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Chapter

Limitations of Textile Recycling: The Reason behind the Development of Alternative Sustainable Fibers

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Abstract

The sharply increasing world population reveals the insufficiency of natural resources in meeting the needs of humanity, while creating a tendency to search for new resources. Textile products constitute one of the most basic needs of humanity and the consumption of textile products is also increasing due to the changing fashion sense, increasing population, and technology developments. Discovery of alternative or renewable energy sources, recycling of all kinds of materials, enhancing engineering methods and technologies used to make recycling effective, and trends like sustainable fashion that promote sustainability and take parts among the hot topics of this field. Recycling studies are also common in textile science. It is feasible to reduce the usage of natural fibers by utilization of recycled fibers. However, there are some limitations to textile recycling. These limitations led the development of new sustainable fibers and processes as alternatives to natural. In this context, most of the recycling and sustainability-based studies carried out in this field emphasized the indispensability of the subject, while neglecting a few points about limitations. Consequently, the limits of recycling in textiles and new fibers developed to overcome these limits are addressed in this chapter.

Keywords: textile recycling, textile wastes, limitations in textile recycling, textile eco-labels, sustainability certifications, sustainability

1. Introduction

Recycling is the process of converting materials from all kinds of waste to produce new products. Textile recycling implies the reuse and reprocessing of clothing scraps or any fibrous textile material [1]. All types of consumer or industry discarded textile goods are used as textile wastes for recovery. It is obvious that recycling, which has evolved into sustainability over time and its importance has been understood even in ancient times. It can be applied in many fields of the textiles as textile-to-textile (closed-loop) recycling or textile-to-nontextile (open-loop) recycling [2].
The demand for textiles and clothing is increasing day by day as a result of the increasing population, rising living standards, and the fast changing fashion trends [3–5]. Consequently, the amount of textile waste increases, and there are accumulations in landfills [4]. In addition to the consumption of high amounts of textile products, the packaging of these products also causes an increase in waste piles [6].

Textile and clothing waste causes environmental problems and deterioration of ecological balance. Therefore, the reclaim and disposal of waste clothing and textiles are important issues. Unfittingly and uncontrolled disposal of waste cause major problems [5]. The importance of recycling is considered in three subjects by Ref. 7 as economic, social, and environmental subjects [7]. Recycling of textile waste and diversifying the content of recycled raw materials could be a way to support the country’s economy. The employment opportunities in the textile sector as in other sectors increase with well-run waste management. The recycling sector is an important supplier to many industries, and wastes are considered as cheap raw materials [8]. A wide variety of garment brand companies offer their products that contain recycled materials at certain rates, as a social responsibility issue in the market and to increase their prestige. It also adds profit to the company by paying less for recycled materials obtained from waste products.

Although there are several methods for the disposal of clothing waste, the most effective methods are recycling and reuse. Evaluation of waste clothing is very complex since clothes are made from different raw materials and may contain various accessories. Clothing may have many components such as labels, sewing threads, buttons, zippers, and interlining, and these components make the separation process difficult. Clothing recycling and textile recycling are two independent topics that are needed to be considered separately [5]. Textile wastes arise out of many production processes, such as fiber and filament manufacture, spinning, weaving, knitting, nonwoven, and clothing manufacturing [9]. In this context, textile wastes can be classified as pre-consumer and post-consumer wastes [10, 11]. Pre-consumer textile waste includes manufacturing waste from the processing of fibers, yarn, fabric, and nonwovens and clothing manufacturing [12]. Pre-consumer textile waste is generally seen as “clean waste” as it is released during the textile production process [13, 14].

When all these wastes are well managed, positive results emerge both in terms of providing economic gains via the recycling of materials and reducing the ecological damage to the world. Despite all advantages, there are recycling limits for all kinds of textile wastes. Not only for textile wastes but also for other solid wastes recyclability varies. Some types of wastes can be easily and well recycled, whereas some types cannot or can formidable be recycled [1]. These limits pave the way for the emergence of new recyclable fibers for the textile industry.

The purpose of this chapter is to present a systematic study for recycling of textiles mentioning the limits and alternative sustainable fibers. The content started with the history of recycling, continued with processes, standards, and certificates about textile recycling. Subsections of recyclable common textile fibers and new recyclable textile fibers are given in detail.

2. History of recycling

Recycling dates back to ancient times [15]. It is claimed that waste management and waste disposal processes date to BC in several references [16, 17]. Recycling is
known as an efficient and effective solid waste management system [18]. In 4000 BC, silkworm wastes were used as protein source food in fish raising in China [19].

Scientifically, the foundations of recycling were laid in the 1980s [20]. When we consider textile recycling, it is known that it is as old as recycling in other fields. There are even references stating that it is one of the oldest fields, so textile recycling is called original recycling [21]. China hosted applications where recycled fibers from used clothing were obtained by hand carding and mixed with virgin fibers BC [14]. The textile recycling industry took its first steps in the thirteenth century [22]. In pre-modern societies, there were sustainability models based on the reuse and recycling of textiles [14]. For example, recycling has been done for years in India, both at the household and industrial level [23]. In the early and mid-1800s, reclaimed spin waste and rags were used for the manufacture of new products, and the invention of carbonization made it a unique technique to separate textile waste comprising of cellulose-based and wool fibers blend [22].

