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REVIEW

Recent Studies on Recycled PET Fibers: Production and Applications: a Review

Banafsheh Sadeghi[1] · Yousef Marfavi[2] · Raouf AliAkbari[2] · Elaheh Kowsari[2] · Farshad Borbor Ajdari[3] · Seeram Ramakrishna[4]

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Abstract

Increasing demand for non-biodegradable plastics undesirably leads to their accumulation and calls for an appropriate solution for this global crisis. Environmental impacts of PET waste have long been addressed; although some remedies have been proposed, their extensive use in the modern world use demands new studies and recycling techniques. It shows the inadequacy of previous solutions to eliminate this environmental problem. Therefore, researching this subject should not be considered an insignificant issue. Distinctively, this review article has a specific reliance on the use of recycled PET fibers in the production of high-consumption and value-added products that, in addition to considering environmental aspects, can also be attractive to the market. This article deals with recent studies in three product categories (concrete, nonwoven fabrics, yarns) made from recycled PET fibers and shows the high potential of PET fibers for the future industry.

Keywords Recycled PET fiber · Cement · Nonwoven · Yarn · Life cycle assessment

Introduction

The reduction of making waste in the world and the return of recyclable materials is highly focused by researchers, and due to the increasing need of the international community, attention to solving this crisis is more than before, such that the proposed new methods pay more attention to the economic aspect (AliAkbari et al. 2020). Today, plastics are an integral part of our modern life and have been widely used due to their low cost of production, ductility, molding in different sizes, and some other unique properties (Barnes et al. 2009; Jambeck et al. 2015; da Costa et al. 2016; De Sá et al. 2018). Their applications include packaging, agriculture, electronics, and construction (Idumah et al. 2019). Presumably, the main reason for the plastic waste crisis is their very long life cycle, which makes it necessary to recycle or reuse them (Li et al. 2019a; Li et al. 2019b). The production of polymers in 2018 is reported to be around 359 MTs, and it is predicted that in the next 30 years, the production of these materials will triple (Lebreton and Andrady 2019; Tournier et al. 2020). It is estimated that PET accounts for 18% of the world production (Leng et al. 2018) and 7.4% of European plastics production (Europe 2018). A small amount of this PET waste is recycled, and the rest is left without recycling, regardless of their destructive effects (Chinchillas-Chinchillas et al. 2020). Also, about 1 million plastic bottles are wasted every minute and are estimated to double in the next 20 years (Magnier et al. 2019), and that many of these bottles are made of PET. As the high level of concern about PET waste becomes clear, it is necessary to apply global laws and mechanisms to reduce the pollution of these plastics. Maybe the most important concepts in this regard to reduce plastic waste are the life cycle assessment (LCA) and circular economy (CE) (Lonca et al. 2020), which we will explain in the next paragraph about this

✉ Elaheh Kowsari
Kowsarie@aut.ac.ir

✉ Seeram Ramakrishna
seeram@nus.edu.sg

1 Mahshahr Campus, Amirkabir University of Technology, Mahshahr P.O. BOX 63517-13178, Iran

2 Department of Chemistry, Amirkabir University of Technology, No. 424, Hafez Avenue, Tehran 1591634311, Iran

3 Department of Applied Chemistry, Faculty of Chemistry, University of Kashan, Kashan, Iran

4 Department of Mechanical Engineering, Center for Nanofibers and Nanotechnology, National University of Singapore, Singapore 119260, Singapore

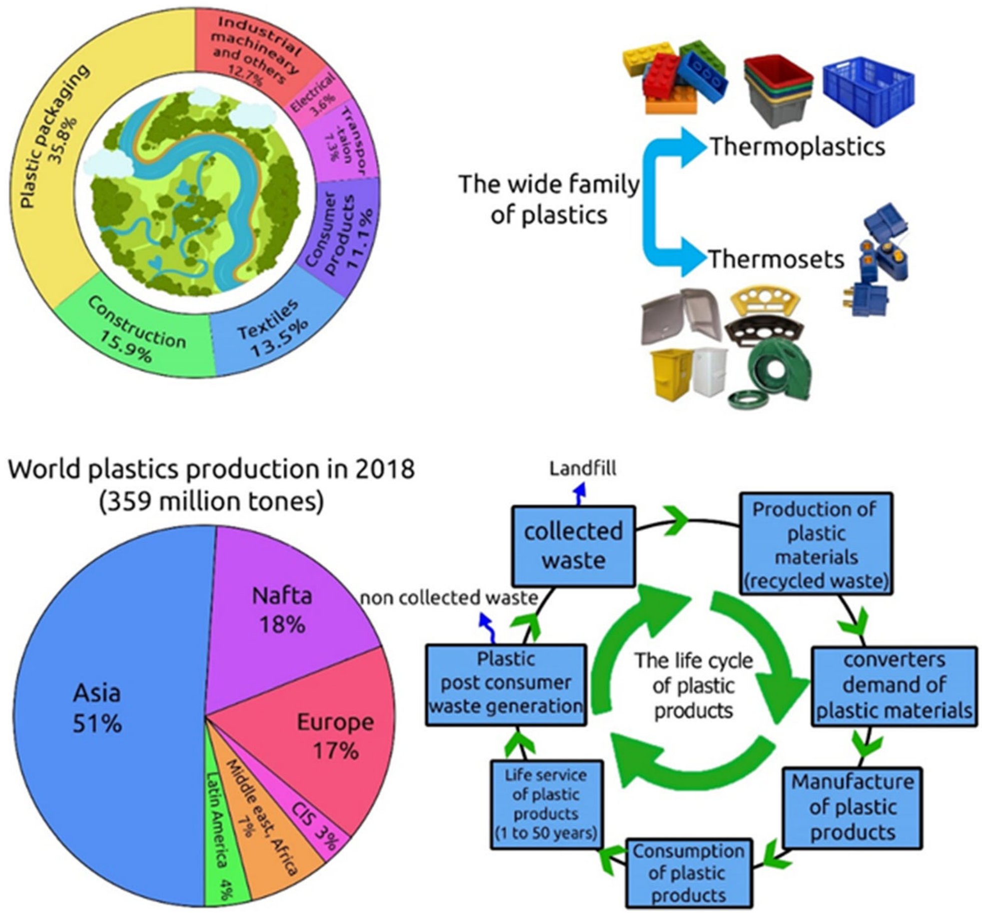


Fig. 1 A summary of the applications of plastics, their production, general classification, and the concept of LCA

concept. Figure 1 summarizes the applications of plastics, production, general classification, and the concept of LCA.

Recycling non-degradable plastics significantly reduces this waste environmental damage by reducing the accumulation in the environment and reducing the need for oil mining (Bataineh 2020a). Life cycle assessment (LCA) is an objective process for assessing the environmental effects associated with certain products, processes, or activities that are performed in the process of recycling PET waste, and shows the recycling results in a significant reduction in biological impact, reducing greenhouse gas (GHG) emissions, and fossil fuel consumption, and eventually, compared with other PET disposal schemes (Saleh 2016; Zhang and Wen 2014; Nakatani et al. 2010; Gomes et al. 2019). High recycling rates lead to high net environmental benefits, so the use of PET waste to product manufacture is increasing that social and environmental values have led to this growth (Foolmaun and Ramjeeawon 2013; Zhang et al. 2020). LCA is an effective method for environmental and economic analysis and management if combined with life cycle costing (LCC) analysis. By considering the systematic quantity of inputs and outputs of targeted products and processes, LCA and LCC can significantly help improve decision-making, products, and policies (Hong et al. 2018; Ye et al. 2018). About the concept of circular economics of plastics and especially PET, this theory should link dynamic research with the prediction of social, environmental, and economic consequences. Also, this theory should provide rational solutions to current misguided policies, and achieve a successful circular economy about to plastics, and studied possible complementarities between chemical and mechanical recycling properties. Fortunately, in recent years, many models have been proposed to achieve the stated goals related to PET (Cámara-Creixell and Scheel-Mayenberger 2019; Majumdar et al. 2020; Sardon and Li 2020; Shi et al. 2020; Velásquez et al. 2020; Bora 2020).

