Recycled Polyethylene Terephthalate Blends and Composites: Impact of PET Waste, Engineering Design, and Their Applications

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1 Introduction

In 2020 alone, around 22.66 million metric tons of polyethylene terephthalate (PET) resin have been produced worldwide and the growth rate is expected to increase by 4% annually until 2025. PET is a general-purpose thermoplastic made of polyester (Zhang et al. 2020). Semi-aromatic PET is made by combining two monomers of modified ethylene glycol and purified terephthalic acid through synthesis. PET has a glass transition temperature of 67–81 °C and a melting point of 260 °C, and exists as an amorphous (transparent) or semicrystalline (opaque and white) thermoplastic

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H. Ismail et al. (eds.), *Recycled Polymer Blends and Composites*,
https://doi.org/10.1007/978-3-031-37046-5_21

material. Semicrystalline PET has excellent mechanical properties in terms of strength, ductility, stiffness, and hardness. Meanwhile, PET with an amorphous structure has better ductility than that of semicrystalline PET but has to compromise with less stiffness and hardness (Ragaert et al. 2017). PET exhibits good dimensional stability, thermostability, and resistance to impact, and it has excellent moisture and fair oxygen barrier characteristics. Therefore, PET has become the material of choice in industrial applications especially for the packaging of fruit juice and soft drink bottles (de Moura Giraldi et al. 2005).

Today, PET is the most recyclable plastic in the world and it can be easily identified from the number 1 indicator in the triangular code printed on the bottle or container. Recognizing the critical threats posed by PET waste, various organizations and entities have collaborated to promote the importance of PET waste recycling. Through numerous attempts, a minimum reduction of 24% carbon emissions can be eradicated and this makes the utilization of rPET a more sustainable option (Khoonkari et al. 2015; Raheem et al. 2019). Predominantly, PET can be recycled multiple times before ending up in a landfill. Plastic waste from other products may be utilized as a low-cost and long-term feedstock in other new production processes (Salwa et al. 2021). Material recycling is essential due to the increasing use of composites in many sectors as well as stricter legislation and concerns about the disposal or incineration of composites in landfills (Ilyas et al. 2021). Apart from recycling, rPET has been successfully blended with various thermoplastics, namely polypropylene (PP) (Subhashini et al. 2021), polyethylene (PE) (Lei et al. 2009), and polyamide 11 (Khan et al. 2021). The improved blending properties have been confirmed by mechanical testing based on tensile and flexural strengths. In addition, studies on the utilization of solid fillers from fly ash (Sharma and Mahanwar 2010; Zaichenko and Nefedov 2018), mineral-based fillers (Negoro et al. 2016; Pivsa-Art et al. 2021), glass fiber (Monti et al. 2021), carbon-based fillers (Baek et al. 2018), and nanoparticles (Chowreddy et al. 2019) in rPET have also gained significant interest among researchers. To provide clear insight, this chapter focuses on the progress of rPET blends and rPET-based composites as well as their impact on engineering design and performance.

2 Source of PET Waste

With the increasing use of PET plastics, the waste will accumulate in the environment and will generate unknown long-term impacts. PET was initially assumed to be harmless and inert, but later researchers have claimed that it could take more than 400 years to completely decompose (Hamad et al. 2013). Based on the Springer Report 2019, China is the world's largest PET resin manufacturer encompassing more than 15% of the global market. Moreover, China is also the largest consumer of PET products in the world. Previously, PET accounted for about 50% of China's waste plastic imports (Sardon and Dove 2018). Between 2000 to 2018, the cumulative amount of waste PET bottles was around 78 million tons in China which

was equivalent to about 7 tons of waste PET bottles generated per minute. Remarkably, China is also a net importer of waste PET bottles, and the number of waste PET bottles imported are 290 times that of export. To address this issue, the Chinese government has taken action to restrict the import of waste plastics in 2018 (Wang et al. 2020).

PET plastic bottles are a popular choice for packaging soft drinks due to their numerous benefits to manufacturers and consumers. About 70% of soft drinks (carbonated drinks, fruit juices, and bottled water) are largely packaged in PET plastic bottles (Singh et al. 2021a). By 2016, annual sales of bottled water in the United States (US) officially surpassed soft drinks. As a result, plastic bottles and bottle caps are the third and fourth most collected plastic waste in the US. Most of the beverages we consume regularly are in single-use bottles and cans for water, sodas, iced tea, cold-brewed coffee, fruit juices, energy drinks, and others (Wang et al. 2020). Furthermore, PET is frequently used as packaging for a variety of products including beverages, bakery goods, frozen foods, salad dressings, cosmetics, and household cleaners. These materials accumulate a large portion of the PET waste in landfills as well as in the ocean.

