Recycled Thermoplastics: Textile Fiber Production, Scientific and Recent Commercial Developments

Sedat Kumartasli and Ozan Avinc

Abstract Plastic production always stands out with the difficulty of recycling after use. Tens of millions of tons of utilized polymeric materials are disposed each year. Polymer recycling is a pathway to diminish ecological obstacles caused by polymeric waste accumulation from daily applications of polymer materials such as packaging and textiles. Yet, the recycling trouble is still a main challenge. Recycling of plastics requires knowledge in four areas. These areas are plastics collection, their separation, rework technology and recycled products. Existing markets will ensure that post-consumer polymer waste has an economic value. These markets are generally textile sector. Recycled thermoplastic polymers take their place in the market after being converted into textile fiber. Recycling of waste plastics into new textile products is very important for ecology and world sustainability. Today, many fashion and sports textile companies use different textile fibers recycled from waste plastics in many different products (from sportswear, from casual wear to textile products used in shoes). In this chapter, information regarding the stages of the recycling processes and recycling types applied to plastic waste materials was given. Furthermore, the important recyclable thermoplastics polymers types such as PET (polyethylene terephthalate), PP (polypropylene), PA (polyamide), and PLA Poly(lactic acid), their recycling processes, and their recent commercial developments were also covered from the textile point of view. In the coming period, it is expected that the interest of textile producers and consumers in recycling and new textile products produced by recycling from plastic wastes will increase day by day.

Keywords Plastic · Thermoplastic · Recycling · Recycled thermoplastic · Fiber · Textile · Fiber production · Melt spinning · Polyester · Polyamid · Polylactic acid · Polypropylene · PET · PA · PLA · PP

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1 Introduction

Consumption and environmental problems continue to increase with population growth in the world. Due to the increasing environmental problems and the waste they cause, different industrial and social researches and studies have recently been carried out to reduce the harmful effects of many products and materials and to ensure sustainability (or recycling) (Askiner et al. 2009). In the current situation of our world, the recycling of plastic solid wastes/recovery of these wastes/effective management of these wastes cause different concerns. The reason why sectors are more interested in plastic production is that many products are produced from plastic. Due to their lifetime and ease of use, plastics have become an important part of our lifestyle leading to increasing global plastic production. For this reason, global plastic manufacture has enhanced enormously in the last five decades (Gu and Ozbakkaloglu 2016). The production of plastic products, which started in 1907 in the world, brought convenience to people's lives (Pagev 2018). Plastic is one of the most widely used and regularly waste materials today. Worldwide studies estimate that approximately 10% of environmental waste produced by humans consists of plastic materials. It should be noted that there is no real estimation of total plastic waste generation, but considering that 70% of overall plastic consumption is disposed of as waste, nearly 5.6 million tons of plastic waste is created per annum. This corresponds to approximately 15,342 tons per day (CPCB 2013). Plastics exhibit various different benefits for specific application types and moreover they are easy to shape. It can therefore be tailored to specific needs by adding certain layers or additives. These properties are additionally the basis of some troubles with plastics. Accordingly, environmental pollutants from synthetic plastics have been detected as a major problem (Zheng et al. 2005). When we consider the recycling of plastic material, the first things we will associate with it will be plastic water bottles, nylon bags similar food cans, shampoo and other cosmetic bottles.

Today, excessive consumption of plastic and low recycling rates have become an environmental problem. Consumption needs are met at this rate through plastic products, and if the recycling rates remain at the current level, according to scientists, it is stated that by 2050 there will be more plastic than fish in the seas (Law 2017). The most effective way to conserve natural resources and use them more efficiently is recycling. Recycling is important in order to protect the ecological balance of our world and to leave our resources to future generations (Yüce 2020). Plastic can remain in nature intact for centuries. A plastic bottle does not perish in nature for 3,000 years and a ton of plastic saves 14,000 kWh when recycled (Kumartasli and Avinc 2020; Pivnenko et al. 2016; Shen et al. 2010). In the framework of increasing demands and environmental concerns, research and efforts in the latest years have focused on the recycling and sustainability of all products used. Of course, this is the case in the textile industry. Textile recycling sector is one of the oldest sectors in our planet. However, there are unfortunately people and communities that do not fully understand the importance of the recycling and recycling industry for the sustainability of the world or do not implement such practices effectively. Of course, there are also companies, people and communities that know the importance and effects of recycling and sustainability very well and try to increase these environmental efforts. As a result of increasing efforts to protect the environment and the world in recent years, many companies and organizations around the world produce new textile and ready-to-wear products by recycling waste plastic products and used waste textile products (Wang 2006). Every day, this and similar efforts and applications are increasing worldwide. Of course, these positive steps and efforts made for the protection of the environment and the sustainability of the world give all of us hope for a beautiful and sustainable future.

Unfortunately, the added value created by recycling is unfortunately lower than expected and remains at low levels for now. When the life cycle of these plastic materials and synthetic textiles, which are used in large quantities, is over, only a small part is recycled and therefore their impact on the economic cycle is less than expected. Additionally, unlike metals and ceramics, the recycling of polymers can somewhat change their properties. So in no way does it mean that the quality of the products cannot be made from recycled polymers (Ignatyev et al. 2014b).

Recycling of plastics is one of the main policies to diminish ecological troubles related with plastic waste. Besides, plastics are primarily produced from petrochemical raw materials, whose price has increased in the last decade. The supply of petrochemicals is expected to further decrease in the next decades due to the rapid depletion of oil resources. Therefore, plastic recycling will lower the dependency on fossil fuels. Recycling is an important strategy for managing end-of-life plastic waste. Recycling is very important in terms of preventing the damage of plastic wastes to the environment and contributing to the economy. Recycling methods continue to be used today, but problems still persist in collecting plastic waste due to technological, economic and social reasons. Consumed plastic packaging must be separated from other plastic waste and domestic organic waste in order to be recycled on a larger scale. In order to increase recycling rates and use recycled plastic instead of original plastic, polymer manufacturers and manufacturers of thermoplastic products need to make more effort and do different studies to contribute to this goal (Tasdelen and Oran 2017). Currently, we can only understand the real problems of plastics when we consider recycling, ecological problems and health effects. The simplest examples of this are far east countries. Far Eastern countries, where synthetic fiber production is intensive in terms of textiles, has a high share in the world textile market. Apart from synthetic textile fibers, many plastic product groups are produced using petrochemicals, also obtained from petroleum. Naturally, sectors and countries that use virgin petrochemical products in large quantities as raw materials may unintentionally contribute to ecological damages if waste plastic products and waste synthetic textile products that have completed their useful lives cannot be recycled efficiently. That is why companies and all countries in the world should increasingly give importance to the recycling of plastic materials. Today, many fashion and sports textile companies use different textile fibers recycled from waste plastics in many different products (from top wear to sportswear, from casual wear to textile products used in shoes). For example, Adidas, H&M, Levi Strauss & Co, Nike, M&S, Gucci, Zara, Patagonia, The North Face and many other big brands use recycled textile fibers from plastic wastes in their products.

In this chapter, the information regarding the progress on polymeric wastes, technics for thermoplastic recycling from some conventional polymers, stages of the recycling processes, different separation methods, recycling types applied to plastic waste materials and the concepts of mechanical and chemical recycling was given. Moreover, more information was given about the important recyclable thermoplastics polymers types {such as PET (polyethylene terephthalate), PP (polypropylene), PA (polyamide), and PLA [Poly(lactic acid): an example of biopolymer]}, their recycling processes, and their recent commercial developments from the textile point of view.