PET production reaction is carried out by ethylene glycol and terephthalic acid or dimethyl terephthalate monomers (Bai et al. 2020). During this reaction, poly-(ethylene terephthalate) is produced as the main product and water/methanol as the byproduct. The reaction is accelerated in the presence of a suitable catalyst (metal oxide or acid). Because the reaction is reciprocating, according to the Le Chatelier principle, by removing the byproducts under vacuum and high temperature, the reaction can be inclined towards polymer production. The reaction steps are as follows: (1) Due to the reaction of monomers, a low-viscosity pre-polymer is produced. (2) Polymer viscosity increases through a melt phase of additional condensation-reaction (> 280 °C). (3) Under vacuum, the esterification reaction products such as H_2O or ROH and further monomers are removed. (4) The melt is expelled into PET pellets (low viscosity). (5) Further condensation is done during a solid-state post-condensation (SSP) mechanism that makes crystalline pellets (Duh 2002; Mendiburu et al. 2020; Wang et al. 2019; Welle 2011; Ravindranath and Mashelkar 1984). PET is produced in 4 commercial grades, which are fiber (textile, and technical and tire cord), film (biaxially oriented PET film, and sheet grade for thermoforming), bottle (water bottles and carbonated soft drink), and monofilament (Gharde 2020; Naz et al. 2020; Bethke et al. 2020; Anjum et al. 2020). A schematic of the PET production and the processes performed can be seen in Fig. 2.

Commonly, the technology of recycling can be categorized into 4 classes, namely primary, secondary, tertiary, and quaternary approaches (Kumar 2020). Product recycling back into the first state is primary recycling or closed-loop recycling. When the recycled product has less physical, mechanical, and chemical properties and even new applications, it is secondary recycling or open-loop recycling. If the process of recycling is done by pyrolysis, gasification, and hydrolysis and waste change to simple chemicals or fuels, it is tertiary recycling. When the heat energy from the incineration of solid waste materials is used in the recycling process, it is quaternary recycling (Esi and Baykal 2020). Recycling post-consumer waste PET bottles and conversion to recycled PET (R-PET) fibers are secondary recycling (Ronkay et al. 2020).

Generally, there are two methods for PET recycling: mechanical and chemical. In general, in the chemical method (16% of recycling), the reverse of the polymerization reaction, i.e., depolymerization, occurs and the primary monomers are obtained (Al-Sabagh et al. 2016; Scremin et al. 2019; Dębowski et al. 2019). Chemical recycling is less used because it causes destructive changes in properties such as mechanical, thermal, and electrical conductivity (El Essawy et al. 2017). The mechanical method, which accounts for 84% of recycling, includes collection, sorting, washing, and shredding (Ragaert et al. 2017; Maris et al. 2018), and due to the disadvantages of chemical recycling, mechanical recycling and products from mechanical recycling use are the best solution for managing this waste (de Lima et al. 2020). Also, incineration and landfill are also two unprincipled methods to prevent the accumulation of PET in some areas, which imposes high environmental damages. Incineration of PET releases large amounts of greenhouse gases and toxic substances into the atmosphere, which is contrary to the goals of a low-carbon economy (Zander et al. 2018; Zheng and Suh 2019; Song and Hyun 1999).

Given the environmental hazards of PET waste and the acceptable performance of mechanical recycling, we want to study on PET mechanical recycling in recent years. The

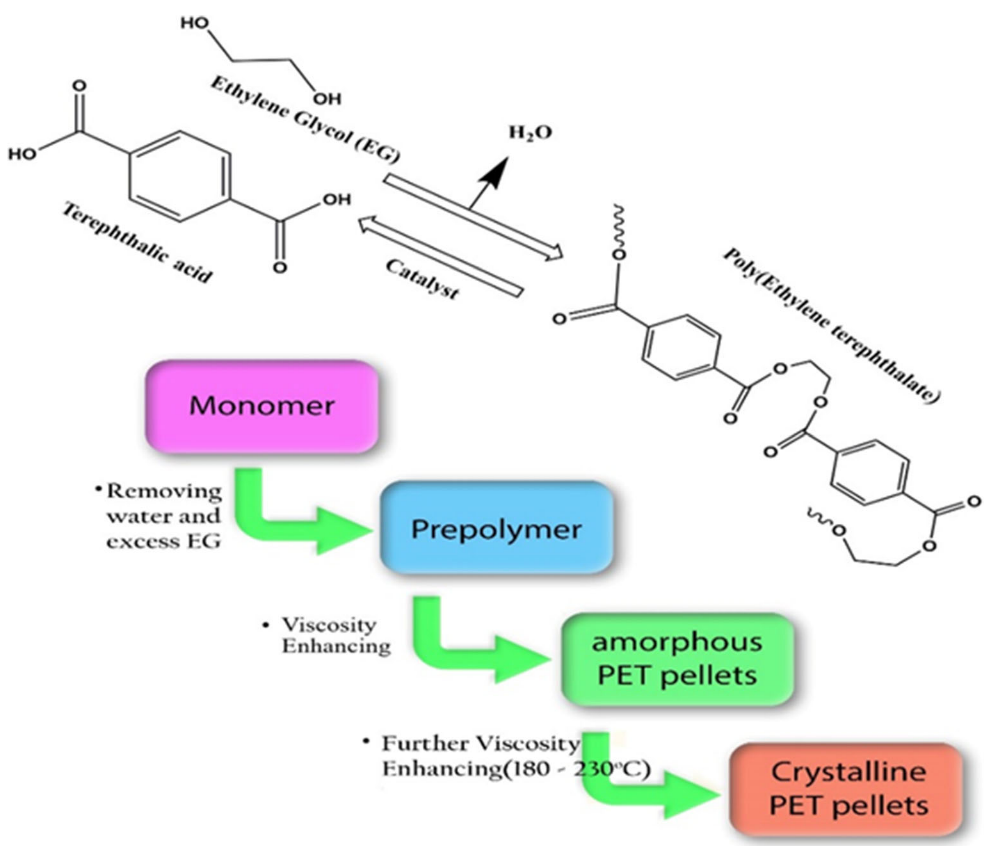


Fig. 2 PET production

difference between this review article and with most of the studies in the use of recycled fibers is that this article is specifically dedicated to recycled PET fiber applications, and our aim in this paper is to elucidate the high potential of recycled PET fibers in various products.

Products Made from R-PET Fibers

The polyester used in bottles can also be applied to produce fibers, especially filament yarn, although this is a new issue and has become an interesting topic for environmentalists (Abbasi et al. 2020). Bottles and containers of PET by a mechanical process change to fibers and other products which is a simple, cost-effective, and environmentally friendly process (Albini et al. 2018). Figure 3 shows the products that are outcome by PET recycling.

In the recycling process, small flakes from the bottles go into the dryer and after drying, they enter the extruder, then after the extrusion process, they turn into yarn and fabric (Montava-Jorda et al. 2020). Doan et al. (Doan et al. 2020) prepared R-PET fibrous membrane by electrospinning and applied them as an oil-water separator. Nonwoven fabrics, air filters, and smoke filters are another product from different applications of recycled PET fibers. Because of increasing worries about environmental air pollution, filtration is one of the best applications for ultra-thin R-PET fibers. R-PET nonwoven fabrics due to their porous structure, mechanical properties, and low cost of production are used in dust filtration (Strain et al. 2015). Also, the flakes can be cut and used to reinforce concrete. Recycled PET fibers have the potential to replace virgin PET (V-PET) fibers, and further research can uncover the potential of these fiber applications. For this purpose, in the following, we reviewed three applications of recycled PET fibers.