Environmental awareness concept had been newly introduced in the 1960s. The conscious interest of consumers and producers had just begun to turn to recycle at that time. Today, it is argued that this interest has evolved into sustainability [24]. Early academic studies conducted in the 1990s focused on presenting a model for the textile waste lifecycle [25]; detailing biological, physical, and chemical treatments of textile wastes [26]; determination of the number of sewn product manufacturers that support recycling in an American state [27]; the recyclability of post-consumer fibers, and market applications, while revealing the advantages of recycling [28]. After this decade, a positive acceleration was observed in the studies on both recycling and textile recycling. When “textile” and “recycling” terms are searched in a topic currently 1843 documents in WOS were encountered at all times. Moreover, 188,487 documents were encountered with the only term “recycling” at all times. The variation of the number of publications by years are given in Figure 1 and in the first quarter of 2022, 41 documents were published about the textile recycling topic. As can be seen from the graph, the number of research on textile recycling has increased in parallel with the number of research on recycling over the years.

![Figure 1](image)

*The number of publications encountered with search terms “recycling” and “recycling and textiles” in WOS.*
3. Processes in textile recycling

3.1 Recyclability of textile materials

Recycled fibers are used to make a variety of products. By producing yarns from recycled fibers, knitted or woven fabrics can be produced, or non-woven surfaces are obtained directly from these fibers. Recycled pre-consumer textile wastes are utilized in the construction, automotive, furniture, paper, and clothing industries. However, fibers obtained from pre-consumer textiles are used especially in coarse yarn production [29]. Many researchers studied about using pre-consumer waste and its conversion into a valuable product in the literature. Jamshaid et al. [30] span open-end rotor yarns from fibers in different blends reclaimed from yarn and fabric wastes. They evaluated the impact of various textile wastes on fiber and yarn quality. They underlined that the length and uniformity values of the fibers recycled from yarn wastes are better than those of the fibers recycled from fabric wastes. However, in terms of yarn manufacturing costs, it has been stated that yarns produced from recycled fabric/rag wastes are more economical than yarns produced from yarn wastes. The impact of cotton waste and various spinning conditions on rotor yarn quality was investigated by Halimi et al. [31]. The results showed that the quality of the rotor yarn is not affected by the addition of 25% waste in the first passage of the draw frame. Yilmaz et al. [32] produced yarns by blending the fiber wastes taken from the blow room, the carding and sucked in the draw frame, roving, and conventional ring spinning machines with the virgin cotton fibers at 5 different amounts varying from 5% to 40%. They emphasized that by designing machinery and process steps based on waste fiber type, it can be possible to produce yarns that are in comparable quality values and low cost.

The post-consumer textile wastes consist of clothing and home textiles that consumers no longer need for various reasons, such as damage, pulling on, or going out of fashion [14]. Contrary to pre-consumer wastes, post-consumer wastes are known as dirty and household waste [33]. Post-consumer wastes are evaluated with reuse and recycling techniques or incineration. The options to be applied to post-consumer waste vary according to many criteria such as the wear condition of the clothing, fiber content, and the technology of the recycling facilities [34]. The progress in recycling technology supports the sustainable disposal of waste clothing, and recycling is far more environmentally friendly and socially beneficial than incineration. In addition to this, technological advancements are required to produce upcycle products from waste clothing. Improvements in the collection and disposal of post-consumer textiles can be made with the application of environmental protection policies [5].

Post-consumer waste of sufficient quality is utilized as second-hand clothing by other consumers or sold to third-world countries. The volume of consumer waste is quite high, and clothes that cannot be worn again are shredded into fibers and used in new products, similar to pre-consumer wastes [6, 14]. The process of producing new clothing from post-consumer waste includes collecting waste, obtaining fiber from waste, and producing yarn by using a certain amount of blend in the yarn production stage [34].

When compared to original fibers, recycled fibers have different properties. The processes that the fibers are exposed to during the recycling process damage them and shorten their length. Fiber length is important factor in converting recycled fibers into yarn or producing nonwovens from these fibers, and the fibers must be long enough. Due to the short length of recycled fibers and the presence of non-fiber remnants such as fabric and yarn fragments, defining some quality parameters of
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these fibers is difficult. Fiber length, material break down degree, and fiber length distribution are three of the most widely analyzed properties of recycled fibers [35]. There are four different approaches to recycling (Figure 2) [36, 37]:

- Primary approach,
- Secondary approach,
- Tertiary approach, and
- Quaternary approach

Primary recycling is the most beneficial method, and in this approach, the product is recycled to its original form. This approach is also known as "original recycling." It is aimed at synthetic fibers such as PET (polyethylene terephthalate) and PA (polyamide) [37]. In this method, which can also be blended with the similar original raw material in order to increase the product quality, cleaned and pure scraps from waste are collected and recycled. In addition to the important advantages of this process such as being cheap and easy, it also has the disadvantage that the type of recyclable material is limited [38].

Secondary recycling is the process of converting waste into a product with different physical or chemical properties than the original [39]. Secondary recycling, which converts post-consumer wastes into raw materials, includes the collection and recycling process [40]. The content of textile waste, the degree of purity of the end product, availability, cost, and processing techniques are important factors for secondary recycling.