Moreover, Norway has a recycling rate of PET bottles over 97% as of 2018, making it a world leader in recycling (Mallakpour & Behranvand 2016). In the same year, the recycling rate of PET bottles in the US was only 29% (Yamada and Thumsorn 2013). The high recycling rate in Norway can be attributed to the country's efficient deposit return system. When customers purchase a plastic bottle, they pay a modest surcharge in addition to the product price, which will be refunded when the bottle is returned to reverse vending machines. Other countries have adopted this approach as it has been proven effective. In the United Kingdom (UK), 86% of the population favored the supermarket deposit return scheme for plastic and glass bottles as well as beverage cans (Raheem et al. 2019).

3 Impact of PET Waste to Humans

Initially, PET was considered harmless and inert, but over the years, perceptions have changed owing to the massive amount of PET being disposed into the environment. Sardon and Dove (2018) predicted that by 2050, the size of plastic waste will continue to grow, and the recycling process will be insufficient causing the mass of plastic waste to exceed the number of fish. Similarly, PET waste has accumulated at landfills progressively and the amount continues to increase yearly, comprising PET-based product and packaging materials (Feng et al. 2013).

Before being converted to the final product, various additives are added into the PET resin during processing for different reasons. The most significant reason is to retain the properties of the resin for a sufficient period. Typically, an inorganic compound, such as antimony trioxide, is used as a catalyst for PET production and rubber vulcanization, and this additive can leach when exposed to extreme and rigorous conditions. For PET plastics, the waste is buried, compressed in layers, and

exposed to rain and hot weather constantly at landfills (Ioakeimidis et al. 2016; Yesil 2013). Although the degradation process can decelerate in the long run, it can greatly expose landfills to toxic additives due to the leaching issue from PET waste.

In addition, PET waste is considered a major burden to the aquatic environments where there is prolonged biophysical breakdown of plastics, negative impacts on ocean habitats, and limited plastic removal options. For synthetic polymer, PET plastic, the degradation process begins as soon as it is disposed into the oceans due to the synergistic effects of environmental variables and inherent material instability. Ioakeimidis et al. (2016) performed FTIR characterization on PET collected from the submarine environment and indicated that the degradation behavior of PET was attributed to environmental conditions. Based on the findings, it was proven that PET remained robust after 15 years of floating in the ocean. Subsequently, a significant decrease in native functional groups has been documented and some have disappeared (Chowreddy and Nord-Varhaug 2019). The PET will then slowly degrade and turn into large amounts of floating marine waste microplastics. Microplastics are small pieces of plastic that are less than 4.76 mm in length, and now they have sparked a huge controversy that seriously endangers marine ecosystems (Gan et al. 2021). According to Cox et al. (2021), Americans consume more than 50,000 microscopic bits of plastic from the food chain each year. Through the food chain, toxins attached to plastics can also move and accumulate in animal fats and tissues through the bioaccumulation process.

In addition, man-made CO_2 emissions pose a serious hazard to both humans and ecosystems. PET bottle releases more than 100 times toxins into the air and water. Moreover, the production process of PET can be classified as a process that is hazardous to workers. Over the years, serious accidents including explosions, chemical fires, chemical spills, and clouds of toxic vapor were unprecedented. On the other hand, PET bottles have contributed significantly to CO_2 emissions in recent years. If preventative actions are not taken, CO_2 emissions from plastic bottles are expected to quadruple by 2021 compared to 2006 (Zhang et al. 2020). Activated carbon derived from industrial waste, especially plastic waste, is considered a promising CO_2 adsorbent that can address PET waste recycling and CO_2 mitigation simultaneously. Wang et al. (2020) studied the PET waste-derived activated carbon for CO_2 capture and revealed that the life cycle process stipulated a large primary energy demand of 5481 MJ kg^{-1} activated carbon. This suggested that a large portion of the total energy was used for CO_2 desorption. The study also revealed the environmental trade-offs associated with this technique, with primary energy use, water resource depletion, and freshwater ecotoxicity being the most significant.

