# Recycling Practices of Pre-Consumer Waste Generated from Textile Industry

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## 1 Introduction

The textile and fashion industry faces criticism from governments, non-government organizations (NGOs), environmental pressure groups, and other stakeholders around the world due to the rapid depletion of resources (to produce cotton, synthetic fibers, and other fibers), dramatic environmental pollution (e.g., water pollution, microplastic pollution, landfill hazards, and openly dumped litters), and lack of employee well-being. It is a complex manufacturing and retail supply chain going through a sustainable transformation phase of late. Sustainable manufacturing in textile and fashion is a relatively new area of research (Mishra et al., 2020). While textile processing was, and still is, environmentally hazardous in most manufacturing countries (Uddin, 2019), also the fashion industry (post-textile garment manufacturing and distribution) is labor-intensive and prone to human compliance issues

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(Anguelov, 2015). Almost all textile and garment manufacturing industries are based in developing countries such as China, Bangladesh, Vietnam, Turkey, India, Indonesia, and Cambodia, and many are still lagging in economic and human development. Hence, the textile and apparel industry has long been operated in an unsustainable manner. However, as the environment started taking its toll and the community became more concerned about compliance issues, sustainable practices began to take place in the textile and fashion industry, mainly in the last decade (Patwary, 2020). The circular economy is suggested as an effective approach for driving sustainable development by transforming the linear economy of take–make–dispose to a circular one by facilitating the reusing and recycling of materials and reducing waste (Skvarciany et al., 2021). For sustainable manufacturing practices in the textile and fashion industry, the circular economy has the potential to drastically reduce material waste and virgin material use. Material waste in the textile supply chain is a major environmental and economic issue. Empirical research done by Khairul Akter et al. (2022) showed that a typical cotton textile production chain generates a total of 126.4 kg of material waste on average in the subsequent production processes (spinning, weaving/knitting, dyeing–printing–finishing, and apparel manufacturing) for every 100 kg of fiber processing in each stage. A large portion of these material wastes are traded through the informal (undercover) market, and the rest ends up in open dumps (or, in a few cases, in landfills), causing different environmental problems. Bangladesh, the second largest apparel producer after China, generates approximately 577,000 tons of such post-industrial textile waste every year (Pavarini, 2021). China is expected to produce more than 100 million tons of pre-consumer textile waste yearly, one of the major contributors to environmental and human health problems there (Li et al., 2021). The circular economy can reduce the environmental loads from textile waste and potentially cease the materials going to the informal market and redirect wastes from the landfills (and open dumps) to increase value addition. However, implementing circularity in the textile supply chain is difficult due to its long production chain, supplier network, and technical complications (Kazancoglu et al., 2020). Recycling of the excess materials from production and unavoidable process leftovers (yarn leftovers and fabric leftovers) in the textile production chain is needed to implement circularity (Leal Filho et al., 2019).

This chapter is composed in a way to educate the readers about the concept of recycling, and recycling of textile materials, followed by case studies from Bangladesh's textile industry. Details of the solid waste generation from the textile–apparel manufacturing process and scopes of recycling textile materials are depicted. The three case studies have information drawn from real-time observations of the authors in three textile factories in Bangladesh. A complete process of transformation of *waste to recycled fiber* and *recycled fiber to recycled yarn* is covered. A discussion on circular economy in the textile supply chain is followed to impart complete knowledge on sustainable manufacturing in textile and fashion.

## 2 Concept of Recycling

Recycling is the third component of the most extensively used waste prevention hierarchy—the 3R: Reduce, Reuse, and Recycle. In Layman's terms, it is the process of converting waste into reusable material. The fundamental difference between reusing and recycling is that there is an additional processing or action needed for the conversion of the waste materials into something reusable. Though it sounds simple, recycling is complicated. How recycling is defined has an impact on the recycling outcomes. Scrutinizing different definitions of recycling given by different relevant bodies reveal interesting point of views.

