDPE and PP. Even if PET is a fossil-derived material, several important insights have been reported, making PET a 'more sustainable' material than in the past. More specifically, innovations in the field of material science unveiled enabled the production of (a) PET through polymerization mechanisms involving monomers isolated from biomasses (this form of PET is named bio-PET); (b) fully recycling PET through advanced chemical methods, enabling the direct and repeated re-utilization (this form of PET is named R-PET); and (c) biodegradable PET via enzymatic reactions which involve isolated bacteria (e.g., *Ideonella sakaiensis*) or enzymes (e.g., PETase).[1]

4.1 | PET recycling

Post-consumer PET recycling involves a cross-disciplinary procedure, which includes polymer chemistry, physics, process engineering, and manufacturing. Two main processes have been applied for PET flakes recycling, that is, chemical and mechanical recycling. According to Welle,[2] over the 2010 decade, the collection of bottles for recycling in Europe has increased significantly. More specifically, in 2016, out of 3.15 Mtn of PET bottles and containers placed in the EU market, a percentage of 59.8 were collected and 1.77 Mtn were mechanically recycled. In some cases, for example, in countries such as Germany, Iceland, Norway and Switzerland, the collection rate reached values up to 90%. PET is fully recyclable and may be re-melted and mechanically recycled as often as required, especially when combined with virgin resin.[2]

4.1.1 | Chemical recycling of PET

Chemical recycling (chemolysis) is achieved by the total or partial depolymerization of PET into monomers of oligomers, respectively. The chemical compounds used for PET depolymerization are water, methanol and ethylene glycol. The most important disadvantage of chemical recycling of PET is the increased costs.[18]

4.1.2 | Mechanical recycling of PET

The mechanical recycling of PET is based mainly on the removal of the contaminants in the plastic material by sorting and washing, then drying and melting processes.[18] This method is also called 'materials recycling', as it includes sorting and separation of waste, washing for removal of contaminants, grinding and crushing and further reprocessing.[19] The so-called 'super-clean' process for PET bottle-to-bottle recycling may use a further, utmost cleansing step (thermal processing at 200°C) for the decrease of the contaminants, close to the respective concentrations in virgin PET pellets.[1,20]

The heterogeneity of the PET waste materials is the most important issue for mechanical recycling. The quality deterioration of the final product is another significant disadvantage of mechanical recycling, which is attributed to photo-oxidation resulted from the heat of fusion and the mechanical stress by the inverse reaction. Therefore, mechanical recycling is not appropriate for providing high quality standards to the final product. In general, high quality recycled PET may be produced when adequate separation is achieved prior to the remoulding step.[21]

4.1.3 | Thermomechanical recycling of PET

The thermomechanical recycling process for PET may result in a significant degradation of the mechanical properties of the plastic material. For this reason, the use of recycled PET is not preferable, and thus, PET waste is consciously accumulated. PET has a high ratio of aromatic terephthalate units, which may reduce the chain mobility, so PET is a polyester that is hardly hydrolyzed. Several PET hydrolase enzymes have been reported; however, their productivity and applicability are limited.[22,23] Recently, the activity of several enzymes has been evaluated prior to PET hydrolyzation, such as *Thermobifida fusca* hydrolases 1 and 2, *Fusarium solani pisi* cutinase, *Ideonella sakaiensis* PETase and leaf-branch compost cutinase, with the latter exhibiting at least 33 times higher efficiency than any other tested enzyme.[24]

4.1.4 | PET bottle recycling and sorting

The PET bottle recycling collection system is different between countries and dependent on the local conditions, governmental policies and social aspects of recycling.[6] Sorting is a crucial step in the recovery of plastic packaging, as this stage determines the purity and value of the secondary materials. In general, PET bottles represent a significant fraction of total use of packaging, exhibiting convenient and effective sorting.[2] In most cases, sorting is implemented manually, and the result is a postconsumer recycled (PCR) PET fraction consisting mainly of bottles of the same colour, an HDPE fraction (for the development of food and non-food containers) and a mixed plastics fraction, mainly used for energy recovery or further recycled with the incorporation of a compatibilizer. After the sorting stage, PCR PET is washed and ground in order to develop flakes of 4–20 mm diameter. Any contaminants at this stage (e.g., low-density polyethylene [LDPE] or PP) is harmful; for this reason, a separation, flotation based step, takes place, before the final stage of drying. A total loss of 18% w/w of the in-coming material is estimated during the process of flakes production.[1,20] A major recycling application for PCR PET flakes is the fibre industry, as it requires lower molecular weight material than do bottle manufacturers.[1]

Regarding the applicability of a recycling system for beverage packaging, it is highly correlated with the participation of the consumers, which depends on regional, educational and cultural issues. For example, according to Zhang and Wen,[6] Chinese consumers have been reported as willing to recycle PET bottles to protect the environment. However, the inconvenience in the recycling process (mainly the collection step) and the absence of financial benefits, penalties and due diligence support are the main obstacles for the expansion of PET recycling. In EU countries and USA, efforts should be made with the aim to improve the convenience and enhance the consumer motivation to follow the appropriate procedures for recycling. Recently, the Directive (EU) 2019/904 has been issued regarding the reduction of the impact of certain plastic products on the environment. According to Simon et al.,[25] the fostering of participation of consumers in beverage packaging collection via focused policies would be highly important. The Kerbside bag collection may be a favourable solution, as a strategy of local authorities to collect recyclable items from the consumer using reusable bags and boxes. Nakatani et al.[26] reported smaller greenhouse gas (GHG) emissions and fossil resource consumptions in domestic and transboundary recycling scenarios compared to incineration practice.