4 Recycling Methods

The general terminology for plastic recycling is described through recycling steps including collection, separation, manufacturing, and marketing (Grigore 2018). This terminology is based on various recycling and recovery processes (Table 1).

Table 1 Different terminologies of plastic recycling and recovery

ASTM D5033 definitions	ISO 15270 definitions	Other equivalent terms
Primary recycling	Mechanical recycling	Closed-loop recycling
Secondary recycling	Mechanical recycling	Downgrading
Tertiary recycling	Chemical recycling	Feed stock recycling
Quaternary recycling	Energy recovery	Valorization

Primary (mechanical reprocessing into goods with equivalent attributes), secondary (mechanical reprocessing into products with lesser properties), tertiary (recovery of chemical constituents), and quaternary (recovery of chemical constituents) are the four types (recovery of energy) (Hopewell et al. 2009).

4.1 Mechanical Recycling

Primary recycling (closed-loop recycling) and secondary recycling are two types of mechanical recycling (downgrading). Primary recycling is the most practical as it successfully separates contaminants from the source and stabilizes them against degradation during reprocessing and subsequent use. It is used to produce an identical product that was recovered in the beginning. This innovative product can be constructed entirely from recycled plastics or a mixture of recycled and virgin polymers. The method of dilution ensures that the product can be recycled at the same rate as the material recovered. All PET bottles, for example, are constructed from similar PET grades appropriate for the manufacture and reprocessing of bottles to polyester fibers (Ragaert et al. 2017). Meanwhile, secondary recycling (downgrading) is used for products that are different from those recovered. For example, textile fibers are made from PET bottles and printer components are made from polycarbonate water bottles (Hopewell et al. 2009).

A physical approach is used to describe the mechanical process, which includes waste collecting, sorting, washing, material grinding, and melting to manufacture new products through extrusion (Fig. 1). Automatic and manual sorting is used to sort items by shape, density, size, color, or chemical composition. Furthermore, Fourier transform near-infrared (FT-NIR) is used to separate the mixed plastic waste, which is then segregated into clear, blue, and green PET using an optical color recognition sorter. Finally, all of these sorted streams pass through a sorting cabin, where trained operators inspect them for false positives and negatives (Ragaert et al. 2017; Grigore 2018). In addition, product washing is required to remove food residues, pulp fibers, and adhesives. To remove residues, several approaches are used, such as wet (water) or dry (friction) surface cleaning (Hopewell et al. 2009). The final step in mechanical recycling is the size reduction from goods to flakes via grinding. Optional treatments for converting flakes into granulates include compounding and pelletizing (Al-Salem et al. 2009; Ragaert et al. 2017).

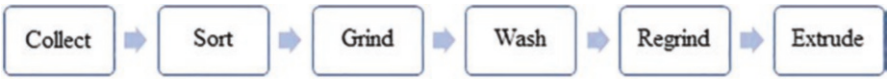

Fig. 1 Basic steps in mechanical recycling

Table 2 Chemical processes involved in the decomposition of polymers into monomers

Types	Definitions
Chemolysis	New approaches are being developed using garbage as a precursor in the production of pure value-added goods for a variety of industrial and commercial purposes.
Pyrolysis	Multilayer packaging, fiber-reinforced composites, polyurethane building, demolition waste, and other plastic waste feeds that are difficult to depolymerize and are not currently (mechanically) recycled but burnt and/or disposed of at landfills.
Fluid catalytic cracking (FCC)	The skewed carbon distribution of the reactor effluent results from the thermal degradation of solid plastic waste.
Hydrogenation	The method is similar to fluid catalytic cracking (FCC), but hydrogen is added to the mixture.
Gasification combined with methanol production	Waste is converted to methanol using Enerkem's cutting-edge technology. Methanol is then converted to chemicals such as acetic acid, thickening agents, and dimethyl ether, e.g., for fibers and adhesives (clean propellant gases).
Katalytische Drucklose Verölung (KDV)	The catalytic pressureless depolymerization process converts biomass and plastic waste into liquid fuels at pressures close to atmospheric pressure.
Toxicity of pyrolysis and gasification products	The toxicity of gaseous compounds produced under different thermal decomposition settings is a major problem.