Concrete

The construction sector and cities in Europe are responsible for 50% of greenhouse gas emissions, and the cement and steel industries account for 10–12% of total greenhouse gas emissions (Favier et al. 2018). In recent years, new approaches to building materials have been developed to reduce greenhouse gases (Zhao et al. 2020; Rasmussen et al. 2020). About cement production, low-carbon approaches can reduce greenhouse gas emissions by up to 80% (Giesekam et al. 2016). The use of recycled materials in concrete production can greatly contribute to the goals of low carbon and circular economics (Nasr et al. 2020); it is also important to reduce the cost of concrete production (Mariri et al. 2019). One of the techniques to reduce the hazardous impact of PET waste on the environment and reduce the costs of building material is to recycle it as a building material as an alternative to sand or fibers added to concrete (Adnan and Dawood 2020). Recycled fibers used in concrete can be prepared in two ways: (1) after collecting used bottles, they are washed, dried, and cut to specific dimensions (de Luna and Shaikh 2020). (2) Pellets R-PET bottles are melted, 20–100 fibers are then extruded from the nozzle, and are drawn into fibers (Ochi et al. 2007). Finally, the fibers produced in both methods are used in the concrete production stage.

The data in Table 1, which are collected in connection with the use of recycled PET fibers in concrete, provide

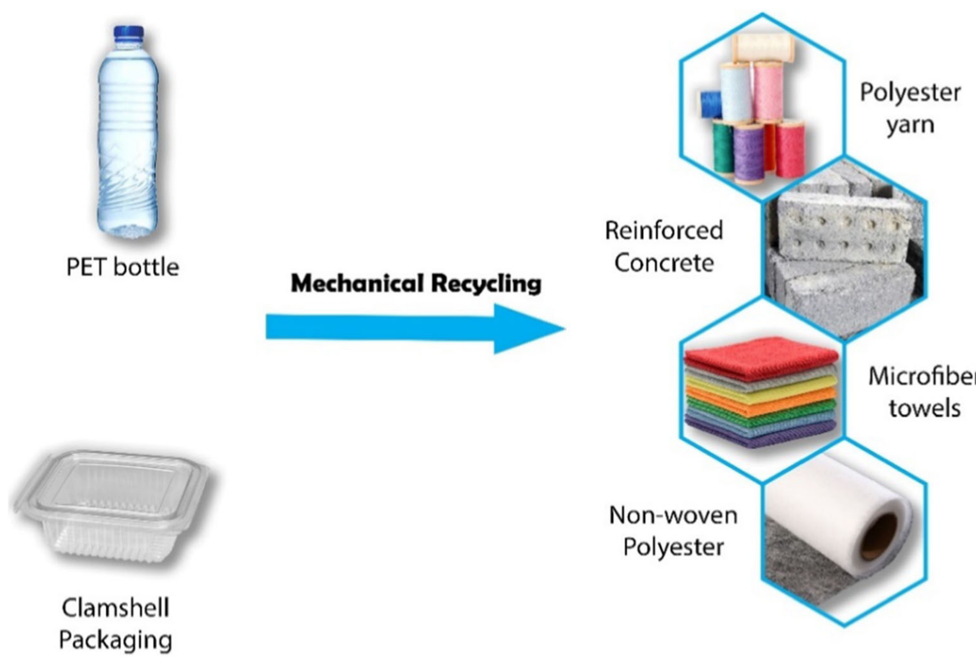


Fig. 3 Recycled PET products

Table 1 Addition of recycled PET fibers to cement and concrete

Type of fiber	Methods and important findings	Ref.
PET waste fiber	The amount of PET fiber in concrete (short or mixture of short and long fibers) = 0.75%: 1 - Compressive strength range = 70.15 to 89.82 MPa 2 - Maximum strength reduction = 29.81% 3 - Elastic modulus enhancement = 21.8% 4 - Tensile strength loss range = 9.1–13.6% 5 - Tensile strength range = 83.03–96.33% 6 - The presence of PET recycled fibers in concrete had a relatively good effect on crack control. 7 - Recycled PET fiber–reinforced concrete had a relatively small effect on the final load capacity.	(Mohammed and Rahim 2020)
Recycled PET Fiber	1 - Residual strength measured of 7% (JSCE standard) 2 - Tensile strength = 104 3 - Pullout stress = 63 4 - Demonstrated anisotropy in the tensile capacity and theory of failure (Mohr criterion) 5 - Negligible PET anisotropy 6 - Superior interfacial bond performance 7 - Similar flexural strength (regardless of fiber lengths) 8 - The number of bridging PET fibers diminished flexural load capacity.	(de Luna and Shaikh 2020)
PET waste	PET volume 0 to 15%: 1 - Increased Fracture energy (0% to 15% PET) 2 - Fracture energy: 2.1 - Normal concrete up to 41.3 N/m (initial value = 31.3 N/m) 2.2 - Rubberized concrete up to 55 N/m (initial value = 42.8 N/m) 3 - Lowered brittleness number 3.1 - Normal concrete: 35.2% 3.2 - Rubberized concrete: 22.5% 4 - Increased C_f, in size effect method (SEM) and $\boldsymbol{a}_\infty^*$ in boundary effect method (BEM) 5 - Decreasing tensile strength with PET increasing 6 - Increasing surface coarseness 7 - Observing bridging of flaky shape PET particles between two cracked surfaces in a tensile fracture 8 - Growing concrete ductility 9 - Lower PET value leads to linear elastic fracture mechanic	(Nikbin and Ahmadi 2020)
Waste PET bottle	The percentages of fiber used were 0.5, 1.0, 1.5, and 2: 1 - Best results in 1% of PET: 36.3 MPa for compressive strength of concrete mix at 7 days and 43.5 MPa for 28 days observed 2 - Fine aggregates (FA): 0.075–5 mm/coarse aggregates (CA): 5–20 mm/the dimensions of PET fibers: 25 × 5 mm 3 - Ultrasonic pulse velocity (UPV) method was used to measure strength in situ of concrete 4 - Ordinary Portland Cement (OPC) was used 5 - As the volume of PET increased, the plasticity of fresh cement decreased. 6 - Due to the negative effect of increasing the water ratio, plasticizer or water reducing admixtures are used. 7 - Microcracks and macrocracks due to compressive loading were observed in the space between the fibers.	(Manaf et al. n.d.)
PET waste fibers (PETWF)	In this study, hand fibers are regular-shaped fibers, and machine fibers are irregular-shaped fibers. 1 - The optimum percentage of PET is 1.5%, and the maximum fiber limit for the production of homogeneous concrete is 3%. 2 - Compressive strength: 2.1 - Machine fiber: 2.1.1 - 3% PET: +1.5%	(Adnan and Dawood 2020)

Table 1 (continued)