4.2 | Environmental aspects of PET

The increase of all kinds of plastic consumption worldwide has led to large amounts of plastic littering, ending in the oceans, which generates impacts on marine life and habitants. Alongside the ecological impacts, also social and economic effects may be related to marine littering, including human health issues and seafood safety. In view of the negative effects generated by the increased production and consumption of bottled water on the environment, potential actions for the ecosystem protection have been proposed, as for example, the development of an indicator by Civancik-Uslu et al.[27] for the determination of the negative impact of plastic bags on the aquatic environment. Based on existing life cycle analysis (LCA) methods, it is not easy to evaluate the marine and terrestrial litter because these issues are not considered by any impact category. Stefanini et al.[28] evaluated the environmental impact of plastic and glass, considering all the phases (from production up to the final disposal), working on different containers of 1 L of milk, that is, a PET bottle, an R-PET bottle, a non-returnable glass bottle and a returnable glass bottle. According to the study by Stefanini et al.,[28] the most impactful phase of the bottle life cycle is the production of the primary packaging, regardless the material. Comparing the alternative options of packaging materials (PET, R-PET, non-returnable and returnable glass bottles), it was concluded that the non-returnable (one-way) glass bottles had the highest environmental impact, as a result of their production process and transport. The returnable glass bottles enabled reduction of emission compared with the non-returnable glass bottles. Assuming that a glass bottle may be used approximately 30 times before its end of life, the contribution to global warming potential of a reusable glass bottle was proven to be similar to a single use PET bottle. Factors such as weight, distance and transport mode and their interactions determine the total CO_2 emissions for each packaging system.[29] Making use of smaller, lighter trucks, for example, could further reduce the transport impacts for the reusable system. Regarding the comparison between PET and R-PET, no difference in their respective marine litter was reported, as a result of their similar weight and biodegradability. However, increasing recycling of PET bottles from 24% to 60% may result in 50% reduction of climate impact.[30]

Brouwer et al.[31] proposed a model for the accumulation of contaminants within PET bottle collection and recycling systems and predicted correlations with critical bottle properties, in order to assist the recycled content policies to adopt the circular economy model.

Recent studies investigate the degradation potential of PET bottles in the marine environment.[32] Stanica-Ezeanu and Matei[33] investigated the effectiveness of novel catalysts such as NaCl, $CaCl_2$, $NaHCO_3$ and $KICO_3$ and marine water as potential alternatives to the conventional catalysts (i.e., Zn, Cu, Co and $MnSO_4$) for the depolymerization of waste PET by hydrolysis and described the rate of reaction as a function of surface water temperature, indicating that in tropical regions 72 years are needed for total conversion and only 4.5 years for 50% PET conversion to the original feedstock monomers TPA and EG.

5 | PET PACKAGING AND LEGISLATION

The general definitions and guidelines in terms of packaging and packaging waste are included in the 94/62/EC Directive of 1994, providing a framework for measures to be taken in order to diminish the volume of packaging waste. Later on, the European Commission obligated the harmonization of waste management and the implementation of the waste hierarchy in national regulation, enhancing the waste prevention, re-use and material recycling instead of incineration or landfill.[25,34] In line with the current European trend to move towards circularity and carbon neutrality, the PET packaging industry introduced a clear objective to achieve 90% collection of PET bottles by 2029.[30] A clear and forward regulatory environment is essential in order to comply with full circularity and carbon neutrality, as well as to implement the EU Green Deal. According to the EU Directive 2019/904 on the reduction of the impact of certain plastic products on the environment, beverage PET bottles will contain at least 25% and 30% recycled plastic from 2025 and 2030, respectively. The member states are committed to take the necessary measures to ensure the separate collection for recycling 77% and 90% of single-use plastic products by 2025 and 2030, respectively.

Several countries have established bottle-to-bottle PET recycling facilities. Germany has been one of the leading countries in PET recycling; however, developing countries such as India are currently reporting recycling rates up to 90%, while South Africa exhibits also a significant rise of PET recycling rates.[35] This increase may be attributed to the enactment and strict implementation of recycling regulations that specifically target PET bottles.[35] Several developed countries, such as USA, Germany, UK and Sweden provide financial incentives in order to promote PET bottles recycling.[36] EFSA has provided scientific opinions, as for example,[36] evaluating the safety of several PET recyclates intended for food contact materials, in terms of migration of potential contaminants into food. As a general guideline, considering the potential migration of contaminants and conservative scenarios of consumption rates for adults and infants, EFSA has reported that the proportion of PET from non-food consumer applications should be no more than 5% in the input to be recycled.[37]