4.2 Chemical Recycling

Chemical recycling is the process of chemically converting a polymer to monomers or partially depolymerizing a polymer to oligomers (chemical structure change) (Singh et al. 2017). The resulting monomers can be utilized to create further polymerization to replicate the original or similar polymer product. Starting with monomers, oligomers, or a combination of various hydrocarbon compounds, this process can convert plastic materials into smaller molecules appropriate for use as feedstocks. Table 2 lists the chemical processes that convert polymers to monomers (Ragaert et al. 2017).

4.3 Energy Recovery

Energy recovery from plastics is a good solution and an effective way to reduce the volume of organic materials through incineration. This method generates considerable energy from polymers, but it is ecologically unacceptable due to the health risk from airborne toxic substances including heavy metals, chlorine-containing polymers, toxic carbon, and oxygen-based free radicals (Grigore 2018).

5 Engineering Design of Recycled PET

While Covid-19 is an immediate challenge, new recycling technologies and alternative feedstocks will become increasingly important in the subsequent five years. The engineering design of recycled PET (rPeT) into new blends and composites is considered an eco-strategy to overcome a large amount of PET waste. rPET is often used as a matrix material in blends and composites and also as a filler in composites. Blending rPET with new virgin materials or with other recycled materials can reduce total production costs. In addition, the utilization of rPEt as a filler can enhance the properties of the composites. This section reviews the engineering designs of various types of rPETs (i.e., commercial rPET resin and rPET flakes from PET waste) used in blends and composites and their final properties.

5.1 Recycled PET Blends

Recycled PET blends can be combined with virgin PET or with other/more materials to produce new materials with unique physical and mechanical properties. Due to the incompatible properties of rPET with other materials, several studies have been conducted to seek an effective compatibilizer for rPET blends. Compatibilization is crucial to ensure an increase in microstructural uniformity, and also enhance the interfacial adhesion between phases. Among the examples of compatibilizers currently used in rPET blends are polypropylene-graft-maleic anhydride (PP-g-MA), polyethylene-graft-maleic anhydride (PE-g-MA), styrene-ethylene-butylene-styrene (SEBS-g-MA), and ethylene-glycidyl methacrylate copolymer (E-GMA) (Lei et al. 2009; Ahmadlouydarab et al. 2020; Adekunle et al. 2020; Subhashini et al. 2021). Furthermore, several researchers have proposed chemical approaches, such as chain extender, to enhance the properties of rPET blends apart from compatibilizers. In this section, the properties and potential applications of several rPET blends combined with compatibilizer or/and chain extender are summarized in Table 3.

Table 3 Recent studies on processing methods, potential applications, and properties of rPET blends

Blend and processing method	Potential application	Properties
rPET/rHDPE—Extrusion	Container for packaging material	This blend has poor compatibility in the presence of HDPE exceeding 5%, where the two phases were clearly differentiated from SEM micrographs (Navarro et al. 2008).
rPET/rHDPE with compatibilizer (PE-g-MA, SEBS-g-MA, and E–GMA)—Reactive extrusion and postextrusion strand stretching	Packaging material	The compatibility of rPET and rHDPE was improved. 5% E-GMA blended with rHDPE/rPET (75/25 w/w) indicated the best performance among compatibilizer with significantly improved toughness and impact strength, and increased tensile fracture elongation by 83% (Lei et al. 2009).
PP/rPET-compatibilizer PP-g-MA—Twin-screw extrusion	Industrial applications	The yield stress and elastic modulus of the blends increased with increasing rPET concentrations in the blends from 0% to 30%. Sample with compatibilizer demonstrated higher yield strength, modulus of elasticity, and impact energy compared to blends without compatibilizer (Ahmadlouydarab et al. 2020).
PP/ rPET PP-g-MA—Extrusion	Low-speed wheel material	The tensile strength, Young's modulus, and flexural strength were improved with increasing rPET content from 10% to 30%. The elongation at break reduced when more r-PET was included in the blends (Subhashini et al. 2021).
RPET/PETV—Melt blending—Haake rheometer Melt spinning	Filament yarn for textile	The melting temperature of the blend fibers decreased with increasing rPET content. The crystallization rate decreased with the addition of rPET into the PETV. The mechanical properties of 30/70 wt.% rPET/PETV blended fibers were comparable to those of virgin PET fibers (Lee et al. 2013).
rPET/PET—Single-screw extrusion	Food contact packaging	The degree of crystallinity of the blends slightly improved at rPET composition of 10–30%. The Young's modulus for the rPET composition of 30/70 showed the highest tensile strength (Masmoudi et al. 2020).
rPET/PET with 5-amino isophthalic acid ($C_8H_7NO_4$) as additive—Reactive extrusion	Matrices for composites	Reactive extrusion has improved the flowability and elastic modulus of the blends (Asensio et al. 2020a).
rPET/PBT—Single-screw extruder	Not mentioned	Tensile strength, impact strength, and degree of crystallinity of PET/PBT (40w/60w) blends containing 60 wt.% rPET improved (Baxi et al. 2010).