Type of fiber	Methods and important findings	Ref.
	2.1.2 - 1.5% PET: +2.11% 2.2 - Hand fiber: 2.2.1 - 3% PET: −17.75% 2.2.2 - 1.5% PET: +42.08% 3 - Flexural strength (10×10×50 cm^3): 3.1 - Machine and hand fibers had little effect on flexural strength 4 - Load deflection: 4-1 A slight reduction in the ultimate load. However, it showed a positive effect on the ductility of concrete (2 to 5 times the reference beam). 5 - NC was used 6 - As the amount of PET in fresh concrete increases, its workability decreases. 7 - In general, the presence of PET in cement reduced the flexural strength and improved the compressive strength (as an exception, the 1.5% PET mixture increased the flexural strength). 8 - Prevents concrete from breaking 9 - In the presence of PET, initial stiffness increases and secant stiffness decreases.	
PET waste fibers (PETWF)	1 - Improved the flexural strength 1.1 - With optimum PET fibers: 1% 1.2 - Decreased compressive strength >2% PET 2 - 33% lower dry density 3 - Increase in permeability coefficients (improving water permeability) 4 - Adding expanded polystyrene (EPS) and PET: better porosity ratio 5 - Adding PET fibers: improve abrasion resistance	(Ali et al. 2020)
Recycled waste PET bottle Fiber (RWPBF)	1 - The percentages of fiber used were 0.2, 0.4, 0.6, and 0.8, which showed the best results in 0.4% in the second mix, which contained 10% metakaolin (MK). 2 - The dimensions of PET fibers: 50×2–2.3 mm/tensile strength of RWPBF: 989 MPa/elastic modulus of RWPBF: 0.705 × 10^4 MPa 3 - The percentage combination was used to prepare M50 grade concrete. 4 - In the first mix, all Ordinary Portland Cement (OPC) was used and in the second mix, 90% of OPC and 10% of metakaolin (MK) were used. 5 - In this study, waste-recycled PET bottles were cut non-instrumentally. 6 - Formaldehyde sulfonate was used to increase the flowability. 7 - RWPBF was added after mixing dry cementitious materials and water in the final stage and then molded. 8 - There was a decrease in the slump in all percentages of fiber. 9 - For a mixture containing 10% MK and 4% RWPBF, a 10.67% and 84.6% improvement in compressive and tensile strength was observed, respectively.	(Thomas and Moosvi 2020a)
Waste PET bottle	1 - Dimensions of PET fibers: (40 × 3.5 × 0.3) mm and added at 1% vol% 2 - The reduced flowability of the mixture with PET fibers because of cross-crossing and cluster formation and high specific surface area of them. 3 - Compressive strength of mixtures containing PET fibers decreased. 4 - The presence of PET fibers improves the final flexural strength at the ages of 28 and 90 days because of the capability to absorb a portion of the load applied by them. 5 - The presence of PET fibers in cement mixture resulted in ductile behavior, improving the splitting tensile strengths and enhancing tensile strain capacity, and decreasing elasticity modulus. 6 - Increasing in flexural characteristics and energy absorption capacity of concrete slabs is a result of addition of PET fibers. 7 - A mixture of 50% Ultrafine Palm Oil Fuel Ash (UPOFA) and 20% Silica Fume (SF) as a binder with cement, and 1 vol% PET fiber was prepared. 8 - Stabilize the generation of cracks and with increasing stress under a compression load absorbed a part of the deformation.	(Alani et al. 2020)

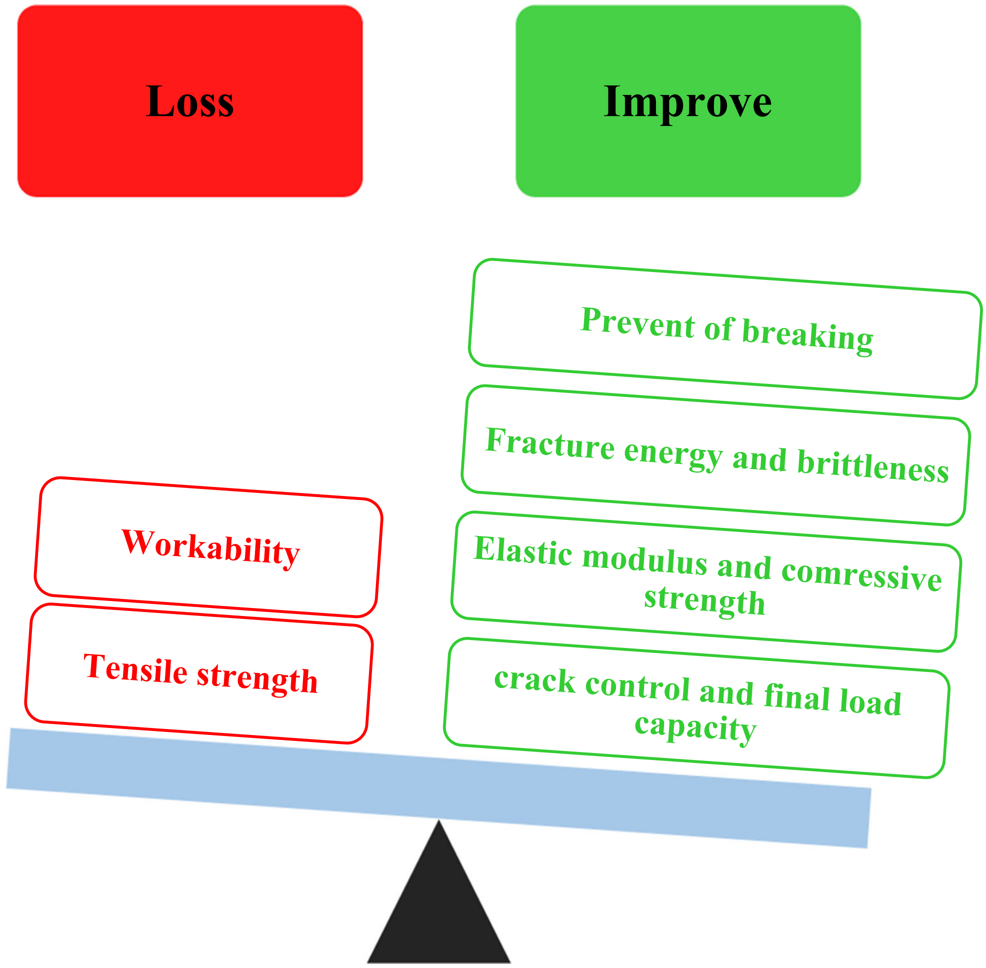
Table 1 (continued)

Type of fiber	Methods and important findings	Ref.
	9 - The bridging effects of PET fibers inhibit the development of cracks and with increasing stress under a compression load absorbed a part of the deformation.	
Recycled Waste PET bottle fiber	1 - Recycled PET fibers were cut to a length of 20 mm. 2 - Samples with PET fibers result in increasing ductile failure. 3 - PET fiber remarkably enhanced the unconfined compressive strength (UCS) of the stabilized soil. 4 - With the addition of PET fiber up to 0.5%, UCS and residual stress enhanced. 5 - For 4% cement, UCS_{max} is created in 0.5% PET fiber. 6 - The addition of PET fibers into the zeolite-cement-loess mixture cause to prevent cracks and increase cohesion and tensile strength due to friction between PET and soil particles. 7 - For treated loess with cement and 10% zeolite, the secant elasticity moduli (E_{50}) with a different content of PET fiber reduced. 8 - Bond strength and friction between the fiber and the soil matrix improve due to attaches their surface into soil particles. 9 - Improving soil strength is arising from graining interlock soil into a unitary coherent matrix because a lot of the fibers function as a spatial three-dimensional mesh. 10 - After tension cracks formation, PET fibers as bridges stopped crack expansion.	(Mariri et al. 2019)
Recycled PET fibers	The percentages of fiber used were 0,0.5, 1.0, and 1.5: 1 - Best results in 1% of fiber; 15.3%, 22.4%, and 18.7% increase in compressive strength, flexural strength, and tensile strength were observed, respectively. 2 - 0.7 mm and 50 ±mm are the length and diameter of PET fiber respectively 3 - 20% cement was used in the mix used and also optima-100 used as an admixture. 4 - In this experimental study, the application of PET fiber in floor concrete has been studied and analyzed. 5 - Compressive strength of concrete in combination with low percentages of PET fiber increased and then with increasing PET fiber, compressive strength decreased. 6 - Flexural strength and energy absorption increased by 0 to 1.5% of PET fiber. 7 - With an increasing percentage of PET fiber, the parameter slump showed a downward trend. 8 - In the test of impact resistance of concrete with 1% PET fiber, it showed about twice the superiority of concrete with 0% PET fiber.	(De Silva and Prasanthan 2019)
Recycled PET fiber from the chopping of PET bottles	1 - Compressive strength of mixture reduced with enhance in fiber content. 2 - ACG mixture shows a higher compressive strength than two another. 3 - The compressive strength of geopolymer mixture with PP fibers is higher than the same mixture with PET fibers. 4 - Flexural strength of ACG composite contains PET fiber is enhanced with the amount of fibers from 1 to 1.5 vol% but no remarkable increase in CC and CFA. 5 - All of the mixtures with PET fiber have higher tensile strength than the same ones with PP fiber. 6 - Tensile strength of ACG with 1.5 vol% PET fiber is the lowest one. 7 - Extension capacity at peak load of mixtures with PP fiber is higher than PET fiber. 8 - Three mixes with 1 and 1.5 vol% PET and PP fibers: (a) ambient cure geopolymer (ACG), (b) cement composites (CC), and (c) cement-fly ash (CFA) composites 9 - Interface bond of PET with ACG is the lowest one.	(Shaikh 2020)

information about the physical and mechanical properties of concretes containing these fibers.