In tertiary recycling, known as feedstock recycling, wastes are separated into chemicals through pyrolysis, gasification, hydrolysis, and condensation [41]. Tertiary recycling, which is preferred for converting plastic wastes into chemicals, monomers, or fuels, utilizes clean and well-sorted pre- and post-consumer wastes [40].

Quaternary recycling is the use of heat produced by the incineration of fibrous solid wastes [42]. In summary, primary and secondary recycling usually involve the mechanical processes of industrial by-products and waste, while tertiary and quaternary recycling includes the pyrolysis and incineration of textile wastes for energy generation [41].

3.2 Recycling processes in textile

3.2.1 Physical processes in textile recycling

3.2.1.1 Mechanical process in textile recycling

Mechanical recycling is a low-cost and easy method [11], which is the preferred method for recycling a diverse variety of textile waste [43]. The recycling of
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post-consumer textile waste is generally carried out by mechanical recycling [42]. In the mechanical recycling technique, the fabric is broken down into fibers by cutting, shredding, carding, and other mechanical processes [44, 45]. Mechanical recycling machines gradually break the fabric into small pieces and make it fibrous, and these obtained fibers are reused in the production of yarn or nonwovens. In the mechanical recycling process, initially, wastes are sorted. Foreign components, such as metals and labels, are eliminated. After the fabric is cut into small pieces with rotary blades, it is separated into fibers by tearing [40].

Since garments are usually made from different raw materials, it is better to use pre-consumer waste instead of post-consumer waste in mechanical recycling. Fibers obtained by mechanical recycling from pre-consumer wastes such as denim scraps can be used to make higher-quality yarns. The length of the fibers recycled by the mechanical recycling process is short, despite the use of clean pre-consumer wastes [40]. The fiber length is shortened by the shredding/tearing process. The main reason for this is the friction between the fibers. Friction causes wear of fibers and melting of synthetic fibers. Lubricants are used to reduce friction between fibers during shredding and thus longer fiber lengths can be obtained [46]. In addition to the lubrication process, product quality is increased by blending original fibers with recycled fibers [45].

Recycled fiber properties such as length, fineness, and strength indicate the field the fibers can be evaluated in [47]. Good quality recycled fibers can be spun into fabrics, while lower quality fibers are used as decoration materials, construction materials [48], automotive components, insulation materials, and nonwovens [45, 47].

3.2.1.2 Thermal process in textile recycling

In thermal recycling, synthetic fibers are melted to be reshaped. The thermal recycling method is preferred for recycling synthetic fibers [48, 49]. Chips and pellets obtained by mechanical process from synthetic wastes are turned into fibers by melt extrusion [50].

3.2.2 Chemical recycling in textile

Chemical recycling, which is another method used in the recycling of textile waste, is the depolymerization of polymers or the process of dissolving polymers [2]. Polymers are converted or broken down into their original monomeric building blocks by chemical and biological methods [51].

Monomer and polymer recycling are the two forms of chemical recycling. The polymer chain is frequently degraded during polymer recycling. As a result, the quality of the recycled fiber decreases. In monomer recycling, original quality fibers are obtained. While monomer recycling is only used for synthetic fibers, chemical recycling is applicable to many textile fibers [49]. In addition to the chemical recycling of synthetic fibers, such as polyesters, polyamides, and polyolefins, in cotton and polyester blend products, the fibers can be chemically separated and then converted into new fibers [47].

3.2.3 Downcycling

Downcycling occurs when the quality and economic value [40] of a product obtained from recycling processes is lower than that of the original product [2, 50]. The use of recycled clothing and home textile wastes in agriculture and gardening
products, decoration materials [48], insulation materials, low-quality blankets, and upholstery fabrics are the examples of downcycling (Figure 3) [2, 50].

3.2.4 Upcycling

When the quality of the recycled material is the same or higher than the original product, this process is called upcycling [2, 50]. Upcycling is a process in which existing resources are used and converted into more useful products. This environmentally-friendly process is an important step for a zero-waste policy [52]. Within the scope of sustainability and circular economy, the production of raw materials such as cotton fibers and yarns from textile wastes with polymer and monomer recycling is an example of upcycling [2, 50].

3.2.5 Open-loop recycling in textile

Open-loop recycling is defined as the use of a product’s raw material in a different production area. Secondary products obtained through open-loop recycling are generally destroyed after their lifetime [40]. The use of fibers obtained by recycling PET bottles in the textile industry (Figure 4) [40] and the usage of recycled textile fibers as insulation material in the construction industry are examples of open-loop recycling.

Figure 3. Downcycling applications in textile.

Figure 4. Open-loop recycling.
3.2.6 Closed-loop recycling in textile

The reuse of recycled textile waste in the textile industry is called closed-loop recycling [2]. The use of mechanically recycled pre-consumer or post-consumer textile waste in garment production is an example of a closed-loop recycling (Figure 5) [40].

4. Sustainable textile Fibers

4.1 Recyclable common textile fibers and limitations

The subject of recycling in textiles comes up with a lot of research based on the advantages created by the recycling process and with a limited number of studies based on recycling limits. In this subsection of the chapter, the limits of recycling in materials traditionally used in textiles are addressed.