2 Technics for Thermoplastic Recycling

Recycling and incineration are among the methods applied to thermoplastic products in waste state. Incineration displays some troubles such as the procurement of toxic gases and residual ash containing lead and cadmium. Recycling offers benefits such as reducing ecological troubles and conserving both material and energy (Grigore 2017; Francis 2016). Mechanical or chemical recycling processes are the best way to use plastic waste (Kumartasli and Avinc 2020; Ignatyev et al. 2014a). It is vital to note that the recycling procedure doesn't lower costs, however maintaining the ecological balance is necessary for a sustainable planet. Although many different methods can be applied for recycling thermoplastic wastes such as PET (polyethylene terephthalate), PE (polyethylene), PP (polypropylene), PA (polyamide) waste polymers, there are basically four main recycling approaches (Voncina 2016). These are respectively, primary recycling (obtaining products with properties equivalent to mechanical reprocessing), secondary recycling (obtaining inferior properties to mechanical reprocessing), tertiary recycling (recycling of chemical components), quaternary recycling (energy recovery gain). Primary recycling, generally closed loop recycling, secondary recycling is described as recycling with the same system but based on waste collection. Tertiary recycling is defined as chemical or raw material recycling obtained by depolymerizing the chemical components of polymers. It is stated that quaternary recycling is the energy recovery route from wastes (Tasdelen and Oran 2017).

- *Primary Recovery*: In primary recovery, waste plastics are mechanically shredded and mixed with the original plastics, and the product can be produced in a final process. The commonly used method has been demonstrated with primary recycling as it is economical and simple. This process shows that the products can be reused in their original form. The disadvantage of this process is that a certain number of recycling can be made (Francis 2016; Hopewell et al. 2009; Singh et al. 2017).

- *Secondary Recovery*: It is a method used for the production of low quality products in the process where different products are obtained from waste thermoplastic products. Here, re-meltable polymers can be used in the process and recycled as different use products. Mechanical recycling does not cause much change in the structure of the polymer. This method is a physical technique in which plastic materials are crushed and melted to make the material to be used in the subsequent process, into granules or pellets suitable for further production. The disadvantage in this technique is related to the weakening of the properties of the resulting products due to the low molecular weight of the recycled waste. Reprocessing with good drying and vacuum degassing is recommended to avoid molecular weight reduction. Also, this technique is relatively inexpensive (Hopewell et al. 2009; Grigore 2017).
- *Tertiary Recovery*: This method is defined as chemical recycling. The aim here is to separate the polymer into its monomers. After the monomer is obtained, the desired materials can be produced. Chemical recycling has not been developed at the desired level. Some companies are working on the process. This technique is a costly method. Currently, procedures with commercial experience are glycolysis and methanolysis (Francis 2016; Achilias et al. 2007; Karayannidis and Achilias 2007).
- *Quaternary Recovery*: In this technique, plastic waste materials are the process of burning with heat. In this process, energy is obtained by burning plastic waste materials. The most efficient way to reduce the volume of waste materials is incineration. This technique is a good solution as it produces a significant amount of energy from polymers, but causes air pollution. Among the techniques above, chemical recycling is the most suitable method for sustainability (Achilias et al. 2007; Al-Salem2009; Andrady 2003; Fisher et al. 2005).

In recycling factories, plastic wastes are passed through a vibrating screen to remove unnecessary substances such as impurities and sludge, and these materials are separated from steel and tin materials with the help of a magnet at the end of the conveyor belt (Sevencan and Vaizoglu 2007). At this stage, it would be appropriate to provide information about the stages of the recycling process in order.

Separation: Each plastic part must be separated according to its construction and type in order to be processed properly in the shredding machine. The different separation methods are summarized in the section below.

- Induction sequencing: The material is sent to a conveyor belt equipped with an inductive sensor. These sensors then separate the various substances with air jets.
- Eddy current separator: "Eddy current" is an electric current that occurs while changing the magnetic field in a conductor and separates non-ferrous materials.
- Drum separator/strainer: Those materials are divided in proportion to particle size. The waste is fed into a large rotating drum drilled with holes of different sizes. Materials smaller than the diameter of the holes fall off and larger particles stay in the drum.

- Synephloate separation: It separates plastic waste according to the density of materials in a water. In the presence of water, some plastics (eg PET, PVC and PS) sink and others float and show buoyancy (eg PE, PP and EPS).
- X-ray technology: X-rays could be utilized to differentiate different kinds of materials based on density.
- Near infrared sensor: Plastics reflect light differently in the near infrared (NIR) wavelength spectrum. The near infrared sensor can differentiate between various materials depending on the way these materials reflect light. It is a method used to separate different polymers.

Sorting: Each plastic material should be spared in accordance with to its structure and kind thus that it could be treated in the shredding machine accordingly.

Washing: After separation, plastic waste must be properly washed to eliminate impurities such as labels-adhesives. Washing procedure improves the quality of the finished product.

Shredding: After the process of washing, the plastic wastes are loaded on various conveyor belts which pass the waste within different shredders. These grinders break the plastic into small lumps and prepare it for recycling in other products.

Identification and Classification of Plastic: After shredding, appropriate tests for the plastic pellets are carried out to determine their quality and grade.

Extruding: Extruding comprise melting the shredded plastic as a result it could be extruded into pellets and afterwards utilized to make various kinds of plastic products (Norcal Compactors 2020).

In the following part, information on recycling types applied to plastic waste materials is given. These are mechanical recycling and chemical recycling, respectively.

3 Recycling Types

3.1 Mechanical Recycling

The material properties obtained here are generally slightly worse than the virgin material. This type of process is also known as physical recycling. In this type of recycling, plastics are milled and then reprocessed and combined to produce a new component that may be the same or different from the original use (Cui and Forssberg 2003). However, the molecular weight, thermal charges change during melting and therefore the fiber tensile strength, tensile and dyeing properties can change. For this reason, manufacturers may choose to regenerate products by polymerization, according to an option for melting and extrusion. Because molecular weight and properties remain the same (Kumartasli and Avinc 2020; Oktem 1998). One of the main matters which mechanical recycling companies face is the degradation and heterogeneity of plastic solid waste. Because chemical reactions which ensure polymer formation (i.e. polyaddition, polycondensation, polymerization reactions) are all reversible in theory, energy or heat supply could result in photo-oxidation and/or mechanical stresses that arise as a result (Al-Salem et al. 2009).

3.2 Chemical Recycling

In this process, waste plastic materials are used as raw materials. With the help of chemicals and catalysts, the decomposition and depolymerization of the materials are provided. In this way, it decomposes into polymer monomers (Garcia and Robertson 2017; Ademiluyi and Akpan 2007). Chemical recycling technique appears economical, however it can reduce the yield of new products made from recycled products by this method (Park et al. 2002). Chemical recycling seeks to convert waste polymers to numerous levels such as oligomers or monomers. In this way, the reproduction of the same type of polymers from monomers or oligomers obtained from waste polymers by chemical recycling and then the production of textile fibers from these produced polymers is done by different applications such as polymerization (Gupta and Kothari 1997). Recently, there has been great interest in chemical recycling as a technique for producing various fuel fractions from plastic solid waste (PSW). Many polymers by their nature are useful for this type of process. Polyethylene terephthalate (PET) and certain polyamides [Nylon 6 (PA 6) and Nylon 6.6 (PA 6.6)] can be effectively de-polymerised. Especially, polyethylene (PE) was aimed as a prospective feedstock for fuel (gasoline) manufacturing technologies (Al-Salem 2009).

The following section gives detailed information about some of the important recyclable thermoplastics polymers types.

4 Recyclable Thermoplastics Polymers Types

In this part of the book chapter, information is given about some types of thermoplastic polymers that can be recycled. The waste thermoplastic materials described here are recycled and these recycled polymers can be used to produce new textile fibers. In short, new textile fibers and thus new textile products can be produced from waste plastics. In this section, information is given about the recycling of polyamides, polyester, polyolefins and biopolymers.

4.1 Polyamides

Worldwide, polyamide 6 and polyamide 6.6 (PA 6 & PA 6.6) are the most utilized polyamides, also important for large scale manufacture of melt-spun fibers (Anton and Baird 2001). The polymer transformed into pellet form becomes fiber with the fiber spinning process (Fig. 1). Both types of fibers display similar properties such

Fig. 1 PA pellets

as very good wear and abrasion resistance, high strength and toughness, brilliant fatigue behaviour and nice flexibility and their slight differences are mainly due to alterations in molecular weight distribution and molecular orientation due to the shrinkage (Mukhopadhyay 2009).