Concrete has relatively low tensile strength, low ductility, and is prone to cracking (De Silva and Prasanthan 2019). The information in Table 1, in addition to confirming the improvement of the mechanical and physical properties of concrete, in the presence of PET fibers, clarifies the fact that the fibers prevent cracking or expansion of cracks. It has also been proven that the presence of fibers prevents corrosion processes in reinforced concrete structures. It can be said that the main function of fibers is to improve the strength and durability of the structure by preventing the formation of microcracks that occur naturally in the early stages of the life of the structure, which is known as the "sewing effect" (Foti 2019). In general,

Fig. 4 Comparison of increasing and decreasing properties of recycled PET fibers on concrete



concerning the studied parameters, PET fibers increased flexural strength, ductility, and unconfined compressive strength (UCS) and decreased drying shrinkage of mortar, total porosity, and compressive strength. This technique is attractive, both economically and environmentally. Also, the information presented in Table 1**,** that was collected from recent studies, confirms the improvement of the physical and mechanical properties of the resulting concrete. The important effects of PET fibers on concrete can be seen in Fig. 4 comparatively. Given the attractive advantages mentioned, it can be hoped that recycled PET fibers will be widely used in concrete. Of course, to achieve this goal, in the future, efforts must be made concerning the following: esthetic improvement of these building materials, better physical and mechanical performance, reduction of production costs, more attention to research and development units, and so on.

Nonwoven

Various definitions have been given for nonwoven fabrics (Karthik and Rathinamoorthy 2017a). Nonwoven fabrics, unlike woven fabrics, are made directly from short or long fibers

Fig. 5 The structural differences between nonwoven and woven fabrics

Table 2 Use of recycled PET fibers to produce nonwoven fabrics

Type of fiber	Methods and important findings	Product	Ref.
Recycled PET bottle flakes	1 - Air permeability in R-PET filters was 7–15% higher than V-PET and so filtration efficiency can be better. 2 - Enhancing fabric weight (GSM) caused decrease air permeability of nonwoven fabrics with both of R-PET and V-PET. 3 - GSM optimum for R-PET filter fabrics is 504 g/m2. 4 - Fiber fineness is 1.66 decitex, staple length is 42 mm, and crimp density is 10 crimps/cm. 5 - Higher inter-fiber cohesion and better interlocking of fibers during needling in V-PET was caused by higher surface roughness than R-PET.	Filter fabric medium	(Debnath et al. 2020)
Recycled PET bottle flakes	1 - Enhancing GSM caused higher filtration efficiency of nonwoven fabrics manufactured with R-PET and V-PET such that V-PET filter fabric (VPFF) always 2.11–3.54% higher than R-PET samples. 2 - Dust-holding capacity in R-PET filter fabrics is better than V-PET samples. 3 - R-PET fibers compared with V-PET fibers have a lower surface roughness causing less cohesion of inter-fiber in them. 4 - GSM optimum for R-PET filter fabrics is 597 g/m2. 5 - Denier, staple length, and staple length of V-PET fibers and R-PET fibers are 1.5, 42 mm, and 10 crimps/cm, respectively.	Dust filter	(Chauhan et al. 2020)
Recycled high-strength PET	1 - The tensile strength of thermal bonding points is lower than high-strength PET fibers. 2 - Increasing the amount of recycled high-strength PET fibers resulted in higher tensile and tear strengths. 3 - PET matrices nonwoven fabrics have low porosity and compact structure. 4 - PET fibers reduce the synergistic effect with LMPET fibers. 5 - The sample contains a lower amount of LMPET fibers which has the highest tensile strength. 6 - The sample contains 10 wt% of LMPET fibers, and 90 wt% of recycled high-strength PET fibers showed the maximum tearing strength. 7 - The sample with a lower amount of LMPET fibers has the highest bursting strength. 8 - Fiber fineness is 1000D/192f, fiber length is 40–65 mm, and single fiber strength is 8 g/d. 9 - Wavy or crimp staple fibers enhance the friction. 10 - The ratio of PET staple fibers to low-melting-point PET (LMPET) fibers was 9:1, 7:3, and 5:5.	Flexible stab-resistant hybrid fabric	(Chuang et al. 2019)
(1) V-PET, (2) R-PETPC, and (3) R-PETPC/PI	1 - All fabrics have enough tensile and tear strength for vehicle needs. 2 - R-PETPC/PI surface after the esthetic wear resistance test has not a good answer. 3 - V-PET and R-PETPC fabrics have well wear resistance and high mechanical properties. 4 - R-PETPC can be a good alternative to V-PET textiles in the automotive. 5 - V-PET is virgin PET fibers; R-PETPC is post-consumer recycled PET fibers; and R-PETPC/PI is a blend of post-consumer and post-industrial PET	Vehicle seat cover	(Albini et al. 2018)
Recycled Kevlar fibers and recycled high-strength PET fibers from wasted selvage of Kevlar and PET woven fabric.	1 - Air permeability reduced with the enhancing of PET fibers. 2 - P300 with a depth of needle 15 (P300–15), indicated the lowest air permeability. 3 - Tensile strength, tear strength, and burst strength enhanced as gaining of the number of staple fibers such that P300-15 has the highest one such that tensile strength, tear strength, and burst strength is 400 N, 397 N, and 1957 N, respectively. 4 - Percent ratio of 50/20/30, nylon fibers, recycled Kevlar® fibers make N/K/L-PET high-strength surface layer. 5 - For low-melting polyester fiber (L-PET) in the surface layer, fiber fineness is 4 D and fiber length is 51 mm; for recycled high-strength polyester fiber (R-HPET) in the core layer, fiber fineness is 1000 D, and fiber length is 66 mm. 6 - P100, P200, and P300 have 100, 200, and 300 g/m^2 recycled PET wasted selvage, respectively.	Sandwich-structured nonwoven fabric	(Lin et al. 2020)
Recycled rapid-melting PET fiber (R-RM fiber)	1 - Dyeability of R-RM nonwovens > virgin (V-PET) yarn > V-PET fabrics. 2 - Dyeability was enhanced by enhancing temperature, time, and liquor concentration. 3 - Sweat fastness shows in grades 4–5 in both acid and alkaline environments. 4 - The rubbing and sweat fastness properties were great. 5 - R-RM nonwoven was dyed uniformly and has a high thermal stability. 6 - *Terminalia chebula* (*T. chebula*) is an economical natural brown dye and was applied for dyeing recycled rapid-melting PET fiber (R-RM) nonwovens. 7 - Because of bulky aromatic rings in PET fibers, they are hydrophobic and so dyeing them is more difficult.	Automotive interiors	(Lee et al. 2020)
Rapid-melting PET (RMPET)			

Table 2 (continued)