Despite the approaches expressing that recycling is a process that only delays the conversion of waste to nature [53], several articles emphasized the importance of process development studies about the determination of recyclability limits [54]. Since it is impossible to apply a uniform recycling method for recycling all kinds of waste materials, different recycling techniques and their combinations have emerged over time [53]. For example, chemical recycling is raised in order to eliminate the limits in mechanical recycling [55]. As recycling can be classified as mechanical, chemical, thermal, and thermomechanical methods; each of them has numerous disadvantages in terms of the imperfections created on the recycled material. Considering these limits, alternatives purposed for the disposal of textile waste as anaerobic digestion, fermentation, composting, and acquisition of construction material [13].

An assessment can be made on the basis of fiber source for recycling limits. Based on the disadvantages, such as shortening or shredding the fibers created the fibers by each recycling cycle, it is stated in the literature that an average of 8 recycling cycles for synthetic fibers and an average of 5 cycles for natural fibers can be actualized [56, 57]. While the recyclability limits are more evident in natural fibers, the same rule is not valid for the fibers formed from thermoplastic polymers. This is the main reason why thermoplastic polymer-based textile waste is the most recycled waste [58].

To increase the quality of the recycled end product in cotton mechanical recycling, there is an obligation to use virgin fibers in addition to recycled fibers at a
predetermined ratio. This can be attributed to the decrease in strength according to the recycling cycles as each cycle results in a lower degree of polymerization [59]. The upper usage limit of 30% for recycled cotton in fabrics is specified due to the shortened fibers. The amounts higher than this value causes decreases in fabric quality and performance [60]. Another study in the literature supported this result [61]. Since the fiber breakages are created in the mechanical recycling of cotton [59, 62], low-performance fabrics may be obtained not suitable for professional wear such as workwear, personal protective equipment, career wear, and uniforms [63].

Recycling is classified as primary and secondary recycling in several references. Secondary recycling can be handled as mechanical recycling and the limits mentioned above are also valid for this type of recycling. On the other hand, in primary recycling, the features of waste such as being from a single source and being pure are indisputable, while the low cycle number for each material and even the non-recyclability of some materials constitute these limits [64].

An important factor limiting the chemical recycling process of cotton is the use of harmful chemicals in the industry. While trying to minimize the damage to nature with waste disposal, the use of harmful chemicals which refers to the duality in this phenomenon creates greater harm to both nature and the consumer [59]. Moreover, the need for the separation of textile waste according to color and/or product type is inconvenient. One of the problems encountered in cotton recycling is that most of the cotton products are dyed ones and it is difficult to work with mixed-colored wastes [63]. Besides, there are studies proving that cotton fibers recycled from colored fabrics tended to possess lower quality values [65]. Thus, the demand for more environmentally friendly approaches continues [59].

Wool is a natural fiber that can only be mechanically recycled. The staple length of wool gets shorter with recycling, and it is used in blend ratios with virgin wool up to 70 recycled/30 virgin. The limited market of recycled wool is also a huge obstacle to the recycling of this fiber [63].

Nylon is a polymer with a wide variety of types that is stated as an infinitely recyclable polymer [66]. It is difficult to recycle nylon with mechanical recycling in the industry. In addition, the low number of nylon suppliers makes recycled nylon fibers more expensive [63]. Vidakis et al. studied the effects of multiple recycling cycles of PA12 on its properties. There was a decrease in mechanical properties above 5 recycling cycles. This weakening in mechanical properties is explained by the decrease in crystallinity and the beginning of degradation [67]. When the thermal recycling of polyamide 6 is evaluated, it was seen that a drying process is suggested before melting. It is revealed that the drying process prevents hydrolytic chain scission in wet materials and the intrinsic properties of PA6 polymer are remained [68].

Various studies were conducted in the literature in the last two decades for the determination of recycling cycle limits of polymers. PET which is a thermoplastic polymer widely used in the textile sector one of the polymers tested. Högg performed four recycling cycles on PET and characterized the basic polymer properties. He revealed that there was a considerable decrease in Young’s modulus according to the decrease in intrinsic viscosity [69].

The polyolefin fibers react with oxygen in remelting cycles. High temperature or UV light applied in remelting cycles result in molecular weight loss. The dissolution/reprecipitation process for the recycling of high-density polyethylene (HDPE) has been suggested to overcome this limit by Poulakis and Papaspyrides. It is remarked that both the polymer and the solvent has been recovered efficiently. According to this process applied as two recycling cycles to HDPE, no changes in molecular weight,
distribution of grain sizes, crystallinity, and mechanical properties were observed [70]. The same researchers applied this technique to virgin PET in pellet form and PET in blow-molded bottle form in two cycles. It was observed that the properties of recycled PET did not change [71].

The effects of seven recycling cycles on PLA (polylactic acid) polymer which is also a polyester was evaluated by Pillin et al. They observed a notable decrease in the molecular weight of the polymer. They attributed the changes in stress and strain at break, modulus, and hardness via recycling cycles to the decrease in molecular weight [72]. Another group studied eight recycling cycles of PLA and concluded that there were no changes in the mechanical properties of the polymer due to the successive cycles [73].

PAN (polyacrylonitrile) is another polymer commonly used in the production of textile products as an alternative to wool. The most critical factors limiting the recycling of PAN are the easy accessibility of perfect virgin PAN and the harsh processing conditions. From this point of view, economic conditions come into play in the recycling of PAN. The high temperature applied during recycling is also shown as a disadvantage for acrylic, which is a polymer inclines to open-loop recycling [74].