The US Environmental Protection Agency (EPA)[1] defines, "recycling is the process of collecting and processing materials (that would otherwise be thrown away as trash) and remanufacturing them into new products." They identify three essential steps in recycling: (i) Collection, (ii) Processing, and (iii) Remanufacturing. The Waste Framework Directive of the European Commission[2] defines, "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes." Here, the recycling process is defined as a recovery operation. This definition provides additional information that the recovered and/or reprocessed products or materials can also be used for other than the original purposes. The Solid Waste Association of North America (SWANA)[3] defines, "recycling is the collection, sorting, marketing, processing, and transforming or remanufacturing of recyclable materials into recycled materials and recycled products, including marketing thereof; and the purchase and use of recycled products." SWANA provides a more holistic definition with the idea of identifying recyclable materials, transforming recyclable materials into recycled materials leading to the processing of recycled products and the marketing of both recyclable materials and recycled products. The new dimension in this definition is the inclusion of the marketing of both recyclable materials and recycled products. It provides the notion that recycling cannot be successful if it does not make economic sense. Another notable definition can be mentioned given by Frank Ackerman (1997) in his book "recycling is an impressively pure form of altruism, a widespread commitment to the greater good/participation in recycling is, in addition to its more literal purposes, a ritual of environmental belief." He says that recycling is a behavior, a philanthropic act. Firm belief in environmental concerns drives participation in recycling.

The implication of the recycling definitions can be found in different research works, such as the idea of the two primary forms of recycling operations: internal and external recycling. Internal recycling involves reusing waste materials generated during a manufacturing process within the same process. This can include scrap materials, excess or leftover materials, and waste products. Waste materials from internal sources in many cases are unavoidable. On the other hand, external

[1] https://www.epa.gov/recyclingstrategy/us-recycling-system

[2] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

[3] https://community.swana.org/communities/community-home/librarydocuments/viewdocument

recycling involves the collection and processing of waste materials outside of the original manufacturing process. These materials are then transformed into new products, which may or may not be related to the original manufacturing process. An example of external recycling is the collection of old newspapers and magazines for re-pulping and their manufacture into new paper products or the collection of post-consumer textiles and recycling them back to produce fibers for remanufacturing new textile goods. Hence, it is understandable that internal recycling is the recycling of materials generated as waste in the internal industrial manufacturing system, i.e., the recycling of pre-consumer waste, whereas external recycling is the recycling of materials after collecting them from consumers who throw them out after the end of their use. An identification and quantification of the internal recyclable materials in textile–apparel manufacturing is shown by Khairul Akter et al. (2022) in their research. Kim and Jeong (2016) designed a closed-loop supply chain model for photovoltaic system manufacturing with internal recycling of materials from solar panel manufacturing plants. Zhao et al. (2017) showed how to utilize converter steel slag in internal recycling in steel industries.

Another aspect of recycling, as stressed by SWANA, is the commercialization of recyclable materials and recycled products. The role of a functional recycling sector is emphasized by many researchers and practitioners. Without adequate recycling infrastructure, policy, and market opportunities, recycling programs tend to become inefficient and ineffective. The collection of recyclable materials depends on the collection infrastructure. A well-designed infrastructure can ensure that recyclable materials are collected efficiently and sorted properly, resulting in a higher percentage of materials being recycled. It requires a separate business sector to handle collection, process, and market or distribute recycled products. Recycling infrastructure and trading of recycled products create thousands of jobs. Unfortunately, if there is no proper infrastructure in place, wastes are traded through the informal market channel, especially in developing countries. In Indonesia, one in every thousand people is found to work in the informal waste recycling and trading sector (Sembiring & Nitivattananon, 2010). More than 50 million people meet their livelihoods working in the "jhut" (textile waste) market in Bangladesh (Hamidul Bari et al., 2017).

Finally, according to Ackerman's definition, recycling is a philanthropic activity, stressing the need for environmental awareness as a driving factor for recycling. It involves individuals and communities taking action to protect the environment and improve the well-being of others. By participating in recycling, one can feel pride in diverting waste from landfills, conserving natural resources, and reducing pollution. Apart from environmental benefits, recycling also has economic and social benefits. It creates jobs providing livelihood to millions of people all over the world. Recycling involves community engagement and education, which can help build a sense of community and encourage people to work together toward a common goal. The development of community awareness and practices is highly stressed by the United Nations to achieve the Sustainable Development Goals (SDG) (Gui, 2020). As a part of sustainable practices, many industries are emphasizing on recycling. The textile and apparel industry has a great recycling scope due to the huge amount of material waste in the production process.