Type of fiber	Methods and important findings	Product	Ref.
	1 - The chemically recycled bicomponent polyester fibers could substituted for virgin bicomponent polyester fibers very well. 2 - Thermal bonding between the fibers and thermal shrinkage in R-RM than the virgin was produced faster. 3 - Sample weight enhanced with higher temperature and time. 4 - The thickness of R-RM nonwoven fabrics reduced with temperature and time. 5 - Thermal shrinkage of the nonwoven fabrics enhanced by going up the temperature. 6 - R-RM nonwoven fabrics have better thermal shrinkage than the virgin. 7 - In higher temperatures, the strength of the R-RM enhanced, but wickability and air permeability of them reduced. 8 - Tensile stress and modulus of the recycled PET nonwoven fabrics enhanced slowly by going up the temperature. 9 - Chemically recycled bicomponent PET fibers were compared with virgin bicomponent PET fibers and because of similar properties, they can substitute for them.	Nonwoven fabrics for automotive interiors	(Choi et al. 2018)
Recycled PET Fiber-driving bottle	1 - In this study, 7 samples were tested, one sample of virgin fiber PET was used, six samples of recycled fiber PET taken from bottles were used and one sample of bicomponent PET was used. 2 - The optimal composition selected contained 85% recycled PET and 15% bicomponent PET, which suggested that it could be used instead of 80% virgin PET and 20% bicomponent PET. 2 - In general, fibers with longer lengths showed better abrasion resistance in the final product. 3 - The virgin PET had more tenacity and less elongation than the other samples. 4 - In this article, recycled PET fibers are used in the made of nonwoven automotive carpets with high abrasion resistance by the needle-punching process. 5 - In order to achieve economic and environmental goals, recycled PET fiber along with virgin PET fiber was used to make the product with acceptable quality. 6 - Replacement of recycled PET in the percentage used in the final product can bring significant economic benefits to the manufacturer, which was investigated in this study.	Nonwoven fabrics	(Atakan et al. 2018)
micro R-PET fibers and PLA	1 - R/Z-PET/nano-PLA mat has a high filtration efficiency of 99.992%, a low-pressure drop of 201.11 Pa, and the quality factor value of 0.047 Pa^{-1}. 2 - Nano-PLA membrane helped with the filtration yield of mats. 3 - Fluffy zigzag-curved R-PET fibers provide a greater chance for particles to move within the filtration material. 4 - The fluffy structures remarkably reduce the rate of pressure drop and increase the dust-holding capacity of mat. 5 - Micro R-PET fibers are the matrix fiber web; the nano-scale electrospun PLA membrane is the fluffy functional filtration layer. 6 - The fiber fineness: R1.5/N-PET of 1.5 denier (linear shape), R2.5/N-PET of 2.5 denier (linear shape), R/S-PET of 7 denier (S-shaped), and R/Z-PET of 7 denier (zigzag-shaped).	Air filtration	(Deng et al. 2019)

by various methods; for example, one of the general and traditional nonwoven fabrics is felt (Müller and Saathoff 2015; Jhang et al. 2020). The structural differences between nonwovens and woven fabrics are shown in Fig. 5 (Karthik and Rathinamoorthy 2017a). Nonwovens can be produced with 3 processes: dry-laying, wet-laying, and extruded polymer-laying (Pourmohammadi 2013). The raw materials for the dry-laying method are textiles; for the wet-laying method they are paper materials; and finally, in the extruded polymer-laying method, melted plastics are used (Durga and Kalra 2020). Spunbonded nonwovens are mainly produced in 3 steps: (1) filament spinning, (2) web formation, and (3) web bonding (Ding et al. 2020). To use recycled PET bottles in the extruded polymer-laying method of nonwoven production, first, the used bottles are cut into flakes, and after washing and drying, they are transferred to the extruder, and the melted PET is used to produce nonwoven fabric in this method. In Fig. 5, you can see the differences between knitted, nonwoven, and woven fabrics.

Fusible nonwoven fabric has been so popular since the mid-twentieth century that it accounted for 80% of the market in the early twenty-first century. At first, these products were connected with the help of binders, and then in the 1960s, the first binder-free nonwoven was produced. In the 1970s, the production of nonwoven began in Kaiserslautern and the industry gradually expanded around the world (Karthik and Rathinamoorthy 2017b). One of the attractions of producing nonwoven fabrics versus woven fabric is its low production cost (Jeon 2016). The other is the ability of nonwoven fabrics to be expanded, followed by the expansion of the market for nonwoven fabrics (). The applications of nonwoven fabrics are

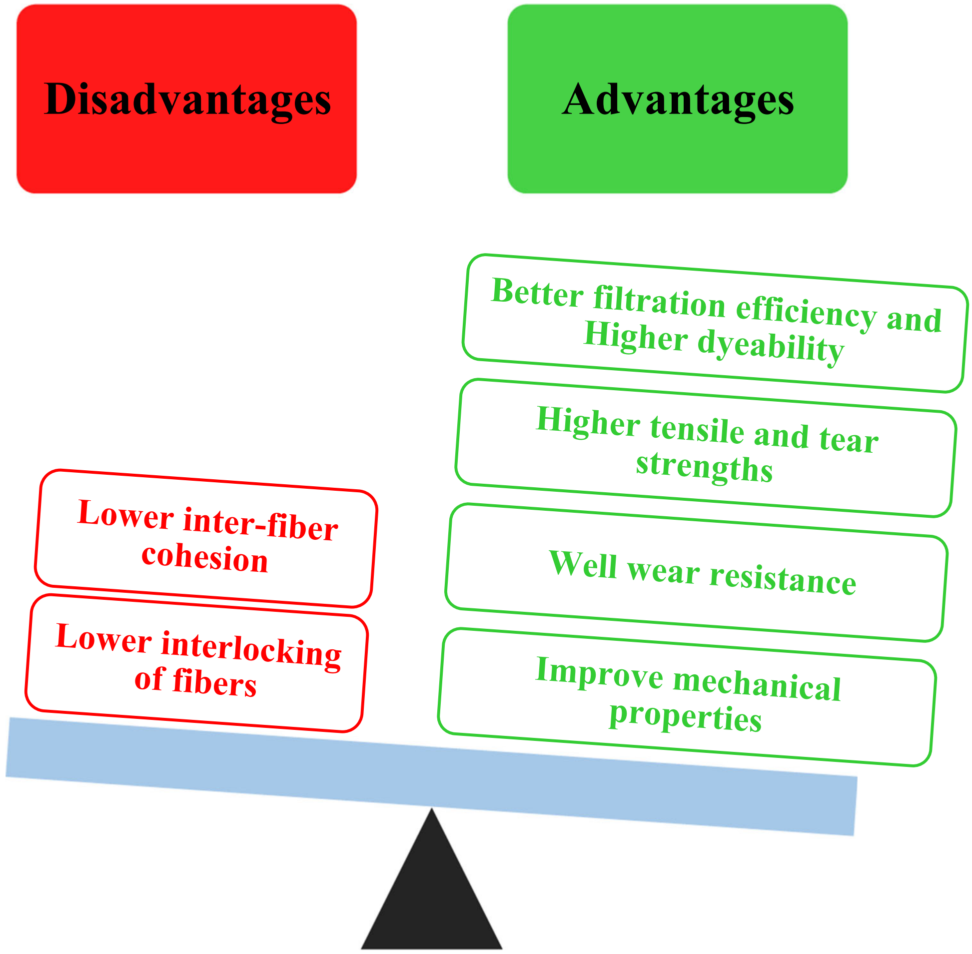


Fig. 6 Comparison of increasing and decreasing properties of recycled PET fibers on nonwoven

very wide, such as sound absorber (Özkal and Cengiz Çallıoğlu 2020), apparel (Anderson 2005), medical textiles (Mothilal et al. 2019), automotive textiles (Atakan et al. 2018), filters (Chauhan et al. 2019), sanitary masks (Opálková Šišková et al. 2020), and packaging (Lin et al. 2018).

The main chemical fibers used in the production of nonwoven fabrics are rayon viscose, polyester, polyamide, and polypropylene. PET is the main raw material of fiber polymers and recently microfiber nonwoven added to the applications of PET (Albrecht et al. 2006). Today, it can be said that all PET waste is recycled. Three quarters of the total production costs of PET fibers are related to its raw materials; so one of the main ways to reduce the production costs of these fibers is to use recycled PET materials (Altun and Ulcay 2004). The same is true of the fibers used in nonwoven fabrics. Hence, from an economic and environmental point of view, the use of recycled PET in the production of nonwoven fabrics has attracted a lot of attention. In Table 2, we summarized the recent researches on the producing nonwoven fabrics from recycled PET fibers.