Textile wastes consisting of blends of various fibers complicate the recycling process and sometimes even make it impossible. These fibers need to be separated, which should be done by expert workers to avoid problems with the recycled final product. In addition, when it is impossible to recycle these wastes, they reach their end-of-life by utilization in energy recycling [75].

From a different point of view, there are basically two main factors limiting the recycling of textile fibers. The first one is the technological limits of recycled fibers and their inability to be used within virgin fiber, yarn, or fabric production methods. The second is that the expected product quality value cannot be reached by using these recycled fibers [76].

There are two types of sustainable fashion drivers in a sustainable fashion as production and consumption drivers. Material, human and intellectual resources form the production drivers and purchasing decisions, usage, and post usage form the latter. While technical limits are considered in the first derivatives, unawareness of consumption causes a considerable increase in waste [77]. The fact that recycled materials are generally suitable for downcycling emphasizes an important point that should be evaluated economically. Another economic point is the low consumer demand for recycled products. The reason behind the low market demand is the use of dangerous chemicals in recycled products. In addition, waste sorting is a big problem and if it is not done properly, it negatively affects the recycling process from the beginning. Finally, the relevant standards are still in their infancy. All of these may be listed as examples of the limits of recycling [78].

4.2 Branded sustainable textile fibers

Cotton and polyester are the most recycled fibers as referred before. Cotton is the most used type of natural fiber in the textile and clothing industry global consumption is reported as 26.16 million tons and the production rate is 26.43 million tons by the year 2021. When we evaluate cotton cultivation in terms of environmental aspects, it requires a large quantity usage of land occupation, water, and also pesticides. Due to pesticides, it pollutes clean water resources. In the textile production process, cotton dyeing needs a high amount of energy consumption, water, steam, and chemicals, such as bleaching agents, soap, softeners, and salts for obtaining the
desired color [55, 79, 80]. Polyester is a non-biodegradable fiber in the environment. Its production process is very similar to polyamide. But polyester is extensively recycled especially as plastic bottles made of polyethylene terephthalate to reduce the landfills. Polyamide is used especially in carpets as referred before. But its recycling process is difficult because of the used dyes and chemicals added to its polymer solution [10].

Besides these types of common fibers, there have also been come out brands with the increasing recycling trend. Renewcell® technology is the upcoming brand from Sweden since 2017. For this process, used garments and textile production waste with high cellulosic content such as viscose, lyocell, modal, acetate, and other types of regenerated fibers (also called man-made cellulosic fibers) are used. Their accessories, such as buttons, zips are removed from the textile material, then it is turned into a slurry. Contaminants and non-cellulosic contents are sorted out from this slurry. This blend, brand named as Circulose® that is consisted of dissolved pulp from 100% recycled textiles dried and packaged as bales for being involved in the textile production process [81, 82].

Repreve® is known as the r-PET staple and filament yarns which are made from post-consumer water bottles and pre-consumer waste, and their fibers are used in many types of industrial product categories. Accessories, apparel, automotive, bedding, flooring, footwear, furnishings, medical accessories, military, outdoor, socks, and hosiery are some of them. As they stated they eliminated the processes; crude oil wellhead, crude oil refinery, Naptha, Xylenes, Paraxylene, TA (Terephthalic Acid) & MEG (Mono Ethylene Glycol). They have chip production (polymerization), extrusion, and texturing for Repreve® polyester filament yarns and feed stock preparation (polymerization), extrusion, and staple processing for Repreve® staple polyester fibers [83, 84]. Moreover, there is a recycled Nylon brand that is Repreve® Nylon 6 fibers. In production, they have also eliminated the processes; crude oil wellhead, crude oil refinery, benzene, cyclohexane, HMD (Hexamethylenediamine), adipic acid, and nylon salt. They have only chip production (polymerization), extrusion, and texturing processes [85].

Trevira® Sinfineco is the brand used for textiles that contain sustainable Trevira® products. They worked together with Thailand-based parent company Indorama whose manufactures recycled chips from PET bottles. They have certificates for recycled chips, fibers, and filaments from GRS (Global Recycled Standard) and RCS-NL (Recycled Claim Standard). Their products are mainly used in the automotive and apparel sectors. Trevira® Sinfineco PLA fibers and filaments are produced from plant sugars (sugar beet, sugar cane, and maize). So, they are recyclable and 100% biodegradable (industrially compostable) fiber materials. The plant sugar is subjected to the fermentation process and it is transformed into lactic acid. Besides their advantageous properties such as UV stability, fastness to light resistance, good wicking properties, it has less environmental impacts. 70% less CO₂ is emitted and 42% less energy is consumed in the raw material production process. They have ISEGA certification for PLA fiber types used in hot water filtration applications (tea and coffee filters) and packaging materials contacting with food [86].

rPET companies supply post-consumer materials in different ways. One of these interesting materials is Bionic®, which collects its source from the coastline of the oceans and waterways to produce rPET PES. Besides environmental benefits, they also get community support both for collecting and cleaning, building up waste management systems including sorting by material and color, compacting, grinding, and warehousing. Besides, they teach the system wherever their collecting point is. Then,
they send them for pelletizing. Finally, the recycling process goes in the traditional way. They have three kinds of yarns; FLX® from marine plastics, DPX® from recycled plastics, and natural or synthetic fibers for gaining softer texture, HLX® from 3 layers; core, recovered with rPET and natural fibers in the outer sheath [87].