## 3 Recycling of Textile Materials

Textile and apparel production is a long and complicated chain of processes generating different types of materials as waste. The feed material is fiber: cotton, wool, hemp, etc., are natural fibers, and polyester (PET), nylon, acrylic, etc., are man-made or synthetic fibers. The use of man-made cellulosic fibers such as viscose-rayon, and lyocell is on the rise. The major fibers used in textile production in 2019 were PET (52%) and cotton (23%) followed by rayon and wool (14%) clearly indicating the dominance of synthetic fibers (Textile Exchange, 2020). The fiber content in clothing can be 100% cotton, 100% PET (or other synthetic fiber), or mixed like a 65/35 CVC blend (chief value of cotton—a popular blend with 65% cotton and 35% PET). Fiber-to-fiber recycling of both cotton and PET textile waste is already developed and in operation in many recycling facilities (Ruuth et al., 2022). However, for blended fiber materials, it is still a challenge to recycle. Technologies to separate the synthetic part from the cotton (or cellulosic) part are developed but still have scalability challenges (Matayeva & Biller, 2022). This chapter discusses textile waste generation, recycling scopes, technologies, and challenges for the circular economy (Fig. 1).

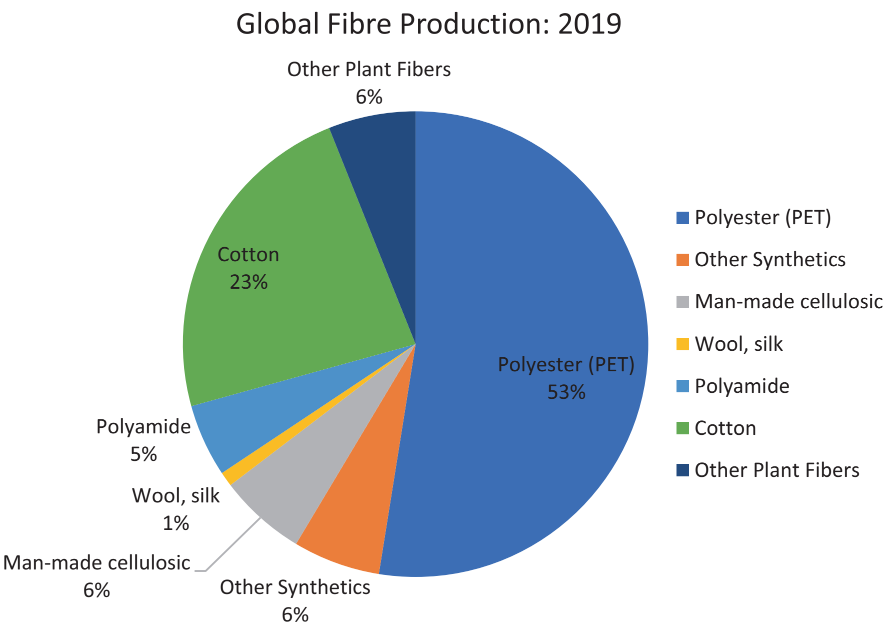


**Fig. 1** Global fiber production, 2019 (Textile Exchange, 2020)

### 3.1 Textile Waste Generation and Recycling Scopes

Textile wastes are generated in the form of fiber, yarn, and fabric from subsequent production processes. Due to incomplete reporting, data on the amount of pre-consumer waste generated from the textile–apparel industry are sparse. However, an indication from the MacAurther Foundation (2017) can be obtained that reports 53 million tons of total fiber consumption in the global textile industry in 2015 of which only 1% was recycled. The textile–apparel production chain consists of at least four processing stages:

- Spinning: It is the yarn manufacturing process that turns cotton into cotton yarns. Spinning is a five-stage engineering process that comprises the blowroom, carding, drawing, combing, and ring section. Cotton is cleaned, stretched, and twisted in the subsequent stages turning it into a continuous web of yarn. The higher the average staple length of cotton is, the higher the quality of the yarn is possible. PET or other polymer-based fibers are manufactured in a different spinning process: wet spinning or melt spinning. Polymer chips are melted and extruded through spinnerets giving them a continuous filament form.
- Weaving/knitting: This is the fabric manufacturing stage. Weaving and knitting are two completely different production processes. Weaving looms are used to interlace two sets of yarn in different orientations resulting in different constructions of woven fabrics. Denim is one of the highest-produced woven fabrics where one set of white yarn is interlaced with another set of indigo-dyed blue yarns in a 2/1 twill construction. Knit fabric, on the other hand, is produced with circular knitting machines where only one set of yarn is turned into fabric form through inter-looping. Due to the inter-looping structure, the yarns are loosely connected resulting in elastic properties in the fabric. Due to its dimensional instability, the production of knitted fabrics is measured in weight units, whereas woven fabric is measured in length units.
- Dyeing–printing–finishing: This stage is termed wet processing as the greige knit or woven fabric from the previous stage is treated with required chemicals, regents, and dyes to impart desired color, properties, and hand-feel. The wet processing stage is the most energy- and water-intensive process and creates the most environmental hazards in the form of effluents. As a result, there is a growing need for sustainable and eco-friendly practices in the textile dyeing and printing industry.
- Apparel manufacturing: This is the final stage that involves assembling finished fabric into apparel. Apparel manufacturing consists of the cutting, patternmaking, sewing, and finishing process. Cut-fabric waste from the cutting section is one of the biggest sources of textile solid waste. Excess production (stock lots), unused fabric, and leftovers from the sewing section are the other sources of wastes.

The schematic of solid waste from the textile–apparel production chain and recycling is illustrated in Fig. 2.