Based on the results in Table 2, nonwoven fabrics prepared from recycled PET can be applied to filter fabrics, automotive interiors, vehicle seat cover, flexible stab-resistant hybrid fabric, etc., and lead to reduce environmental pollution. Also, due to reducing the cost of raw materials in the production of these products, the production cost is reduced. As can be seen from the comparison chart in Fig. 6, the use of PET recycled fibers can bring attractive benefits to manufacturers.

Yarn

From 1998 to 2013, the consumption of textile fibers per person enhanced by approximately 1.5 times, and by 2050 will be twice. Nearly 63% of the textile fibers are made from petrochemical materials, and polyester is the most popular fiber in the textile industry (Majumdar et al. 2020). Recycling reduces the storage and transportation of wastes and makes new economic and environmental trends (Sarioğlu et al. 2020). In the last years, R-PET production has enhanced dramatically, but just 30% of PET bottles were recycled. R-PET fibers are 20% cheaper than other ones with similar physical properties (Abbasi et al. 2020). Therefore, their use in the textile industry, that has a major role in the trade of any country, has been considered. Recent studies on the use of recycled PET in yarn production are shown in Table 3. The recycling process of polyester staple fibers from the post-consumer PET bottle was indicated in Fig. 7.

Table 3 Use of recycled PET fibers to produce yarn

Type of fiber	Methods and important findings	Product	Ref.
R-PET from irregular garbage bottles	1 - Density, thermal properties, X-ray diffraction, and tensile and crimp properties of FG-, BG-, and R-PET changed with enhancing the total draw ratio. 2 - No enhancement in the elongation at break was observed. 3 - R-PET crystals' lateral dimension is developed satisfactorily. 4 - V-PET yarns than R-PET have a higher crystallinity of drawn so heat stabilization of them is harder. 5 - The crimp properties of R-PET than BG and FG-PET were better. 6 - In this study, the production of filament yarns is compared with the recycled pet and virgin pet (fiber grade (FG-) and bottle grade (BG-)). 7 - R-PET has an intrinsic viscosity of 0.75 and a density of 1.383 g/cm^3.	Filament yarns	(Abbasi et al. 2020)
Cotton (Co) and viscose (Cv) blend with R-PET fiber	1- Ring-spun yarns than vortex-spun yarns have better strength. 2 - Cv/R-PET ring-spun yarns had the best elongation. 3 – Vortex-spun than ring-spun yarns have higher unevenness. 4 - Co/R-PET vortex-spun yarns have the highest imperfection index. 5 - Enhancing the amount of r-PET in ring-spun yarns from in both blends, the hairiness of the ring-spun yarn a little reduces. 6 - Yarns were produced by a ring spinning system and a vortex spinning system 7 - Yarns have 19.7 tex linear density with various blend ratios of Co/r-PET and Cv/r-PET.	Vortex-spun yarn and ring-spun yarns	(Sarioğlu et al. 2020)
Recycled PET staple fiber	1 - The higher level of crystallinity in V-PET than R-PET resulted in the lower T_m of it. 2 - In R-PET was observed the double melting peaks. 3 - V-PET than R-PET absorbs more energy during melting. 4 - The degree of crystallinity was 51% for V-PET and 48% for R-PET. 5 - Tenacity of R-PET fiber is 15% lower than that of V-PET fiber. 5 - Enhancing the content of R-PET has resulted in decreasing thermal resistance and raising bending and shear rigidity of the woven fabric. 6 - Mechanical properties of R-PET fiber blended with cotton and V-PET were analyzed. 7 - R-PET had linear density of 1.4 denier and staple length of 32 mm. 8 - The performance of V-PET and R-PET fibers is not similar.	Fiber, yarn and fabric	(Majumdar et al. 2020)
R-PET flakes	1 - Smoothness, tensile strength, and thermal shrinkage of the fibers and air permeability of the fabrics were affected by the kind of clay. 2 - Heat resistance and limit oxygen index of R-PET fibers were enhanced with the presence of clay. 3 - Dispersion of clay has a remarkable effect in the properties of R-PET fibers. 4 - 30B had the highest uniformity, thermal stability for boiling, and air permeability of the fabric. 5 - 15A had the highest strength and elongation at break. 6 - R-PET had IV of 0.62 dl/g. 7 - Four types of organically modified montmorillonite clay (Cloisite 10A, 15A, 20A, and 30B) used for R-PET/nanoclay nanocomposites.	Multifilament fiber and fabrics	(Kiliç and Yilmaz 2020)
Waste PET bottles and virgin PES yarns	1 - Fabrics including both R-PET and V-PES yarns have enough strength as upholsteries. 2 - The weft-breaking strength of fabrics containing 100% r-PET did not change significantly. 3 - The strength and elongation of fabrics did not change with changing raw materials of chenille yarns. 4 - Strength and elongation of fabrics were affected by Binder yarn count. 5 - Binder and pile yarns were made from Nm 68/2, Nm 47/1, and Nm 68/1 yarns. 6 - Nm 68/2 yarn was made from folded Nm 68/1. 7 - Chenille yarns of r-PET yarn were applied as weft.	Binder, pile and chenille yarns and upholstery fabrics	(Esi and Baykal 2020)
R-PET from bottles, FG-PET, and BG-PET	1 - The structure was affected by the draw ratio. 2 - Enhancing the draw ratio resulted in going up the tenacity and initial modulus. 3 - BG- and R-PET than FG-PET have better tensile properties. 4 - No obvious boundary between FG-PET and R-PET was seen, so it had good adhesion. 5 - Shrinkage difference in FG/R-PET was better than FG/BG-PET, so it indicated higher crimp properties. 6 - Virgin FG-PET has IV of 0.6 and a density of 1.38 g/cm^3; R-PET has IV of 0.75 and a density of 7.383 g/cm^3; and BG-PET has IV of 0.82 and a density of 1.40 g/cm^3. 8 - Bicomponent fiber was made from FG/BG, R/BG, and FG/RPET.	Bicomponent fibers	(Abbasi and Kotek 2019)

Fig. 7 Process of producing recycled polyester fibers from R-PET

There is little literature on the properties of R-PET spinning and yarn production (Abbasi et al. 2020). In Table 3, we summarized the research conducted to produce yarn and fabric from recycled PET.

According to the results in Table 3 and by comparing mechanical and thermal properties of R-PET and V-PET for yarns, it can be concluded that the use of recycled PET yarns in the production of more stable and environmentally friendly fabrics will be useful. Due to the cost-effectiveness of these materials, studies conducted in this path can be attractive for the textile industry with different applications. If necessary, these fibers can be blended with other polymers and create the required properties of each application. Figure 8 shows a comparison of the advantages and disadvantages of using recycled PET in yarn production.

Summary and Outlook

Integrated recycling systems for plastics are essential, especially in situations where export and landfilling are not available (Sheldon and Norton 2020). In Fig. 9, you can see the price differential in the form of virgin PET minus recycled PET flakes based on S&P Global Platts' reports (Platts, and P. Global, S&P Global Platts 2018). This chart shows the approximate price difference between virgin and recycled PET from 2008 to 2019, and surprisingly in 2019, the price of recycled PET is higher than the virgin one. This is because of the easier access to virgin PET. The high volume of extraction of gas and light petroleum liquids, as well as greater access to new ethylene crackers, has led to a drop in the price of virgin PET, but on the other hand, the ban on imports of Chinese mixed waste in 2018 has caused a relative shortage of recycled PET (Lee 2019; Sears n.d.). Assuming the price of virgin PET is lower, using recycled PET is recommended because, despite the lower cost of materials used, the use of virgin PET brings more environmental and health costs (Engel and Scott 2020; Dubé et al. 2020; Lourenço et al. 2020).