The international plastic recycling market reached U.S. $ 34.80 billion in 2017, and one of the most crucial and precious recycled plastics is PA 6. Amongst recycling techniques, physical recycling of Polyamide 6 (PA 6) by melt re-processing is the most preferred recycling method, because this process type is a comparatively simpler method, requires low investment and is more eco-friendly (Murphy 2001). Nevertheless, during the recycling process, PA 6 is exposed to high temperatures and mechanical forces which cause the polymer chains to deteriorate. The decrease in the molar mass of PA 6 causes the loss of mechanical and thermal characteristics and restricts the application areas of recycled PA 6 (r-PA 6). Some companies around the world can recycle polymaide waste by mechanical or chemical methods. Related information about this was mentioned in the commercial applications section.

4.2 Polyesters

Polyamide is more challenging to recycle than polyester, the market share of recycled polyamide (r-PA) is much lesser than that of recycled polyester (r-PET). R-PA could be manufactured from pre- or post-consumer waste. It can be pre-consumer waste and scraps processed. It is made from materials such as post-consumer polyamide, discarded fishing nets, carpets or other utilized textiles and the its recycling process could be mechanical or chemical.

PET (polyethylene terephthalate) is the major polyester utilized in fiber manufacturing not only due to its end use characteristics and production economy, but also mainly owing to its physical and chemical ease of use (Militky 2009). The spun polyethylene terephthalate forms a stable, supercooled melt because of the relatively high glass transition temperature (Tg ~ 75 °C). Only when fully drawn is a molecular

Fig. 2 Recycled PET pellets

orientation in the direction of the fiber that develops oriented crystallites (Sattler and Schweizer 2011). Its excellent properties are responsible for polyester fibers and filaments that find utilization in all fiber application areas. Pellets are used for PET fiber production (Fig. 2).

Recycled polyester is more sustainable raw material, as the use of recycled polyester saves natural re-sources, conserves energy in the manufacturing process, and results in lower greenhouse gas emissions and the utilization of chemicals (Shen et al. 2010). PET wastes could be recycled by both mechanical and chemical techniques. Mechanical recycling is cheaper and environmentally friendly (Kumartasli and Avinc 2020). It is the right point to state in here that polyester fiber (especially PET fiber) is a textile fiber that is the most produced-consumed textile fiber in the world. Therefore, the recycling of polyester plastics and the use of this recycled polyester polymer to produce new polyester fibers is very important and essential not only for the environment but also for the world textile industry. For this reason, the production of polyester textile fibers from the recycled waste polyester plastics is increasing day by day worldwide. Many companies around the world can recycle polyester waste by mechanical or chemical methods. Related information about this is also mentioned in the commercial applications section.

4.3 Polyolefins

The most important polyolefins utilized for melt spinning are polypropylene, low density polyethylene and high density polyethylene (PP, LDPE and HDPE), which are mainly composed of saturated aliphatic hydrocarbon macromolecules (Mather 2009). Technologies for converting polyolefins to fiber and fabrics comprise monofilament and multifilament spinning, staple fiber, spunbond, meltblown and slit film (Ouederni

Fig. 3 PP granuls

2016). It is the material of preference for disposable hygiene and medical applications such as polyolefin based spunbond and meltblown fabrics, diapers, incontinence pants, hygienic pads, surgical gowns and masks (Malkan 2017). Polyolefin filaments, which are polymeric hydrocarbons, have luster and a waxy handle that can be lowered by non-circular fiber cross-sections such as trilobal or cross-shaped (Mather 2009). Polyolefins (LDPE, HDPE, PP) are the main thermoplastic type utilized in applications such as bags, toys, containers, pipes (LDPE), household items, industrial packaging and film, gas pipes (HDPE), film, fiber, battery boxes, automotive parts, electrical components (PP). In the western European countries alone, about 21.37 million tons of these three polymers are consumed each year (2003 data) and represent 56% of total thermoplastics Unlike condensation polymers [i.e. poly (ethylene terephthalate) (PET)], additional polymers (such as polyethylene) cannot be easily recycled by any method (Karayannidi and Achilias 2007). Instead, recycling techniques such as thermochemical pyrolysis have been proposed as the procedure that produces a range of refined petrochemical products. Polypropylene reprocessing involves melting at a temperature above 200 °C in an extruder and then granulation for utilization in novel manufacturing (Fig. 3). Polypropylene is ultimately influenced by thermal degradation that concedes the structural density of the plastic because of the weakening of the bonds between hydrogen and carbon. This depends on the utilization of polypropylene, but it is generally accepted that four closed recycling loops are probable before the negative impact of thermal degradation is detected (Thomas 2012).

4.4 Biopolymers

The term "biopolymer" is usually bio-based (manufactured from biogenic materials considered as renewable resources), but frequently biodegradable (biodegradable), biocompatible (no adverse effect on humans or animals). The key biopolymers considered for melt-fiber spinning are PLA [Poly(lactic acid)], PCL (Polycaprolactone), PGA (Poly glutamic acid), PBAT (polybutyrate adipate terephthalate), PEF (polyethylene furanoate) and PHA (Polyhydroxyalkanoate). One of the most important (probably the most important) of these biopolymers is PLA. PLA is a type of biopolymer that is on the agenda today with its positive environmental and performance characteristics and its use is expected to increase day by day in the future. Therefore, this part of the book section focused on PLA polymer, waste PLA plastics and the production of new PLA fibers from these wastes. PLA could be manufactured from lactic acid, the raw material of which is naturally occurring starch, usually derived from corn (Mochizuki 2009). PLA can also be produced from rice, wheat, sugar beet or bio waste. Composed of L lactic acid (LLA), fiber-grade PLA is one of the most gifted bio-based, biodegradable and biocompatible polymers commercially available (Mochizuki 2009; Niaounakis 2015; Avinc and Khoddami 2009; Avinc 2011a, b; Avinc et al. 2006, 2009, 2010a, b, c, d, 2011c, 2012a, b; Khoddami et al. 2010, 2011; Hasani et al. 2013). The natural biodegradability of PLA is less than that of other biopolymers and less sensitive to microbial attack (Tokiwa and Calabia 2006). The major disadvantage with melt processing is the low thermal stability in the existance of moisture (hydrolysis) (Södergård and Inkinen 2011).

The appearance of the r-PLA (recycled PLA) and r-PET (recycled PET) fiber samples and the comparison of their mechanical and dyeing properties displayed that r-PLA fibers could be a nice replacement for r-PET fibers. This determination shows that PLA waste plastics can be recycled and reused, and that PLA fibers showing adequate textile performance properties can be produced from these waste PLA plastics.For this reason, and also due to the environmental, renewable, sustainable and biodegradable properties of PLA, biodegradable PLA bottles and plastic packaging are expected to replace PET bottles and plastic packaging in the near future. Moreover, this could provide an cost-effective and beneficial recycling method for PLA's valuable waste compared to the traditional recycling process (Tavanaie 2014). Additionally, PLA waste streams could also be processed utilizing composting, chemical recycling (hydrolysis depolymerization) and anaerobic digestion (Farrington et al. 2005). These PLA waste recycling methods are expensive and difficult. The mechanical recycling of PLA is better than the chemical recycling of PLA from the point of human and eco-system health and the utilization of resources. Otherwise mechanical recycling results in down-grading thus the recycled poly(lactic acid) would be of a lesser quality that if it was chemically recycled (Cosate de Andrade et al. 2016). When PLA is mechanically recycled, it is likely to include a chain extender that aids partially recover the impaired molar mass and other mechanical characteristics, making the recycled poly(lactic acid) more comparable with virgin poly(lactic acid) (Fig. 4) (Cosate de Andrade et al. 2018).