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Table 3 (continued)

Blend and processing method	Potential application	Properties
rPET/PBT with multifunctional epoxide as chain extender—Reactive extrusion	Not mentioned	The addition of only 0.2 wt.% Joncryl to the rPET/PBT (75/25) blends dramatically improved its thermal stability, dynamic rheological properties, and processability (Guclu et al. 2021).
rPET/PBT—Twin-screw extruder	Home appliances, electrical, and automotive applications	The addition of a chain extender increased the melt viscosity of the blend. In the amorphous region, the blends were totally miscible, but after rapid cooling, the crystalline phases became immiscible. The chain extender did not significantly influence the mechanical properties (Nofar and Oğuz 2019).
rPP/rPET with compatibilizer SEBS-g-MA—Internal mixer (Brabender)	Fibers applications	50/50 rPP/rPET blend with 20 phr compatibilizer showed better tensile strength, impact resistance, and resilience modulus compared to those without compatibilizer (Araujo and Morales 2018).
rPP/rPET uncompatibilzed—Injection molding	Substituted to rPP for similar applications	The elastic modulus improved at 20% and 30% of opaque rPET (rPET-O). An increase in rPET-O from 10% to 30% has improved the fatigue life, diminished overall deformation, prevented local heating, and changed fatigue failure to quasi-static failure (Tramis et al. 2021).
rPET/PC—With styrene acrylic copolymer as chain extender—Single-screw extruder		The tensile modulus improved with the addition of 30% PC in the blend. The tensile strength and modulus further increased by adding chain extender from 0.5% to 2% (Srithep et al. 2017).
rPET/EVA with pyromellitic dianhydride (PMDA) as chain extender—Extrusion & reactive extrusion	Microfibrillar composite	The rate and degree of crystallinity of rPET decreased with the addition of PMDA and EVA. rPET/EVA showed co-continuous morphology, while the addition of 0.5 wt.% PMDA showed microfibrillar matrix-disperse state (Moghanlou and Pourabbas 2020).
rPET/PA11 uncompatibilized—Twin-screw extruder	Automobile, packaging, and various industries	Tensile and flexural strength improved significantly with the addition of PA11 into the rPET (Khan et al. 2021).
rPET/PE/PP/PS with EGMA as compatibilizer—Extrusion	Not mentioned	The Izod impact strength improved with increasing EGMA content in the rPET/PE/PP/PS blend. The miscibility of the blends also improved with increasing EGMA content and was evidenced by SEM images (Imamura et al. 2014).
rPET/rHDPE/rPP (ethylene-glycidyl methacrylate copolymer (EGMA)—Injection molding	Automobile bumper	Blending 164 g rPET, 18 g rHDPE, and 18 g rPP with 10% EGMA produced the best mechanical properties of a car bumper (Adekunle et al. 2020).

5.2 *Recycled PET Composites*

Recently, rPET has also been used as a matrix material in the production of various polymer composites, which is economically effective. It also has the potential to reduce the consumption of virgin materials and address the environmental contamination issue that results from postconsumer PET waste. In rPET composites, several fillers have been widely used such as organoclay, glass fiber, wood, titanium dioxide, carbon fiber, rubber particles, kenaf, and others (Singh et al. 2021a, b). The type of fillers, compounding process, and performance of rPET blends and composites are summarized in Table 4.