PET has the ability to be recycled over and over again by washing, drying, and melting and using it in the production of new products (Gu et al. 2020). Simon et al. (Simon et al. 2016) examined the life cycle impact of beverage packaging systems and, after reviewing 20 times PET recycling, concluded that

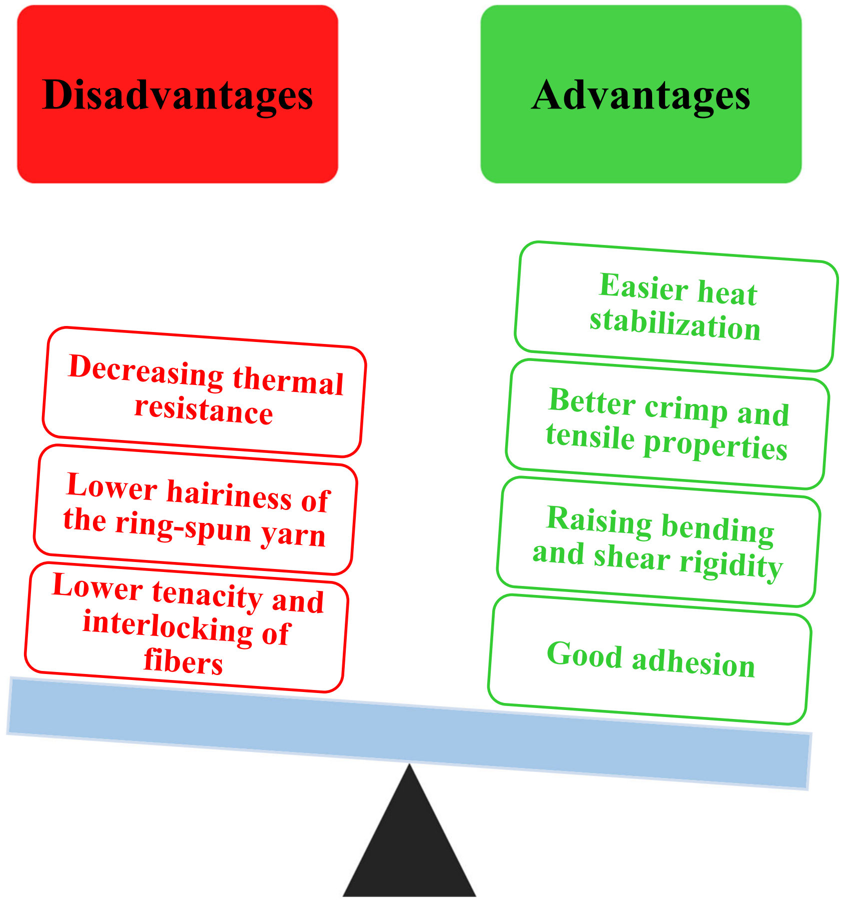


Fig. 8 Comparison of advantages and disadvantage of recycled PET fibers on yarn

the first seven cycles caused a considerable decrease in GHG emission, but the further enhancement in the number of recycling does not yield considerable environmental advantages.

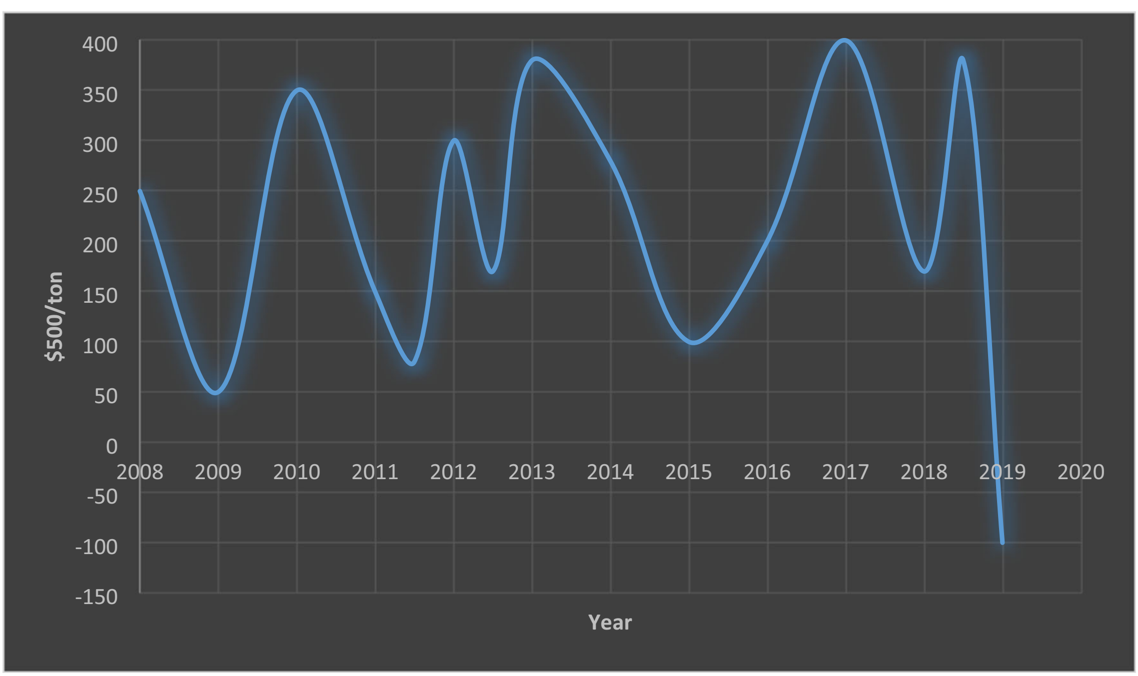


Fig. 9 Approximate price difference in the form of virgin PET minus recycled PET flakes

The life cycle assessment (LCA), by evaluation of energy and material consumptions, emissions in the environment, and disposal of wastes, can be a helpful way to the determination of the potential advantages of recycling works (Martin et al. 2020). Many studies have been published on the LCA of recycling post-consumer PET and have reported that better environmental gains can be achieved from mechanical recycling compared to landfill and incineration with energy recovery (Wäger and Hischier 2015; Wäger et al. 2011; Al-Maaded et al. 2012). Bataineh (Bataineh 2020b) studied the LCA of recycling post-consumer PET and showed that the total energy requirements for the recycled PET flake are 14–17% of the virgin PET flake. The life cycle impact difference between resin made of recycled PET and virgin PET mainly is the result of reducing virgin PET production (Ren et al. 2020). Finally, it can be concluded that PET recycling presents more considerable environmental benefits than single-use virgin PET and can improve eco-efficiency (Mahmud and Farjana 2020).

In this review article, the goal is to summarize recent studies on the practical results of returning post-consumer PET to the production cycle. To implement the macroenvironmental goals, it is very important to pay attention to economic issues. In this review, both aspects, economic and environmental, are discussed, because as mentioned in the previous sections of this review, relatively high value-added products were obtained from a wide range of applications of recycled PET fibers, which in most of the work done did not show a decrease in the quality of the product or even improved the quality with special techniques used.

In three separate sections, the use of recycled PET fibers in the production of concrete, nonwoven fabrics, and the yarn is discussed. In the concrete sector, PET recycled fibers are used without heat treatment and special process, but in the manufacture of nonwoven fabrics and yarn, recycled fibers need to be heat-treated in a special process of production of these two categories of products.

To improve the properties of products or to obtain new properties in recycled PET fibers, additives must be used or blended with another polymer (Chinchillas-Chinchillas et al. 2020; Deng et al. 2019; Sarioğlu et al. 2020; Thomas and Moosvi 2020b). Therefore, in the future, it may be possible to get better properties from products made from recycled PET fibers with new and better auxiliary compounds or to increase the amount of use of recycled PET fiber without lowering the quality, which is in line with economic and environmental goals. Also, the use of modern and innovative process techniques can further expand the industrialization of these products.

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