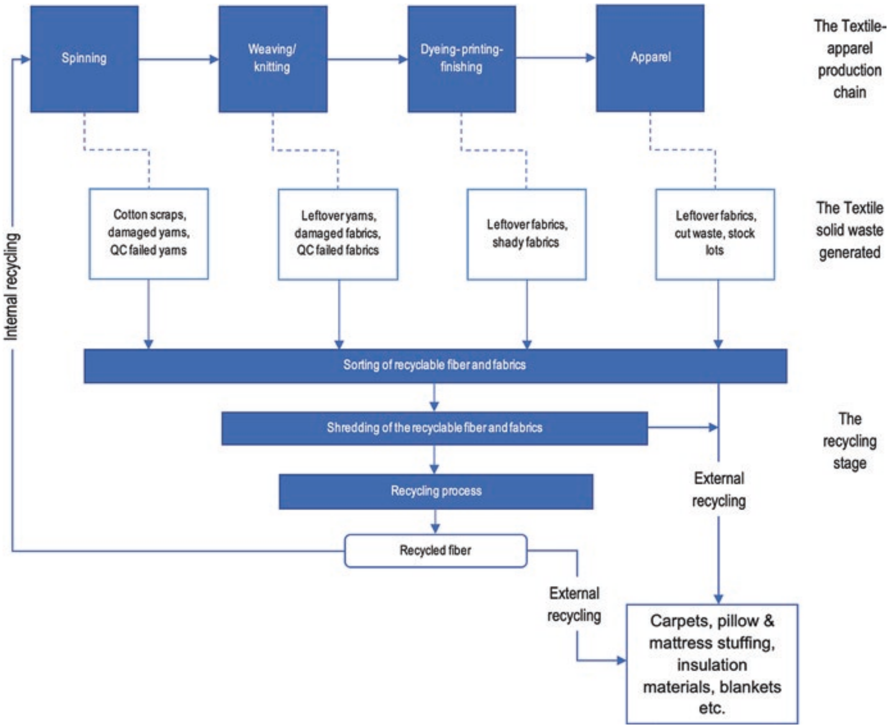


**Fig. 2** Schematic of waste from textile–apparel production chain and recycling. (Author generated)

The illustration represents the cotton textile waste recycling process in the textile–apparel production chain. The solid wastes generated from the subsequent processes are fibers and fabrics that are damaged, rejected by the quality control team, or excess to the production need. Fabrics that fail the color requirement tests during the dyeing process are termed shady fabrics. Cutting waste from the apparel manufacturing stage is the largest source of fabric waste. The stock lots are the extra development samples and additional production outputs. The recycling stage starts with the sorting of the recyclable fiber and fabrics. Recyclable materials are sorted according to color, pre-treatment used, and quality. After sorting and shredding of the right quality of material, it is processed through a mechanical recycling system and eventually re-fed to the spinning system to make recycled yarn. However, the mechanical recycling process shortens the staple length of the recycled cotton fibers which creates non-uniformity (Ütebay et al., 2019). Hence, recycled cotton has limitations for making finer count yarns. Recycled cotton is generally used to produce coarser count yarns that are mostly used in denim production. Finer count yarns can be produced from recycled cotton after mixing it with new cotton fiber as per count requirement. The internal recycling system of using waste material generated from the production stages as the feed material of the same production line is an effective way of closing the material loop in textile production. However, pertaining to the loss of properties in cotton due to the mechanical recycling process, not all materials can be reused in the production system. Those inferior quality materials are downcycled (external recycling) to make inferior quality products such as materials for carpets, stuffing for pillows and mattresses, blankets, and insulation materials.

## 3.2 Technologies and Challenges

Recycling of cotton-made fabrics is a mechanical process. It is reported that the quality of recycled cotton depends on the type of waste and its origin, and the degradation of resultant apparel made from recycled fiber. However, studies on the properties of recycled fiber are limited only to yarn production, and more studies are required on how it affects the apparel quality (Ütebay et al., 2019). The quality of shredded fibers derived from waste materials is dependent on the inherent structure of the waste and the applied finishing processes. In the context of cotton recycling, a significant challenge pertains to the relatively inferior quality of the resulting fibers. Consequently, it is critical to identify the key parameters that influence the quality of the recycled fibers. To achieve superior clothing made from recycled fibers, an understanding of the impact of waste properties on recycled fibers is essential. The mechanical recycling technology of cotton textiles is in operation in most textile-producing countries such as China, Bangladesh, and the European Union. Though there are technological challenges, internal recycling of cotton textile waste is a big step toward a circular economy in textile production.

Recycling of polymer-based fibers or polymers (plastic waste) is a highly studied area of research. PET accounts for 8% by weight and 12% by volume of global solid waste, and the textile industry is one of the largest users of PET fibers (Atta et al., 2006). Data on pre-consumer PET textile waste are limited. However, as PET is the dominant fiber used in the textile industry, it can be inferred that most solid waste generated from apparel factories is PET or PET mixed with cotton fiber. Notably, 100% polyester textiles are technically plastic products, and recycling involves converting PET to its monomers. PET can be recycled practically by mechanical, thermal, and chemical recycling methods, of which chemical recycling (chemolysis) is the most successful method (George & Kurian, 2014). Recycled PET does not have quality issues like recycled cotton, as they are converted to its constituent monomers or oligomers. Hence, 100% internal recycling of PET is possible, and textiles are extensively produced from recycled PET bottles (Majumdar et al., 2020).

Furthermore, the scope of external upcycling of PET is higher than that of cotton, as plastics have diverse applications (Leonas, 2017). However, the challenge still prevails for mixed fiber textiles. Multifiber apparels are outnumbering mono-fiber ones due to their better properties and economic benefits, creating a big problem for recycling. The practice is to hand-sort the blended garments into recyclable categories such as white cotton, colored cotton, or polyester fabric (Ishfaq, 2015). An advanced sorting technology like Fibersort claims to sort textiles based on composition (e.g., wool, cotton, nylon, and PET) and even color but can only process mono materials (Harmsen et al., 2021). The latest innovation in separating cotton and polyester from textiles is the enzyme-based solution. A “cocktail” of enzymes in a mildly acidic solution is used to chop up cellulose in cotton, thereby separating components (Egan et al., 2023). However, such technology is still developing and requires further innovations to deploy it in an industry-level operation. Though challenges pertain, recycling textile solid waste is essential to developing a circular economy in the textile–apparel supply chain.