6 Applications of Recycled PET Blends and Composites

The evolution of rPET in new plastic packaging was introduced in 2002 by Triantafyllou et al. (2002). PET Recycling Company NPC or known as PETCO is one of the companies established in 2004 to handle the rPET (Petco n.d.). PETCO has commercialized new food grade and nonfood grade packaging from rPET. Then, Artenius (LSB) has commercialized a new packaging material in early 2012 which was a combination of virgin PET with recycled PET (Gallant 2012). Moreover, Artenius UNIQUE F10 currently uses a chemical recycling process to produce rPET-Artenius FLOW (virgin resin with 10% clean recycled PET). Furthermore, Coca-Cola Great Britain has recently stated that Sprite bottles would be changed from green to clear plastic to allow bottle-to-bottle recycling, with the quantity of rPET in all bottles increased to 50% (Maile 2019). It has good mechanical properties and was intended for stretch blow molding processes to make packaging for highly carbonated soft drinks and all direct food contact applications.

In addition, Greiner Packaging has also shifted to sustainable materials by combining PET with 30% rPET in new packaging for ketchup and sauce bottles (Edbauer 2019). Extensive research on this area is escalating over the years due to the increased production and consumption of PET plastics as new plastic packaging. Meanwhile, Covestro introduced Arnite® AM2001 GF (G)-recycled PET, high-performance, glass-fiber-filled rPET for 3D printing filament in 2021 (Product News 2021). It allows fast and cost-effective of additive manufacturing for large-scale items. It has potential for structure, small recreational boats, tooling, and infrastructures such as footbridges and cycling, or pedestrian tunnels as well as architectural applications. Konica Minolta was another pioneering business that has successfully produced a new rPC/rPET for the exterior parts of a multifunction printer (MFP). The strength, flame resistance, and molding of rPET were successfully enhanced with polycarbonate (PC) to produce composite materials (Business solution, n.d.). The rPET/PC combination is also commonly utilized in automobile applications for bumpers, wheel covers, body panels, and electrical components.

Table 4 Recent studies on processing methods, potential applications, and properties of rPET composites

Composites	Compounding process	Properties
rPET/organoclay nanocomposites	Twin-screw extruder	The glass transition temperature (T_g) and melting temperature (T_m) of the composite decreased slightly in the presence of 1 wt.% clay. However, concentrations higher than 1 wt.% did not cause further reduction in T_g and T_m. Yield strength and modulus improved with increasing MMT up to 5 wt.% (Bizarria et al. 2007).
rPET/ clay nanocomposites	Twin-screw extruder via masterbatch dilution	The composite with 1 wt.% clay exhibited Newtonian behavior, while more than 1 wt.% up to 6 wt.% showed the shear thinning effect. In contrast, the viscosity of the composite decreased with increasing clay content. The T_g decreased with increasing clay content. The tensile strength increased gradually with the clay content. The impact strength did not change when 4 wt.% clay was added but decreased by 28% at 6 wt.% clay (Chowreddy et al. 2019).
rPET/glass fiber	Twin-screw extruder	The impact strength and tensile strength improved with the addition of 30% glass fiber (de Moura Giraldi et al. 2005).
rPET /recycled LDPE-HDPE	Single-screw extruder & injection molding	Different rPE/rPET ratios were used. The time taken to extrude the composite increased with increasing rPET. The viscosity also increased, but the compressive strength decreased with decreasing rPET ratio (Laria et al. 2020).
rPET/micronized rubber	Extrusion	The T_g and degree crystallinity increased with the addition of rubber. The toughness improved by adding rubber powder (Zander and Boelter 2021).
rPET/glass fiber/ wood laminated composites	Compression molding	The alternating arrangement of rPET and wood layers influenced the final properties of the sandwich composite. The rPET layers decreased water absorption by the composites. The addition of an rPET layer decreased the flexural strength and modulus (Bakir et al. 2021).
rPET/glass fiber	Pultrusion	Different types of rPET were used. Composites with chemically modified rPET showed higher flexural strength and modulus compared to unmodified rPET and colored rPET. Composites with chemically modified rPET showed the highest tensile strength (441 MPa) (Asensio et al. 2020b).
rPET/glass fiber composites with impact modifier	Twin-screw extruder	The addition of an impact modifier slightly improved the impact properties. Composite with E-MA/24-GMA impact modifier showed the highest impact. From SEM images, the impact modifier tended to form the largest rubber particles (Monti et al. 2021).