As technological sustainability process Lenzing™ introduced Refibra™ Technology which is called as reborn Tencel® Fiber Technology and they addressed that it is one of the circular economy solutions. It is a closed-loop technology in which cotton scraps and wood are used for pulping processes. For cotton scraps, they use a special and patented method for transforming colored cotton rags into the lyocell grade pulp by dye removal process and degree of polymerization adjustment. Recycling and upgrading of cotton scraps to new virgin lyocell fibers are free from water and solvent usage. It is certified according to Recycled Claim Standard (RCS) and Global Recycle Standard (GRS) [88, 89]. Lenzing™ EcoVero™ fibers are sustainable viscose fibers that are produced by the use of certified and controlled sustainable wood sources, ecological production process, and supply chain transparency as stated. It has 50% lower emissions and water impact than generic viscose. Lenzing™ EcoVero™ fibers are certified with the EU Ecolabel. It means that the production method has a lower impact on the environment compared with other products in the market [90]. Livaeco by Birla Cellulose™ is eco-enhanced viscose manufactured using a closed-loop process. As they declared, they make a series of changes in the process to be more environmental-friendly. They used a molecular tracer so that they can follow the product from fiber stage to garment form and they can verify the product easily. They emphasize that their source is from certified sustainable forests, they consumed lower water compared with other types of natural fibers, lower greenhouse gas emissions and biodegrades in 6 weeks. They stated that cost of Livaeco™ is 4–5% higher than the conventional type of their fibers produced [91]. Livaeco™ has the FSC® C135325 certificate that refers wood is sourced from the forests following the principles of Sustainable Forestry Management provided environmental, social and economic benefits. They also have various certificates, tools, and documents about sustainability for different processes. They have Forest Stewardship Council (FSC®) certificate for obtaining wood, pulping, fiber production processes regularly; Rainforest Alliance certificate in pulping process; Higg Index, Thinkstep in fiber production step; Tracer tool (fiber, yarn, fabric, garment), OEKO-TEX 100, Sustainable Textile Solution for their Livaeco™ viscose fiber, BLOCKCHAIN for Fiber 2 Retail Process. Besides these certificates, they achieved Dark Green Shirt, Ranking in Canopy’s Hot Button Report in 2020 [92]. Kelheim Fibers have also CELLANT Viscose which is introduced as the first in-fiber sustainable viscose infrared (IR) solution that is an alternative to synthetic fibers. They use natural minerals and embedded them into plant-based fibers. It is certified by FSC® or PEFC™ about raw material used. They are also awarded with a dark green/green shirt in Canopy’s 2021 Hot Button Report, which is a sustainability indicator for viscose fiber producers [93].

When polyamide is considered, one of the brand marks is Econyl® by Aquafil S.P.A. It has two types of nylon textile filament yarns; ECONYL® FDY yarns on beam and ECONYL® texturized yarns on cones that are both types of yarns produced via using 100% recycled post-consumer and post-industrial recycled content. They use fishnets, carpets, oligomers (generated by polymer industries), and other types of PA6 materials as wasted content. In ECONYL® plant operation processes has two steps as depolymerization step (where the specific mix of waste is transformed back into secondary raw material-caprolactam) and the purification step of caprolactam [94].
Fulgar is another company that has various types of sustainable fibers with the brand names; Q-NOVA®, Q-CYCLE®, EVO®, AMNI SOUL ECO®. Q-NOVA® PA 6.6 yarn has an eco-friendly process called as MCS (Spinning Continuous Melting). MCS is a mechanical regeneration system that does not involve using chemical materials which would lessen the sustainability of the end product. More than half of it is produced by pre-consumption waste. This waste is remolded using a mechanical regeneration process, then after, it is turned into a form of a polymer. Its prominent features are stated as lightness, breathability, having bright colors. It has certificates as The Global Recycled Standard (GRS), EU ECOLABEL, Higg index [95]. Q-CYCLE® yarn is their new eco-sustainable PA 6.6 yarn produced with their interaction with BASF’s ChemCycling™ recycling project. They use post-consumer recycled contents like plastic wastes (used tires) that is not possible to be mechanically recycled. Its certifications are under the evaluation process [96]. EVO® is the other trademark of Fulgar that is a bio-based origin polyamide that its polymerization is partially or completely sourced from castor oil (from castor seeds) [97]. AMNI SOUL ECO® has enhanced PA 6.6 formula, developed by Rhodia-Solvay group, which enables garments to be a biodegradable feature when left in landfills [98].

Considering the polyurethane known as elastane in the market, COREVA™ can be mentioned. It is a plant-based yarn obtained from natural rubber for replacing synthetic, petrol-based yarns and is patented by Candiani Denim. Organic cotton is wrapped around a natural rubber core, so they produce plastic-free yarn by replacing conventional synthetic and petrol-based elastomers. As they declared, Candiani has created an innovative, biodegradable stretch denim fabric but still, it has the features such as elasticity, physical qualities, and durability that are important factors for producing jeans [99].