## 4 Opportunities of Recycling in Bangladesh Context

Bangladesh is a major textile and apparel manufacturing nation and the second-largest exporter of ready-made garments globally (Swazan & Das, 2022). Over 5000 apparel companies in Bangladesh employ more than four million people, and the RMG sector has emerged as the country’s leading industry, contributing more than 10% of its GDP (Islam, 2021). According to the Bangladesh Textile Mills Association, there are 433 yarn manufacturing mills, 828 fabric manufacturing factories, and 251 dyeing–printing–finishing mills in Bangladesh (BTMA, 2020). Although the growth of the textile sector has significantly boosted the Bangladeshi economy, growing textile solid waste is causing alarming environmental impacts (Shamsuzzaman et al., 2023). Due to the huge amount of waste generated as a byproduct of textile production, Bangladesh also becomes a key player in the textile waste recycling industry (Saha et al., 2021). Only in the Narayonganj area (one of Bangladesh’s prime locations of apparel industries), 120–125 tons of apparel waste is generated daily (Alom, 2016). Apparel factories produce waste as selvages, end-of-roll wastes, broken materials, and partially finished or finished apparel from design to bulk production in those factories. Determining the amounts and fiber composition of this waste is the prerequisite to utilizing it through recycling to develop new products for clothing, furniture, vehicle, filtering, mattress, paper, and other sectors (Dobilaite et al., 2017). Cotton yarn is the main raw material used in Bangladesh to produce knitted and woven fabrics in the knitting and weaving industry (Guha & Sadi, 2016). These factories generate unfinished fabrics, scrap yarn, and fly fiber material wastes as a byproduct of different stages of weaving or knitting. The dyeing, printing, and finishing industry produces rejected color fabric and excess finished fabric as material waste (Khairul Akter et al., 2022). An average apparel factory in Bangladesh can generate 250–300 kg of production leftover daily as waste, costing 0.1–3 USD per kg, depending on the quality and size of the waste (Islam & Khan, 2021). Bangladesh has a considerable underground market that deals with “Stock lot” (excess inventory apparel) and “*Jhut*” (leftover yarn, fabric, and cutting waste). Using unofficial practices, the traders purchase cutting waste or stock lots from the clothing manufacturers often twice a year, in January/February and October/November. The types of waste vary periodically and follow the local business's product category, much like the fashion trend and market need. Although it is an informal business, this market provides a good model of circularity. Figure 3 shows the traceability of Bangladesh's post-industrial textile and apparel waste. "Waste" generated from the export-oriented factories becomes the primary source of raw materials for the informal local apparel factories that make cheaper clothing for the domestic market. Moreover, the underground marketing of the *jhut* contributes to reducing the apparent environmental effect of textile waste (Khairul Akter et al., 2022).

In the context of a cotton spinning mill, it generates blowroom droppings, like in waste fiber, flat strips, carding waste, comber noil, sweeping wastes, hard waste, roving ends, rejected yarn, excess production, gutter fly, and micro dust waste in various processing stages, and they are highly heterogeneous. The cellulose content of cotton wastes varies significantly based on its geography and the processes from where it has been obtained. For example, cotton linter waste contains 99% cellulose content (Ranjithkumar et al., 2022). The spinning mill's waste is separated into two categories: soft and hard waste. "Soft waste" refers to fibrous waste produced from carding to the speed frame. Hard waste is defined as waste that cannot be reused. This waste is generated in the winding and ring frame departments. This spinning waste can be converted into value-added products by reclaiming fiber from soft wastes or yarn and mechanically recycling it into open-end yarn. Even fiber from yarn waste has better uniformity percentage and tensile strength than recycled fiber from rags (waste of weaving). The authors suggest that this recycled yarn can be used to produce higher-quality textile items such as denim and chino cloth for towels and pants (Jamshaid et al., 2021). Like cotton, polyester, wool, silk, and other