Based on further EFSA opinions, recycled PET obtained from specific processes is not of safety concern when used at up to 70% in mixtures with virgin PET for manufacturing bottles for drinking water. For the manufacture of materials and articles for contact with other types of foodstuffs, for long-term storage at room temperature, with or without hot fill, recycled PET can be up to 100%.[38–41] For some specific PET recycling processes, with no concerns of safety, even when they are used at up to 100%, EFSA recommends that the final articles are not to be used in microwave or conventional ovens.[42]

6 | PET PUBLIC PERCEPTION AND MEDIA

PET bottles were patented in 1973 as a lightweight, safe and cost-effective container, being at the same time recyclable. As the global consumption of plastic bottles is continuous rising, the environmental impact of the discarded plastic materials raises issues to the consumers under two pillars, i.e., (a) efforts to reduce the use of plastic bottles at the consumption level and (b) efforts to introduce alternative ways to handle discarded bottles, including the convenience of the alternative collection systems.

Microplastics pollution in nearshore marine environments has been introduced as 'increasingly prominent' and currently receives widespread attention. Excessive media projections and articles regarding microplastics in the aquatic environment target PET bottles as the main and most important source, among other materials used widely, such as vehicle tires/rubber, HDPE, PP and PVC, with comparable, limited or finite capacity for reuse and recyclability. Gao et al.[43] reported that the microplastics at the bathing coasts of Qingdao (China) consisted mainly of lines (80.5%) and fragments (7.9%), with PET being responsible for the 16.9% of the total microplastics (rayon dominated with 41.8%). Other components detected in seawater included PS (12%), PVC (5.1%), polyphenylene sulphide (PPS) (5.1%), phenol formaldehyde (PF) (4.3%).

A number of trends have been expressed via consumer demands for plastic packaging materials, which are strongly related to PET bottles for water and soft beverages. A major issue has been the increasing demand for transparency, reflecting the good barrier properties of the packaging materials while at the same time retaining the product visibility, which is a prerequisite in the case of bottled water. The degree of transparency of a polymer container depends on the matrix structure (amorphous, i.e., transparent, or crystalline, i.e., translucent) and the thickness.[44] Recognizability, that is, the extent to which the sustainable features of the material are reflected on the packaging, plays a key role and may affect significantly consumer preferences.[3] However, although R-PET represents a widespread sustainable alternative to conventional PET, the Italian consumers seem reluctant to shift to the R-PET water bottles direction, according to a recent consumer study performed in Italy in 2019.[3] Consumer negative attitude towards recycled materials has been also previously reported. People tend to associate the recycled materials to higher risks for contamination, especially when dealing with food and beverages.[3,45,46] Orset et al.[47] reported an increasing consumer interest for innovation in plastics, with the aim to provide environmentally friendly materials, focusing on biodegradability and recycling. By systematic analysis of willingness to pay, the aforementioned study reported a significant premium associated with R-PET and organic and biodegradable plastic packaging, mainly polylactic acid (PLA). At the same time, based on a recent study in United States, 53%–57% of consumers recognize plastics as extremely or very sustainable packaging materials. Interestingly, USA consumers rank glass, paperboard and paper only a little higher than compostable plastic films or fully recyclable plastic films and bottles.[48] Within the framework of plastic recycling, a process of turning plastic bottles into clothing material has been reported, by collecting clear bottles made from PET, followed by melting, spinning them into fibres, which are therefore woven into fabrics. Based on a study from 2019, consumers express greater intention to use a product made from recycled bottles with a function which does not affect the skin (e.g., a carrying bag), rather than an item (such as a T-shirt) with direct contact with skin.[49] According to Stefanini et al.,[28] raising the consumers and stakeholders' awareness of the potential environmental issues, investing in plastic recycling and use of recycled plastic as R-PET, may reduce the pollution of the aquatic environment and enhance the sustainability of plastic packaging materials. A 20% shift in consumption from smaller to larger bottles may decrease the annual production of PET waste by over 10 000 t in USA.[50]

7 | CONCLUSIONS

The advantages of PET are well documented, in terms of its mechanical properties, barriers, convenience of use and safety as a food contact material. Therefore, it remains (and will remain) one of the prominent polymers to be exploited in the food packaging sector. The limitations and drawbacks of its increasing application have been introduced and refer mainly to the environmental impact of the single-use plastics. Recent research and advances have been reported, making PET currently more sustainable than in the past. Recyclability is an important advantage of PET, relating to its increased sustainability compared to other polymers. Recycling of PET bottles not only has the potential to conserve fossil fuels but it can also reduce energy usage and greenhouse emissions. In any case, changes in the production for a specific material should be considered, as significant differences are observed in the environmental impact as a function of the design and production process. For example, the alternatives of fossil-based, recycled or bio-based recourses for PET bottles result in considerably different environmental impact. Consumers' and stakeholders' awareness of plastic packaging, focusing on the 'facts and myths' about the safety and environmental aspects, coupled with targeted educational campaigns for appropriate and effective recycling is essential locally and at global level.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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