PLA offers some exciting characteristics such as biodegradability, sustainability, renewability, recyclability, environmentally friendly characteristic, nice processability, low manufacturing cost, low environmental impact and optical and mechanical characteristics akin to that of polystyrene or poly (ethylene terephthalate) (PET). These nice characteristics have led to an increased interest in PLA and this made it

Fig. 4 PLA pellets

one of the most critical bioplastics in the market, especially in packaging applications, with a worldwide manufacturing capacity of 0.21 million tons in 2016. PLA reached 0.5 million tons in 2020 (Aeschelmann and Carus 2016). It should be noted at this point that PLA can be recycled mechanically or chemically (Castro-Aguirre et al. 2016). Mechanical recycling involves the recovery, sorting, re-grinding and re-processing of poly(lactic acid) (Chariyachotilert et al. 2012). Even though this method necessitates simpler techniques and can be easily implemented, it lead to deterioration of the physical characteristics of PLA and foreign contaminants that cannot be completely removed, as the molecular weight is decreased because of shear and temperature (Hamad et al. 2013). Otherwise, chemical recycling transforms PLA polymer to monomer LA (Lactic Acid) by hydrolysis and separation of contaminants so that lactic acid could then be utilized as raw material with the same characteristics as virgin poly(lactic acid) for new PLA production (Piemonte et al. 2013). Here we have seen that PLA waste plastics can be successfully recycled and used in the production of new PLA textile fibers. Here, an important point should be emphasized. The biodegradability of PLA polymer, PLA plastic waste, PLA fiber textile products is incredibly important for the sustainability of the environment and the world. It is known that PLA plastic wastes or PLA textile wastes turn into water and carbon dioxide (the basic necessities for new growth) when biodegrades. The recycling of PLA wastes, to new plastic materials or new textile fibers, instead of allowing them to be biodegraded as much as possible will provide added value to the world both economically and in terms of efficient use of resources.

In the next part of the book chapter, commercial steps, commercial developments and final products regarding the recycling of thermoplastics and the creation of different textile fibers obtained from different recycled thermoplastics are mentioned.

5 Recent Commercial Developments

In this section, recent commercial developments regarding the creation of different commercial textile fibers produced from different types of recycled thermoplastics are discussed. First of all, it would be appropriate to take a look at the generally applied recycling steps from plastic waste to the production of new textile fibers. For this purpose, general transformation steps required for the transformation of thermoplastic wastes into textile products are shown in Fig. 5.

As mentioned above, new thermoplastic textile yarns are produced from the polymers produced after the recycling steps from waste plastic materials with the help of fiber melt spinning process; in the desired fiber cross-section, filament number and yarn count (Fig. 5). Later, these recycled thermoplastic yarns are then used to create many different textile products for many different purposes after their respective classical textile product production processes such as conventional fabric surface forming process (knitting, weaving etc.), coloration process (dyeing, printing), finishing processes (softening, water repellency finishing, antimicrobial finishing, flame retardant finishing process etc.), and finally end-use manufacturing processes (such as garment manufacturing etc.).

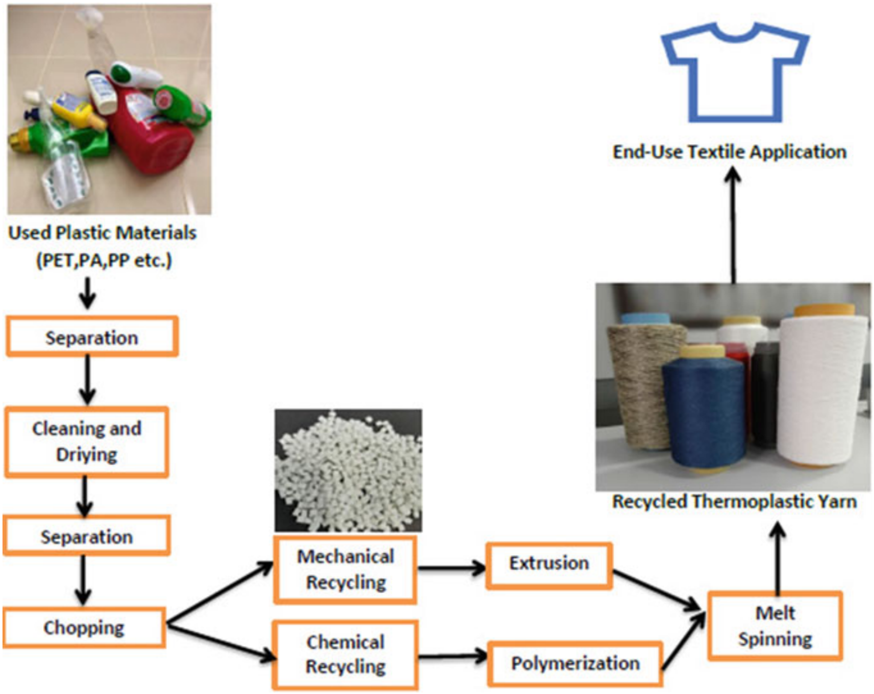

Fig. 5 The stages of transformation of thermoplastic wastes into textile products

According to 2019 data, 52% of the annual total fiber production is polyester. When looking at the recycle polyester market, an increase of approximately 5% is seen between 2009 and 2019 (Textile Exchange Report 2020).

Recycling and use of PET bottles in recycled plastics is an important issue for the textile industry. One reason for this is that unprocessed polyester is manufactured in much greater volumes. Sports equipment manufacturers such as Nike and Adidas are increasing the use of recycled polyester in their new textile products. In recent years, large companies have increasingly started using fibers recycled from PET bottles. The steps taken by some of these fashion giants towards the use of textile fibers recycled from plastic waste in the new textile products they produce are summarized later in this section.

Polyteks production of polyester yarn from Turkey is performing. The company's recycled PET yarn brand is POLY-eco®. Turkey is one of the leading brand of recycled PET yarn (Fig. 6). This type of recycled polyester yarn is used in a variety of textile products. Figure 6 shows the transformation steps of used waste PET bottles into recycled PET yarn (POLY-eco®).

One of the important commercial developments in this field is that Igloo has announced their softside cooler collection woven with REPREVE, a fiber generated from recycled, post-consumer plastic bottles. Several of the most well-known world-wide international textile brands in our planet utilize the REPREVE brand. These companies have recycled more than 14 billion plastic bottles to date. Based on this momentum, Unifi intends to recycle 20 billion bottles by 2020 and 30 billion bottles by 2022 (Södergård and Inkinen 2011).

One of the textile recycling company called as Waste2Wear alleges to have manufactured the planet's first collection of plastics generated from recycled ocean plastic fabrics that is fully traceable utilizing blockchain technique. Waste2Wear introduced a beta version of its blockchain system, embedded in its new Ocean Fabrics collection, at the Première Vision international textile fair in Paris. The company, a frontrunner in creating fabrics from plastic waste, says using blockchain technology will bring more transparency to the supply-chain of recycled textiles.

H&M, one of the important textile companies, included the use of recycled textile fibers in its new products. It was reported that world-wide clothing company H&M utilized 325 million PET bottles in recycled polyester in 2018. H&M textile company

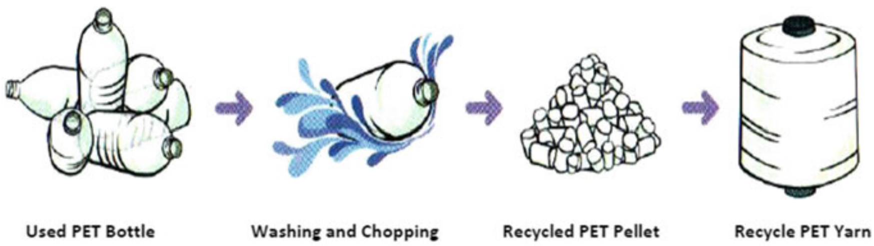

Fig. 6 The plastic bottles to turn into recycled PET yarn (POLY-eco® recycled PET yarn brand, POLYTEKS)

is the 6th largest consumer of recycled polyester (r-PET) in our planet as said by the company's 2018 sustainability report (Inside Waste 2019).