4.3 Sustainability certifications for textiles and textile eco-labels

Environmental issues are a trending topic and their importance increase gradually. There are some international treaties to regulate the behavior of the countries to reduce greenhouse gases and protect the ozone layer. Kyoto Protocol and Montreal Protocol are exemplary treaties for the sign of industrialized countries, describing the precautions that they should take [55]. The carbon footprint is the amount of the greenhouse gases released from fossil fuels used for electricity, heating, and transportation purposes. Textile and clothing sectors are the leading sectors that have high carbon footprint generation and greenhouse gases emissions [37]. Energy is the other critical case for the textile industry. The consumed energy according to textile processes can be given as 34% for spinning, 23% for weaving, 38% for chemical process, and 5% for various purposes [100].

All the efforts for sustainability including getting certifications, discovering new sustainable processes, producing new sustainable fibers, getting textile ecolabels, United Nations‘ The Sustainable Development Goals (UNSDGs) are playing a major role. United Nations’ 17 goals can be listed regularly as; no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions, partnerships for the goals. There are various studies about the relationship between UNSDGs and fashion brands, certifications, and new type of sustainable fibers [101, 102].
In the past, products are disposed of after the end-of-life or disuse of the products. But today, solutions and precautions for sustaining the environmental cycle are steadily taken. ISO 14040:2006 (Environmental Management-Life Cycle Assessment-Principles and Framework) is the valid standard to evaluate the sustainability of the product cycle [103, 104]. Life cycle assessment (LCA) is a methodology that is determined by the ISO 14040 and ISO 14044 [80]. It merges the environmental impacts of the studied product or service through the value chain [104]. It is possible to determine the potential environmental benefits of various systems of textile reuse and recycling processes within the methods of LCA [50]. LCA does not contain design and development stages because it is considered that design of the product has not environmental impact. But the design of the product can be affected by the other life cycle stages such as emissions to air, water, and land at each stage of manufacture, use, and disposal of the product [105].

There are various textile sustainability standards and certifications. EU Ecolabel supports Europe strategy for zero pollution and circular economy targets by minimizing products’ harmful impact on the environment. Products labeled with EU Ecolabel make a reduction in water consumption, make less pollution in the air, restrict the use of hazardous chemicals, and minimize the waste [106, 107]. Better Cotton Initiative (BCI) is claimed itself as the world's leading sustainability initiative for cotton. Their mission is to help cotton communities survive and thrive while protecting and restoring the environment. They have selected five impact areas consisted of climate change mitigation, soil health, pesticide use, smallholder livelihoods, and women’s empowerment [108, 109]. In BCI’s Better Cotton Assurance Model, they have a roadmap for Better Cotton Farmers and farmer groups to move from baseline performance to meeting the key indicators of the Better Cotton Principles and Criteria and ultimately achieving long-term improvement goals. The model has four overarching goals. The first one is giving license to sell their cotton as Better Cotton if they can meet the standards and criteria to license for selling their cotton as Better Cotton. The second one is improvement in the framework for making sustainable practices. The third one is the development in the improvement of connection between producers and partners. The last one is measuring the sustainability performance of the farmers [109, 110].

Besides OEKO-TEX Standard 100, OEKO-TEX has series of Sustainability Standards comprising of Oeko-Tex Sustainable Textile Production (STeP), Made in Green by OEKO-TEX®, ECO PASSPORT by OEKO-TEX®, OEKO-TEX® DETOX TO ZERO. ECO PASSPORT by OEKO-TEX® is used for chemical products (textile and leather chemicals, colorants, and auxiliary agents) that are used in the textile, leather, and clothing industry. Oeko-Tex Sustainable Textile & Leather Production (STeP) is the standard for modules, such as chemical management, environmental performance, environmental management, social responsibility, quality management, health, and safety in production chain. To get Made in Green by OEKO-TEX® certificate, some criteria (some OEKO-TEX® certificates) should be taken due to finished products that consumers can buy at retailers or semi-finished products sold to companies within the supply chain. This certificate means that textile or leather products’ materials are tested for harmful substances, produced as environmentally, safe, and socially responsible workplaces are supplied [111].

GOTS is also one of the textile processing standard for organic fibers, also both for ecological and social criteria. It comprises the whole textile supply chain starting with harvesting of the raw materials till packing and labeling. It is important to use dyes and chemicals that have a low impact on environment and even it has water norms in production, besides this, it also considers fiber requirements,
environmental criteria, social criteria, and traceability. GOTS have various production criteria limits. For example, additional fiber limits for natural fibers both for vegetable and animal fibers (linen, hemp, wool, silk, mohair, etc.) is up to 30%; for sustainable regenerated fibers is (Lyocell® & protein based fibers: from organic, FSC(Forest Stewardship Council™)/Programme for the Endorsement of Forest Certification (PEFC) certified recycled raw materials is up to 30%; for Recycled Claim Standard (RCS from Textile Exchange), Global Recycle Standard (GRS from Textile Exchange), Recycled Content Standard (from SCS) certified synthetic fibers (polyester, polyamide, polypropylene, and polyurethane) is up to 30%. There are also restricted fibers in blends like conventional cotton, virgin polyester, conventional angora hair, acrylic, asbestos, and carbon, silver. They have also an obligation for using virgin synthetic and regenerated fibers like viscose, modal, polyamide, elastane, and polypropylene in fiber blends as the maximum ratio is 10%. They have given some more examples like it is permitted to use 70% organic cotton, 30% lyocell from the organic plantation; but, it is not permitted to use 70% organic cotton, 30% lyocell from conventional wood [112, 113].