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Table 4 (continued)

Composites	Compounding process	Properties
rPET/TiO_2	Semi-industrial extrusion calendering process	Two composites made of two types of rPET (i.e., transparent bottle grade (rPET-T) and mix transparent colored with opaques (rPET-O)) containing 1.45 wt.% TiO_2 were produced. The glass transition of rPET-T was higher than that of rPET-O. rPET-O showed stable and uniform color. Both samples demonstrated almost similar Young's modulus and yield strength. Physically aged rPET-T showed higher tensile strength than the physically aged rPET-O sample (Loaeza et al. 2021).
rPET/nano-TiO_2	Twin-screw extruder and melt spinning	The tenacity and elongation at break of bicomponent fibers increased with the increase of nano-TiO_2 up to 3 wt.%. The 90/10 bicomponent multifilament fiber with 3 wt.% TiO2 achieved the highest antibacterial activity (Pivsa-Art et al. 2021).
rPET/sawdust	Dry blending & hot flat pressing	The modulus of elasticity decreased with increasing sawdust content (40–70%). The modulus of rupture also decreased gradually (Rahman et al. 2013).
rPET/carbon fibers	Hot pressing	Tensile strength improved by increasing the processing temperature up to 270 °C. The interlaminar shear stress (ILSS) also showed a similar trend (Baek et al. 2018).
rPET/fly ash	Injection molding	The compressive strength of the composite increased by adding modified fly ash (Zaichenko and Nefedov 2018).
rPET/talc	Twin-screw extruder	The rPET was more crystallized using air cooling than the water cooling system during extrusion. Tensile strength and modulus improved with the addition of 5 wt.% talc. The tensile modulus of the composite prepared by water cooling was higher than that of the air cooling system (Negoro et al. 2016).
rPET/ newspaper fiber	Twin-screw extruder	The tensile and flexural strength improved by adding newspaper fiber (NPF) up to 5 wt.%, then gradually decreasing at 10 wt.% and 15 wt.% NPF. The impact strength decreased with increasing NPF content up to 15 wt.%. The degree of crystallinity of the composites increased with increasing NPF content (Ardekani et al. 2014).
rPET/rPP/kenaf	Twin-screw extruder	Composites reinforced with kenaf bast fiber have higher mechanical properties than kenaf core fiber composites. For both bast- and core-filled composites, the maximum tensile strength was 5 phr and the highest impact strength was 20 phr (Marzuki et al. 2021).
rPET/PAN composite nanofibers	Electrospinning	The compressive and flexural strength of the mortar improved by adding rPET/PAN fibers. Water penetration decreased with increasing rPET/PAN composite nanofibers (Chinchillas-Chinchillas et al. 2020).

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Table 4 (continued)

Composites	Compounding process	Properties
rPET/PBAT/wood	Twin-screw extruder	The tensile strength improved by increasing wood content up to 30 wt.%. The impact strength decreased in proportion to the decrease in rPET content. The flexural strength increased when wood content increased up to 15 wt.% (Chaiwutthinan et al. 2019).
rPET/ poly (ε-caprolactone) (PCL)/sawdust	Cryogenic solid-state milling & hot flat pressing	The optimal tensile strength for 25% sawdust was 35.8 MPa, with a high modulus of elasticity of 1100 MPa (Allaf et al. 2020).

The rPET content employed is between 50% and 80%, while the PC content ranges from 25% to 30%, and this is cheaper than materials made of acrylonitrile butadiene styrene (ABS) (Thakur 2015). Glass-filled rPET composites have also been used in automotive applications for headlamp bracket, window hardware, roof rack, and others, and Ford uses them for grille opening reinforcing panels of cars and trucks (Koester 1997).

7 Challenges in PET Recycling

Washing is required prior to mechanical and chemical recycling to remove impurities from the surface of plastic waste. Contaminants are critical factors affecting the suitability of postconsumed PET flakes for recycling in terms of the amount and nature of contaminants present in the flakes, resulting in deterioration of physical and chemical properties during reprocessing and problems of recycling postconsumed PET (Giannotta et al. 1994). PET (contaminated flakes) produces 43.9% carbon dioxide/acetaldehyde and 3.66% 4-(vinyloxycarbonyl) benzoic acid as its main components. The most prevalent by-products of faster pyrolytic breakdown due to the catalytic effects of remaining pollutants (i.e., D-limonene, chlorobenzene, benzophenone) are products with low molecular weight (CO_2, acetaldehyde) (Dimitrov et al. 2013). Several contaminants can contaminate rPET (Table 5).