Sports equipment giant Adidas has been introducing Parley sports shoes made from recycled plastics since 2015 (ISPO 2019).

One of the main ways brands add sustainability to their products is via the utilization of recycled materials, especially recycled polyester (r-PET). Main international brands have taken this approach, containing Zara, H&M, Marks and Spencer, Levi's, G star and many other companies (Kumartasli and Avinc 2020; InsideFasion 2020). Today, many fashion and sports textile companies use different textile fibers recycled from waste plastics in many different products (from top wear to sportswear, casual wear to textile products used in shoes).

It was earlier reported that Henkel tapped Austrian manufacturer Greiner Packaging to develop the novel design sleeve and container. It was stated that the outer cardboard sleeve was made from 92% recycled content. Even Though the inside of the plastic container was still made from white virgin material, its exterior layer now contains recycled polypropylene from the post-consumer sources (Halbrook 2020).

It is the reason why Trützschler and EREMA started the production of recycled yarn in cooperation. Both companies combined their efforts to develop a one-step system for pretreatment of polyester flakes and spinning to BCF (Bulked Continuous Filament) for carpet applications.The new system precisely connects EREMA's VACUREMA technique with Trützschler Switzerland's symTTex BCF machines. The EREMA part comprises a vacuum reactor, a directly connected single screw extruder and a high performance filter. The washed r-PET flakes are dried in the reactor and decontaminated, melted in the extruder and then passed through a variable fineness large area filter. The high-quality melt is then fed into the Trützschler spinning system. Well-known and well-established high-quality spinning packages, double-shell draw rollers, HPc texturing system and fully driven winders form filaments and wind them into bobbins. An industrialized line based on this latest model is already running effectively in Poland (Textile Magazine 2020).

In Canada, a partnership for the PET waste chemical recycling facility was established in 2018 in partnership with Loop Industries/Indorama venture (Textile Exchange 2020).

Many companies in the USA recycle PET wastes mechanically and chemically. Ambercycle company recycles PET from waste clothes. The recycling process is completed using biological and chemical methods (Ambercycle 202; ChangeMakers 2020). BIONIC® fibers, yarns and fabrics are produced from plastic collected from the sea and seaside. Bionic yarns form durable fabric yarns from recycled plastic (Textile Exchange 2020; BionicYarn 2020).

Eastman Chemical Company announced that Avra, a family of high performance fibers, will be produced from 100% post-consumer recycled PET plastic from spring 2020. The process will take place with the new chemical recycling process through Carbon Renewal Technology. Eastman will collect the polyester carpets, separate the polyesters and recycle them chemically (Eastman Chemical 2020).

Lycra EcoMade fiber is the company's first branded spandex made from pre-consumer recycled materials and more than 65% of the T400® EcoMade fiber total fiber content comes from a combination of recycled plastics (PET bottles) and renewable plant-based resources (corn). PET recycling is done chemically (Textile Magazine 2020; Textile World 2019).

Focusing on developing bio-industrial solutions, the French company Carbios started construction of its industrial facility for the enzymatic recycling of polyethylene terephthalate (PET) plastic. The recycling used is different from mechanical recycling. PET wastes separated into their monomers biologically and chemically can then be recycled to the desired product (Textile Exchange 2020).

Seaqual is an initiative in Spain to clear the oceans of marine litter. Seaqual yarn is a 100% recycled material with full traceability and Madrid-based Seaqual combines creativity and eco-responsibility by turning the litter trapped in fishermen's nets into a revolutionary new fiber (Seaqual 2020; Apparel Staff 2017).

ECOPET™, launched by the Japanese company Teijin, are polyester products (fibers, textiles, clothing and products) made from recycled resources: it uses various types of polyester waste through a mechanical or chemical recycling process. Provides efficient use of limited natural resources (Teijin Fibers 2020). The ECOUSE™ brand, launched by Toray from Japan, is yarn, cotton, textile and fiber products made from PET bottles and materials from the production process. Toray actively promotes fiber recycling with its basic "Total Recycling" concept, using less energy under ECODREAM™, the general brand name for environment and recycling (Toray 2020).

Japan-based firm Jeplan envisions a world where all used or unwanted personal items are collected, materials are recycled, and new products are launched and sold. Starting with cotton and polyester, the company is redesigning waste disposal to reduce oil use and reduce carbon emissions. The firm has set up nationwide collection points to collect discarded garments, collaborating with major retail and apparel brands. Jeplan then recycles the materials and sells them back to these brands and consumers, supporting a circular economy. One of his projects turned used clothes into bio-ethanol, which was later used to sustainably power a car. Jeplan is working towards its goal of recycling 10% of used and unwanted clothing around the World (Jeplan 2020).

Nan Ya Plastics is a SAYA branded, commercially available, chemically recycled, GRS certified PET made from pre and post consumer textile products. Nan Ya Plastics, the parent company of SAYA, is one of the world's largest producers of recycled PET and targets more than 75 billion bottles each year (Textile Exchange 2020; Saya 2020).

The Swiss company Gr3n has once invented a new process for chemically recycling PET bottles and food containers. They developed an innovative technique based on a novel application of microwave technology to a well known chemical reaction, which enables an economically effective chemical recycling method of PET (Polyethylene Terephthalate) and allows the industrial application of this recycling technique. This new process could potentially change the way PET is recycled worldwide and could provide a massive financial gain for the recycling industry.

Launched by former Slovak professional cyclist and twins Martin and Peter Velits, Isadore produces an Alternative Preferential clothing line that includes jerseys, bib shorts, jackets and base layers, all made from recyclable materials. The jerseys were produced utilizing plastic bottles (30 pieces each) and the bib shorts are made from chamois leather, while the rest of the shorts are generated from recycled Italian Lycra. All garments that reduce weather resistance are produced locally where the Veltis brothers are based in Slovakia (Calvert 2020).

Along textile waste, nonwoven manufacturers supply recycled polyester bottles to produce PET nonwoven. The need for these bottles is gradually increasing due to foreign demand as well as recycling companies in the USA. Like the National Container Resources Agreement, NAPCOR0 rPET reduced energy consumption by 84% and greenhouse emissions by 71%. The conversion of 1.5 billion pound PET bottles into textile fiber has saved 46 trillion BTUs of energy, enough to power 486,000 homes.As a result, 85 16-oz polyester bottles will produce fiber filling source for 1 sleeping bag, 72 tissue box 5 pieces two liter bottle and 5 16-oz bottles can form a collection distribution layer (McIntyre 2013).

Some Japanese companies also give an importance to the use of materials recycled from plastic waste. One of these companies is Teijin firm. Teijin hybrid fiber contains chemically recycled PET. Solotex is the brand name for the Japanese firm's highly flexible yarn made from recycled and plant-derived materials (Taylor 2020).

H&M, for example, said it will switch to fully recycled and sustainable materials by 2030. Likewise, Uniqlo casual wear operator Fast Retail has introduced the use of biofiber in its products. Additionally, in 2020, the company announced its accession to the UN's Fashion Industry Charter for Climate Action, which is designed to reduce greenhouse gas emissions from the clothing industry by about 30% by 2030 (Walimbe 2020). Adidas, H&M, Levi Strauss & Co, Nike, Patagonia, The North Face and several other big brands view sustainability hand in hand with invention and innovation. In the last few years, those firms have been seeking the paths to diminish their ecological effect, launching special programs and encouraging sustainable inventions and innovations (Tonevitskoya 2019).

Recycled Nylon (r-PA) possess the similar advantages as recycled polyester (r-PET). Much of the recycled nylon generated from old fishing nets. This is a good solution for removing garbage from the ocean. Polyamide is still more costly to recycle than new virgin nylon, however possesses several ecological benefits. Many different studies are currently carried out to improve the quality and to diminish the costs of the recycling procedure. Econyl® is a nice example of certified, environmentally friendly, recycled polyamide textile.