BlueSign® is one of the sustainability standards that offer a system with solutions for industry and brands for increasing their sustainability performance. They have various criteria such as chemical products for end-consumer use, surface treatment of metals, and plastics/non-textile substrates, fiber manufacturing, textile manufacturers, down and feathers processing, flame retardants, nanoscale materials/structures [114]. They have also a restricted substances list (RSL). In fiber manufacturing for production sites, it is stated that 99% solvent recovery (lyocell, acetate, etc.) rate should be aimed at dry spinning or wet spinning. They encourage their partners to develop fibers that meet their requirements for supporting a circular economy and to give ahead manufacturers to produce and use of recyclable and recycled fibers for circular textile production. It is obligatory for fiber manufacturing sites to pass the chemical assessment that they use Alkylphenol ethoxylates (APEO), free agents, in all preparation and sizing agents used. It is possible to give more examples for other type of fibers. In polyester fiber production, they have limited values of volatile organic compounds (VOCs) not only for year, but also limited emission factors per PET chips (one kg) and filament fiber (one kg). It is also important to have wood policy for cellulosic regenerated fibers, such as viscose, lyocell, and acetate. In production, 25% of sourced pulp fibers/pulp should be used from the wood certified by independent third-party certification with the label of the Forest Stewardship Council (FSC®). Besides this, independent third-party risk assessments, audits and on-site visits should be taken with positive results by audits (preferably a CanopyStyle Audit with at least bronze status) or independent third-party certification of sustainable forest management programs (e.g. Rainforest Alliance) [115].

The Higg Index is used as a tool for the standardization of sustainability measurement. It is comprised of five tools; the Higg Facility Environmental Module (FEM), Higg Facility Social & Labor Module (FSLM), Higg Brand & Retail Module (BRM), Higg Materials Sustainability Index (MSI), and Higg Product Module (PM). They evaluate the social and environmental performance of the value chain together with the environmental impacts of products. It gives an opportunity to consumers using the Higg Index to inform their individual sustainability strategies in crosswise topics, such as water use, carbon emissions, labor conditions, consumer goods brands, retailers, manufacturers, and governments [116].

The Recycled Claim Standard (RCS) and Global Recycled Standard (GRS) are stated as international and voluntary standards. They set requirements for third-party
certification about recycled input and chain of custody. Their aim is to raise the usage ratios of recycled materials. The GRS contains also social and environmental processing requirements and chemical restrictions as additional criteria compared with RCS [117]. For RCS, labeling can be applied to all products containing at least 5% recycled material for textiles. It also enhances the traceability of recycled raw materials, transparent communication, clear labeling, and stakeholder engagement [118]. The GRS label assured that there are high percentages of recycled contents in products, the harmful impact is reduced both for people and the environment, traceability and stakeholder engagement are supplied [119].

Cradle to Cradle Certified® is another global standardization for safe, circular, and responsibly made products. It evaluates the safety, circularity, and responsibility of materials and products in five categories of sustainability performance such as material health, product circularity, clean air & climate protection, water and soil stewardship, and social fairness [120].

Forest Stewardship Council® (FSC) forest management certification endorsed that the management of forests is made by taking care of biological diversity and benefits the lives of local people and workers. There are 10 principles for forest operation for receiving FSC forest management certification. These principles include a broad range of issues, from maintaining high conservation values to community relations and workers’ rights, as well as monitoring the environmental and social impacts of forest management [121].

There are also some other sustainability standards like Cotton Made in Africa, Organic Content Standard (OCS), Soil Association Organic Standard, Responsible Down Standard (RDS), Responsible Wool Standard (RWS) [122–126].

5. Conclusions

Recycling has shown continuity since ancient times as a technique that people comprehended its importance towards the purpose of living with scarce resources and applied it even if not in a scientific sense. Recycling has reached scientific meaning throughout history, and then the subject has evolved towards sustainability. Textile recycling has a great place within the scope of this subject, which has been on the agenda for a long time and will also continue to be, with the advantages it creates in both environmental and economic terms. Human beings fall into textile products from the moment that they are born, they need these textile products throughout their lives (even when they die in some cultures—due to the rituals of burial with various fabrics). The indispensability of textile has always kept it at the forefront in various areas for years.

Engineering-based scientific research always aims to increase the quality of life and make the world habitable for a longer period. In this context, these purposes are embodied as the main objectives in the studies on recycling and sustainability. As the decrease in natural resources, population growth, changes in fashion causing excessive consumption of resources, and technological developments continue, the interest in recycling and sustainability will increase accelerately. As emphasized herein, recycling in textiles, recycling limits in textile wastes, and the search for sustainable new textile resources will continue to be hot topics of the area. In conclusion, approaches on more effective utilization of traditional fibers, the discovery, commercialization, and popularization of new sustainable fibers, and the representation of new models for the management of textile waste will be the focus of researchers for years.
Conflict of interest

The authors declare no conflict of interest.

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Next-Generation Textiles