Contamination issues can be solved by improving the recycling process. The super-clean PET recycling technique based on pellets, according to Damayanti and Wu (2021), is an alternative to overcome the difficulties. This approach is extremely similar to current mechanical procedures and uses the same apparatus, but it uses solid-state polycondensation (SSP) technology to accomplish it. The first stage involves the removal of all pollutants that have adhered to the PET surface. The PET is thoroughly cleaned in the second stage using SSP technology. With parameters such as residence time, temperature, vacuum, and inert gas stream, the SSP can be operated in a batch or continuous mode. Depending on the reaction temperature and the desired viscosity of the PET material, the residence time for the solid-state

Table 5 Types of contaminants that can affect properties of recycled PET

Type of contaminants	Effect	Problem solving
Water	Before the molten PET reacts rapidly, the hydrolytic chain cleavage and moisture content are devolatilized. The viscosity of the polymer can be lowered by a small amount of moisture (La Mantia 1996). PET hydrolysis is aided by its starting pace. It results in water loss in the sample, whereas the slower pace is due to thermooxidative chain depolymerization by thermal energy (Seo and Cloyd 1991).	PET should be rigorously dried before melt-reprocessing. The drying temperature for recovering PET flakes is 160–180 °C (La Mantia 1996).
Coloring	Before melt-reprocessing, the PET should be thoroughly dried. To recover PET flakes, the drying temperature ranges from 160 to 1800 °C (La Mantia 1996).	A few additives (Bacha et al. 2012) can be used.
Acetaldehyde	(i) Food packaging and containers use copper phthalocyanine blue.	
Heavy metal	(ii) UV stabilizers, such as benzotriazole, are used to protect food from the sun.	

reactions is between 6 and 20 h. For this scenario, the temperature range is 180–220 °C. The virgin rPET is homogenous, and postconsumer PET contamination is evenly dispersed, according to the findings.

The main difference is the presence of oxygen in the atmosphere. This leads to the formation of oxygenated groups on the polymer chain and affects the final properties of the material. In addition, the subsequent challenge is the processing of complex mixtures as the polymers in the mixed plastic waste differ in melting points and processing temperatures. When reprocessing these mixtures, recyclers often need to reprocess them at the highest melting component processing temperature. This often leads to overheating and degradation of some of the lower melting components, which in turn reduces the final properties (Ragaert et al. 2017).

Mechanical recycling has several obstacles, including (1) thermal-mechanical degradation, (2) degradation over time, and (3) complex mixed processing. The polymer is heated and mechanically sheared during melt processing, causing thermal-mechanical deterioration. Chain scission and chain branching are the most typical processes observed in commercial polymers (Beyler and Hirschler 2002). The photooxidation process, due to the mixture of heat, oxygen, light, radiation, moisture, and mechanical stress, causes the degradation of plastic items over their lifetime. Thermomechanical degradation and structural changes in polymers are extremely comparable. When comparing mechanical and chemical recycling, the industry promotes chemical recycling more aggressively, despite the fact that it consumes a lot of energy and does not mitigate CO_2. Chemical recycling, in reality, has its own set of obstacles and disadvantages. The production of fuel from plastic waste through chemical recycling is inconvenient as more CO_2 is released into the atmosphere when this fuel is consumed.

As a result, it is preferable to convert waste into energy (quaternary recycling) in a waste incineration plant rather than using fuel as an intermediary step. If the plastic waste contains too many distinct materials or is too filthy, the quality of the product will be affected, and the entire process will become economically unsustainable. Chemical recycling currently receives more funding than mechanical recycling. A chemical recycling factory, for example, will be developed in Rotterdam, Netherlands. It will convert 360,000 tons of plastic waste to methanol annually. Meanwhile, Air Liquide of France, AkzoNobel Specialty Chemicals of the Netherlands, Enerkem of Canada, and the Port of Rotterdam each spent a total of EUR nine million at the start. The factory is projected to cost around EUR 200 million in total (ChemViews Magazine 2020).

8 Conclusion

PET waste has dominated the world ranging from large pieces of water bottles to tiny-sized microplastics that are harmful to the environment, humans, and wildlife. The recycling method has evolved since the first existed to address the PET waste issues globally and continue to seek ways to utilize rPET. The evolution involving engineering design through reactive blending and chemical approach (i.e., chain extenders and compatibilizer) for rPET blends, as well as the addition of various fillers and fibers for rPET composites has created different high-end products for many industries and offered an economically feasible rPET business.

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