Recycled polyamide is generally produced from post-industrial waste (for example; polyamide yarn manufacturing waste or carpet cuts) as well as post-consumer waste (used carpets, discarded fishing nets). This chemical recycling allows for reducing waste, reducing dependence on oil resources, and minimizing the pollution of consumer and post-industrial polyamide waste (Recycled Nylon 2020).

The NUREL company recycles pre-consumer waste by recycling it into a higher quality sustainable yarn from nylon. Reco branded nylon performance is similar to standard nylon 6 threads and is sustainable (RecoNylon 2020).

Nilit company (from Israel) recycles polyamide wastes through the re-melting process. The process diminishes energy consumption in comparison with fiber spun from virgin polymers (Haemek 2009).

Q-NOVA®, a brand of Fulgar company, is a traceable and environmentally sustainable nylon 6.6 fiber obtained from regenerated raw materials.In particular, Q-Nova yarn is supported by many companies especially in the footwear and woven material industry for the apparel, intimate apparel and sportswear industry, has been adopted (Q-Nova 2020; Nylstar 2020).

Meryl® yarn can now be produced using INVISTA recycled nylon 6.6 polymer with Global Recycled Standard (GRS) certification. Although the yarn contains 50% or more recycled content, it will retain the world-renowned quality of Meryl®. INVISTA buys post-industrial nylon 6.6 material from its factory in Kingston, Canada, where fibers for airbags and carpets are produced. Through its proprietary process, INVISTA converts post-industrial fiber waste into pellet form and supplies it to Nylstar for spinning, enabling some of the world's best fashion houses to bring sustainable clothing to the market. "Through our Advanced Recycled Materials Research Center, it is the first company to commercialize and manufacture these recycled materials for use in fine denier yarns for the athleisure market" said Nylstar CEO and president Alfonso Cirera (Nylstar 2020). Athleisure is a type of hyrid clothing of athletic wear and leisure wear and a new fashion trend that started with the combination of stylish clothes (clothing worn at work, school and other casual and social occasions) and sports pieces (clothing worn during athletic activities) (Athleisure 2020).

Prior to fall 2020–21, Gucci developed Gucci Off The Grid, the first collection of Gucci Circular Lines, an initiative designed to boost House's vision of circular manufacture. Designed for those who care about their ecological effect, Gucci Off The Grid utilizes recycled, organic, bio-based and sustainably sourced materials, comprising ECONYL® (Econly 2020).

Britain's swimwear brand Fatface has launched a new swimsuit using Hyosung's Mipan regen fiber made from recycled polyamide, reducing energy consumption.He stated that Control Union is an environmentally friendly product with Global Recycling Standard (GRS) certification.

Procotex is one of the market leader companies in recycled 100% PP fibers. Usually, any PP waste from the extrusion industry or carpet industry is recycled. Procotex guarantees 100% purity. This way, any possible contamination with other fibers is guaranteed to be eliminated (Procotex 2020). In this way, many PP plastic wastes are evaluated and new PP fibers are produced.

The French company Veja, known around the world for producing sustainable shoes, takes fair trade shoes and accessories to the next level by launching a material called B-mesh ("Bottle Mesh"). Each pair of sneakers comprises three bottles. The fabric created from them is both breathable and waterproof—perfect for shoes. In addition, by way of example, our shoes can be made from environmentally friendly renewable products such as organic cotton and natural rubber produced by farmers who maintain their livelihoods through farming (Textile Focus 2020). Sheico Group produces recycled spandex from spandex waste. It has Global Recycled Standard certification (Spanflex 2020).

As can be seen, many textile companies around the world produce recycled textile fibers and include recycled textile fibers in their many different products. All these developments indicate that the importance and interest given to recycling will increase day by day.

6 Conclusions

Disposing of plastic instead of recycling unfortunately means that these plastics will go to landfills and oceans. The biggest problem here is that storage areas are overcrowded and occupation of areas that can be used for different needs. In addition, these discarded plastics pose a great danger to animals living in the oceans. The recycling of plastic must be considered for our future. As a result, thermoplastics must be recycled to use landfills for different purposes and to protect the environment. Therefore, recycling is very important. Today, the use of recycled thermoplastic yarns is expected to expand its market share. When yarn manufacturing in the world is examined, it is visible that the highest production amount belongs to synthetic fibers. Nowadays, thermoplastic fibers are important for the textile industry owing to their important properties. Recycled thermoplastics are a more ecological and sustainable raw material, as conversion to recycled thermoplastic yarn saves natural resources, saves energy in the manufacturing process and results in low greenhouse gas emissions. It is very important for the sustainability of our planet to produce new textile fibers and textile products or different types of products from thermoplastic waste and to realize the recycling processes. For this reason, large textile companies are increasingly using recycled thermoplastic products. Therefore, recycling is an irremissible cure for a more sustainable and greener world and to carry our planet to the future in the best possible way for future generations. It is expected that the interest of textile manufacturers and consumers in new textile products produced by recycling from recycling and thermoplastic waste is expected to increase in the upcoming period. The combined effect created by the increase in the production and utilization of new textile products produced by recycling from thermoplastic wastes, as well as the increase in the production of sustainable textile products, will make greater contributions to the goal of a more sustainable world.

References

Achilias DS, Roupakias C, Megalokonomos P, Lappas AA, Antonakou EV (2007) Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). J Hazard Mater 149:536–542

Ademiluyi T, Akpan C (2007) Preliminary evaluation of fuel oil produced from pyrolysis of low density polyethylene water sachet wastes. J Appl Sci Environ Manag 11(3):15–19
Aeschelmann F, Carus M (2016) Biobased building blocks and polymers: global capacities and trends 2016–2021. Ind Biotechnol 11:154–159
Al-Salem SM (2009) Establishing an integrated databank for plastic manufacturers and converters in Kuwait. Waste Manag 29(1):479–484
Al-Salem S, Lettieri P, Baeyens J (2009) Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Manag 29:2625–2643
Ambercycle (2020). https://www.ambercycle.com/. Accessed 25 Sep 2020
Andrady AL (2003) Plastics and the environment. Wiley, Hoboken, NJ, USA
Anton A, Baird BR (2001) Polyamides, fibers. In: Mark HF (ed) Encyclopedia of polymer science and technology, vol 3. Wiley, Hoboken, NJ, USA, pp 584–618
ApparelStaff (2017) Eco-friendly SEAQUAL fiber uses recycled ocean waste. https://risnews.com/eco-friendly-seaqual-fiber-uses-recycled-ocean-waste. Accessed 25 Sep 2020
Askiner G, Palamutcu S, İkiz Y (2009) Cotton textiles and the environment: life cycle assessment of a bathrobe. Text Appar Mag 13:197–198
Athleisure (2020). https://en.wikipedia.org/wiki/Athleisure. Accessed on 29 Sep 2020
Avinc O (2011a) Clearing of dyed poly (lactic acid) fabrics under acidic and alkaline conditions. Text Res J 81(10):1049–1074
Avinc O (2011b) Maximizing the wash fastness of dyed poly (lactic acid) fabrics by adjusting the amount of air during conventional reduction clearing. Text Res J 81(11):1158–1170
Avinc O, Khoddami A (2009) Overview of Poly(lactic acid) (PLA) Fibre. Fibre Chem 41:391–401
Avinc O, Bone J, Owens H, Phillips D, Wilding M (2006) Preferred alkaline reduction-clearing conditions for use with dyed Ingeo poly (lactic acid) fibres. Color Technol 122(3):157–161
Avinc O, Phillips D, Wilding M (2009) Influence of different finishing conditions on the wet fastness of selected disperse dyes on polylactic acid fabrics. Color Technol 125(5):288–295
Avinc O, Wilding M, Bone J, Phillips D, Farrington D (2010a) Evaluation of color fastness and thermal migration in softened polylactic acid fabrics dyed with disperse dyes of differing hydrophobicity. Color Technol 126(6):353–364
Avinc O, Wilding M, Gong H, Farrington D (2010b) Effects of softeners and laundering on the handle of knitted PLA filament fabrics. Fibers Polym 11(6):924–931
Avinc O, Wilding M, Phillips D, Farrington D (2010c) Investigation of the influence of different commercial softeners on the stability of poly (lactic acid) fabrics during storage. Polym Degrad Stab 95(2):214–224
Avinc O, Wilding M, Bone J, Phillips D, Farrington D (2010d) Colorfastness properties of dyed, reduction cleared, and softened poly (lactic acid) Fabrics. AATCC Rev 10(5)
Avinc O, Khoddami A, Hasani H (2011) A mathematical model to compare the handle of PLA and PET knitted fabrics after different finishing steps. Fibers Polym 12(3):405
Avinc O, Day R, Carr C, Wilding M (2012a) Effect of combined flame retardant, liquid repellent and softener finishes on poly (lactic acid)(PLA) fabric performance. Text Res J 82(10):975–984
Avinc O, Eren HA, Uysal P (2012b) Ozone applications for after-clearing of disperse-dyed poly (lactic acid) fibres. Color Technol 128(6):479–487
BinoicYarn (2020), https://www.bionicyarn.com/. Accessed 25 Sep 2020
Calvert (2020) Thebesteco-consciouscyclingclothingbrands. https://www.cyclingweekly.com/cycling-weekly/the-best-eco-conscious-cycling-clothing-brands-470275. Accessed 14 Sep 2020
Castro-Aguirre E, Iñiguez-Franco F, Samsudin H, Fang X, Auras R (2016) Poly (lactic acid)—mass production, processing, industrial applications, and end of life. Adv Drug Deliv Rev 107:333–366
ChangeMakers (2020). https://www.changemakers.com/fabricofchange/entries/ambercycle. Accessed 25 Sep 2020
Chariyachotilert C, Selke SE, Auras RA, Joshi S (2012) Assessment of the properties of poly (L-lactic Acid) sheets produced with differing amounts of post-consumer recycled poly (L-lactic Acid). J Plast Film Sheet 28:314–335

Cosate de Andrade MF, Souza PMS, Cavalett O, Morales AR (2016) life cycle assessment of poly(lactic acid) (PLA): comparison between chemical recycling, mechanical recycling and composting. J Polym Environ 24:372–384

Cosate de Andrade MF, Fonseca G, Morales AR, Mei LHI (2018) Mechanical recycling simulation of polylactide using a chain extender. Adv Polym Technol 37:2053–2060. https://doi.org/10.1002/adv.21863

CPCB (2013) Website material on plastic waste management Central pollution control board report, India

Cui J, Forssberg E (2003) Mechanical recycling of waste electric and electronic equipment: a review. J Hazard Mater B 99:243–263

Econly (2020). https://www.econyl.com/blog/case-studies-fashion/gucci-off-the-grid-featuring-econyl-yarn/. Accessed on 24 Sep 2020

Eren HA, Avinc O, Uysal P, Wilding M (2011) The effects of ozone treatment on polylactic acid (PLA) fibres. Text Res J 81(11):1091–1099

Eastman Chemical (2020). https://sustainablebrands.com/brands/eastman-chemical. Accessed 25 Sep 2020

Farrington DW, Lunt J, Davies S, Blackburn RS (2005) Poly(lactic acid) fibers. In: Blackburn RS (ed) Biodegradable and sustainable fibres. Woodhead Publishing, Cambridge, UK

Fisher MM, Mark FE, Kingsbury T, Vehlow J, Yamawaki T (2005) Energy recovery in the sustainable recycling of plastics from end-of-life electrical and electronic products. In: Proceedings of the 2005 IEEE international symposium on electronics and the environment, New Orleans, LA, USA, pp 83–92

Francis R (2016) Recycling of polymers: methods, characterization and applications. Wiley, Hoboken, NJ, USA

Garcia JM, Robertson ML (2017) The future of plastics recycling. Science 358(6365):870–872. https://doi.org/10.1126/science.aaq0324

Grigore E (2017) Methods of recycling, properties and applications of recycled thermoplastic polymers. J Recycl 2(4):24

Grigore ME (2017) Methods of recycling, properties and applications of recycled thermoplastic polymers. Recycling 2(4)

Gu L, Ozbakkaloglu T (2016) Use of recycled plastics in concrete: a critical review. Waste Manag

Gupta VB, Kothari VK (1997) Manufactured fiber technology. Chapman and Hall, India

Haemek (2009) Eco-care from Nilit. https://www.knittingindustry.com/eco-care-from-nilit/. Accessed 25 Sep 2020

Halbrook (2020) Igloo launches cooler line created with fiber made from recycled plastic. https://www.environmentalleader.com/2020/08/igloo-launches-cooler-line-created-with-fiber-made-from-recycled-plastic/. Accessed 21 Sep 2020

Hamad K, Kaseem M, Deri F (2013) Recycling of waste from polymer materials: an overview of the recent works. Polym Degrad Stab 98:2801–2812

Hasani H, Avinc O, Khoddami A (2013) Comparison of softened polylactic acid and polyethylene terephthalate fabrics using KES-FB. Fibres Text East Eur 3(99):81–88

Hopewell J, Dvorak R, Kosior E (2009) Plastics recycling: challenges and opportunities. Philos. Trans R Soc Lond B Biol Sci 364:2115–2126

Ignatyev IA, Thielemans W, Beke BW (2014) Recycling of Polymers: a Review ChemSusChe 7:1579–1593

Ignatyev IA, Wim T, Bob B (2014) Recycling of polymers: a review. Chemsuschem 7(6):1579–1593

Iñiguez-Francoa F, Aurasa R, Dolanb K, Selkea S, Holmesc D, Farrington DW, Lunt J, Davies S, Blackburn RS (2005) Poly(lactic acid) fibers. In: Blackburn RS (ed) Biodegradable and sustainable fibres. Woodhead Publishing, Cambridge, UK

InsideFashion (2020). http://insidefashion.net/InsideFashion/Features/tabid/122/ArticleID/231/Recycled-Polyester-Sees-Steady-Growth-but-Apparel-is-Not-the-Key-Driver.aspx. Accessed 21 Sep 2020

InsideWaste (2019) H&M boosts RPET fibre consumption. https://www.insidewaste.com.au/index.php/2019/04/18/hm-boosts-rpet-fiber-consumption/. Accessed 11 Sep 2020
ISPO (2019) Adidas x parley: run to victory with ocean plastic shoes. https://www.ispo.com/en/companies/adidas-x-parley-run-victory-ocean-plastic-clothes. Accessed 12 Sep 2020
Jeplan (2020). https://unreasonablegroup.com/companies/jeplan/#:~:text=Jeplan%20envisions%20a%20world%20in,products%20are%20released%20and%20sold.&text=Jeplan%20then%20recycles%20the%20materials,consumers%2C%20fostering%20a%20circular%20economy. Accessed on 25 Sep 2020.
Karayannidis GP, Achilias DS (2007) Chemical recycling of poly(ethylene terephthalate). Macromol Mater Eng 292:128–146
Khoddami A, Avinc O, Mallakpour S (2010) A novel durable hydrophobic surface coating of poly (lactic acid) fabric by pulsed plasma polymerization. Prog Org Coat 67(3):311–316
Khoddami A, Avinc O, Ghahremanzadeh F (2011) Improvement in poly (lactic acid) fabric performance via hydrophilic coating. Prog Org Coat 72(3):299–304
Kumartasli S, Avinc O (2020) Important step in sustainability: polyethylene terephthalate recycling and the recent developments, sustainability in the textile and apparel industries
Law KL (2017) Plastics in the marine environment. Ann Rev Mar Sci 9:205–229
Malkan SR (2017) Improving the use of polyolefins in nonwovens. In: Ugbolue SCO (ed) Polyolefin fibres. Woodhead Publishing, Cambridge, UK, pp 285–311
Mather RR (2009) The structure of polyolefin fibres. In: Eichhorn SJ, Hearle JWS, Jaffe M, Kikutani T (eds) Handbook of textile fibre structure, vol 1. Woodhead Publishing, Cambridge, UK, pp 276–304
Mclntyre (2013) Second chance. https://www.nonwovens-industry.com/issues/2013-04/view_features/second-chance/. Accessed on 28 Sep 2020
Militky J (2009) The chemistry, manufacture and tensile behaviour of polyester fibers. In: Bunsell AR (ed) Handbook of TensileProperties of textile and technical fibres. Woodhead Publishing, Cambridge, UK, pp 223–314
Mochizuki M (2009) Synthesis, properties and structure of polylactic acid fibres. In: Eichhorn SJ, Hearle JWS, Jaffe M, Kikutani T (eds) Handbook of textile fibre structure, vol 1. Woodhead Publishing, Cambridge, UK, pp 257–275
Mukhopadhyay SK (2009) Manufacturing, properties and tensile failure of nylon fibres. In: Bunsell AR (ed) Handbook of tensile properties of textile and technical fibres. Woodhead Publishing, Cambridge, UK, pp 197–222
Murphy J (2001) Additives for plastics handbook. Elsevier Advanced Technology, Oxford
Niaounakis M (2015) Biopolymers: processing and products. William Andrew Publishing, Oxford, UK
Norcal Compactors (2020) Plastic recycling process. https://www.norcalcompactors.net/processes-stages-benefits-plastic-recycling/. Accessed on 15 Sep 2020
Nylstar (2020) Nylstar introduces yarn made from INVISTA recycled nylon 6.6 polymer with Global Recycled Standard (GRS) Certification. ,https://www.nylstar.com/2020/08/20/nylstar-introduces-yarn-made-from-invista-recycled-nylon-6-6-polymer-with-global-recycled-standard-grs-certification/. Accessed on 12 Sep 2020
Oktem T (1998) Evaluation of polyester waste textile and apparel 6:396–400
Ouederni M (2016) Polyolefin compounds and materials: fundamentals and industrial applications. In: Al-Ali AlMa'adeed M, Krupa I (eds) polyolefinsin textiles and nonwovens. Springer International Publishing, Cham, Switzerland, pp 231–245
PAGEV (2018) Türkiye Plastik Sektor Izleme Raporu
Park JJ, Park K, Park J, Kim DC (2002) Characteristics of LDPE pyrolysis. Korean J Chem Eng 19(4):658–662
Piemonte V, Sabatini S, Gironi F (2013) Chemical recycling of PLA: a great opportunity towards the sustainable development? J Polym Environ 21:640–647
Pivnenko K, Eriksen MK, Martín-Fernández JA et al (2016) Recycling of plastic waste: presence of phthalates in plastics from households and industry. Waste Manag 54:44–52

Procotex(2020)‘Using Recycled PP Fibres Is A Wise Decision. https://en.procotex.com/products/synthetic-recycled-fibres/100-pp.php. Accessed on 15 Sep 2020
Q-Nova (2020). https://www.fulgar.com/eng/products/q-nova. Accessed on 25 Sep 2020
Reco Nylon (2020) https://fibers.nurel.com/en/products/eco/reco-nylon-fibers. Accessed on 25 Sep 2020
RecycledNylon (2020) https://ckh.wrap.org.uk/rawMaterialsAndFabrics/recycledNylon/. Accessed on 25 Sep 2020
Recycling and recovery routes of plastic solid waste (PSW) (2009) A review S.M. Al-Salem , P. Lettieri, J. Baeyens. Waste Manag 29:2625–2643
Rubinoa M, Soto-Valdezd H (2018) Chemical recycling of poly(lactic acid) by water-ethanol solutions. Polym Degrad Stab 149:28–38
Sattler H, Schweizer M (2011) Fibers, 5. Polyester Fibers. In: Ullmann's encyclopedia of industrial chemistry. Wiley-VCH, Hoboken, NJ, USA
Saya (2020) SAYA launches sustainable fiber made from fabric scrap & overstock. https://www.snewsnet.com/press-release/saya-launches-sustainable-fiber-made-from-fabric-scrap-overstock. Accessed on 25 Sep 2020
Seaqual (2020). https://www.seaqual.org/. Accessed 25 Sep 2020
Sevencan F, Vaizoglu S (2007) Pet and recycling TAF preventive medicine bulletin 6:307–312
Shen L, Worrell E, Patel MK (2010) Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling resources. Conserv Recycl 55:34–52
Singh N, Hui D, Singh R, Ahuja I, Feo L, Fraternali F (2017) Recycling of plastic solid waste, A state of art review and future applications. Compos. Part B Eng 115:409–422
Södergård A, Inkinen S (2011) Production, chemistry and properties of polylactides. In: Plackett D (ed) Biopolymers—new materials for sustainable films and coatings. Wiley, Chichester, UK, pp 43–63
Spanflex (2020) RecycledSpandex. https://spanflex.net/english/fabrics/detail.php?dpid=17. Accessed on 25 Sep 2020
Taşdelen MA, Oran S (2017) Plastik Geri Dönüşümünde Zorluklar ve Fırsatlar. http://www.turkchem.net/plastik-geri-donusumunde-zorluklar-firsatlar.html. Accessed on 12 Sep 2020
Tavanaie MA (2014) Melt recycling of poly(lactic acid) plastic wastes to produce biodegradable fibers polymer-plastics technology and engineering 53:742–751
Taylor (2020) ChemicallyRecyledPET. https://www.recyclingtoday.com/article/teijin-recycled-pet-content-yarn-japan/. Accessed on 2 Sep 2020.
Teijin Fibers (2020). http://www.hknonwoven.com/eng/pr/ECOPET%20New.pdf. Accessed 25 Sep 2020
Textile Focus (2020) Sustainable fashion brands, making product from plastic. http://textilefocus.com/sustainable-fashion-brands-making-product-plastic/.Accessed. Accessed on 18 Sep 2020
Textile Exchange (2020). https://textileexchange.org/wpcontent/uploads/2020/06/Textile-Exchange_Preferred-Fiber-Material-Market-Report_2020.pdf. Accessed on 25 Sep 2020
Textile Magazine (2020) A new technology for BCF yarn production from recycled PET. https://www.indiantextilemagazine.in/yarn/a-new-technology-for-bcf-yarn-production-from-recycled-pet/. Accessed 18 Sep 2020
Textile World (2019) The LYCRA company announces GRS certification for its new LYCRA® EcoMade Fiber. https://www.textileworld.com/textile-world/fiber-world/2019/11/the-lycra-company-announces-grs-certification-for-its-new-lycra-ecomade-fiber/. Accessed 25 Sep 2020
Thomas (2012) Recycling of polypropylene (PP). https://www.azocleantech.com/article.aspx?ArticleID=240. Accessed 18 Sep 2020
Tokiwa Y, Calabia BP (2006) Biodegradability and biodegradation of poly(lactide). Appl Microbiol Biotechnol 72:244–251
Tonevitskoya (2019) Textile waste resource or trash? https://medium.com/@stonev/textile-waste-resource-or-trash-151114d1fcff. Accessed on 19 Sep 2020
Toray (2020). https://www.toray.eu/products/fibers/fib_0132.html. Accessed 25 Sep 2020
Voncina B (2016) Recycling of textile materials, 2bfuntex multidisciplinary teams (MDTs), pp 1–37

Walimbe (2020) Novel polyester fiber technologies to play a key role in ushering the textiles industry towards sustainability. https://www.globaltrademag.com/novel-polyester-fiber-technologies-to-play-a-key-role-in-ushering-the-textiles-industry-towards-sustainability/. Accessed on 12 Sep 2020

Wang Y (2006) Recycling in textiles. Woodhead Publishing In Textiles. Cambridge, England

Yüce (2020) Plastiklerin Geri Dönüşümü. https://www.bilgiustam.com/plastiklerin-geri-donusumu/. Accessed on 12 Sep 2020

Zheng Y, Yanful EK, Bassi AS (2005) A review of plastic waste biodegradation. Crit Rev Biotechnol 25(4):243–250