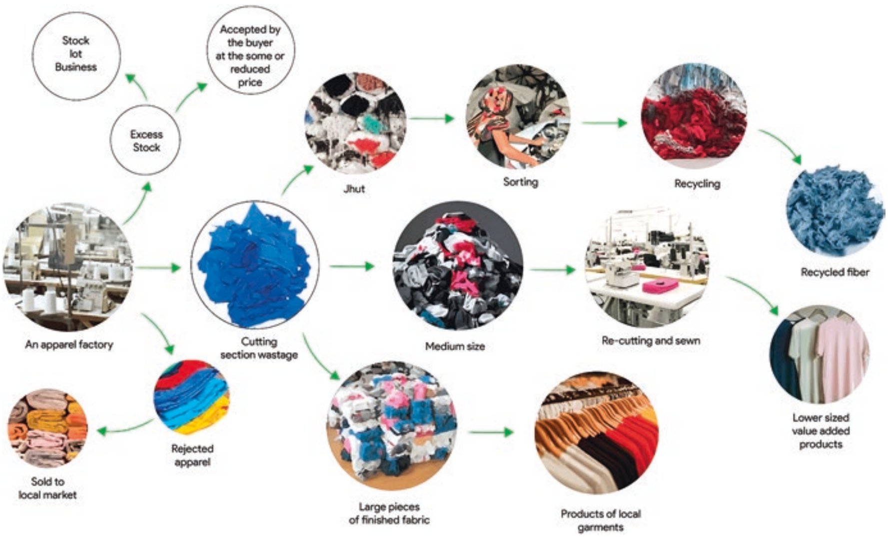


**Fig. 3** Traceability of post-industrial textile and apparel waste in Bangladesh (Khairul Akter et al., 2022)

textile fibers from woven, nonwoven and knit fabric waste can be recycled, but it becomes challenging for composites when cotton and synthetic fiber are used simultaneously in yarn and fabric manufacturing. Choosing a particular recycling process is difficult for blended fabrics as natural and man-made fibers have distinct properties and often require multiple techniques to separate them. (Rashid et al., 2023). Ventura et al. created fiber-reinforced cementitious composite plates for the construction and building sector using recycled fiber from textile waste. Unidirectional fiber strands, meshes, woven textiles, or nonwoven fabrics are strongly recommended for recycling for greater tensile and structural strength (Ventura et al., 2022). Three case studies are presented here from Bangladesh, showing how the recycling process takes place in the recycling factories transforming textile waste into recycled fiber and yarn.

## 4.1 Case Study 1—Mechanical Transformation of Post-Industrial Textile Waste into Recycled Fibers

To convert textile waste into recycled fiber, mechanical transformation is the dominant technology in the fiber recycling sector due to its low cost and environmentally favorable (i.e., nearly no use of hazardous chemicals) operations (Yalcin-Enis et al., 2019). Three essential phases are involved in the mechanical recycling of post-industrial textile waste. Step 1 involves sorting the items that have been collected through various means. Step 2 involves cutting the sorted material to a length between 80 and 180 mm. After being shredded, the material is processed to create recycled fiber in Step 3, which is used by the yarn producer to create a recycled yarn with different blend ratios. The two main sources for collecting textile waste are either local markets or available textile factories such as spinning, knitting, wet processing, and apparel. In the following, the key steps are discussed in detail.

## 4.2 Sorting

The waste typically comes to a fiber recycling factory in bale form (Fig. 4a). Sorting is the first step the fiber recycling factory takes after receiving the waste from the local market. Although local waste vendors carry out some preliminary sorting, fiber recycling plant still needs more sorting before manufacturing due to various factors, such as less color homogeneity due to the mixture of different yarn and fabric lots, and the presence of buttons, labels, and zippers (Fig. 4b)—*a* high degree of sorting results in high-quality end products. After sorting, the materials are exposed to UV light to ensure disinfection and detect the presence of OBA (Optical Brightening Agent), especially for white cut pieces. Then the goods are passed through the metal detection section to ensure that no metal or metal particles are present in the material.


**Fig. 4** Different sections of the mechanical fiber recycling industry: (**a**) collection of waste from available sources, (**b**) manual sorting and putting the pieces into the conveyor belt for cutting, (**c**) manual checking of the size of cut pieces for the required length after cutting, (**d**) main shredding operation to open fibres from fabric cut piece, (e) checking quality parameters of shredded fibers and (**f**) ready fiber for spinning. (Author generated)

## 4.3 Shredding

Shredding is a mechanical technique that reduces the post-industrial textile waste fiber length through a series of production processes (Shen & Worrell, 2014a, b). As the size uniformity of the cut-fabric waste is crucial for having the necessary recycled fiber qualities and cut-fabric waste from textile and apparel production consists of different sizes, cutting processes are applied to reduce the size of cut-fabric panels as the first step of the shredding process. Cutting has been carried out in two to three stages to achieve the highest level of size homogeneity consistently. The length of the fabric pieces that both cutters can simultaneously cut ranges from 80 to 180 mm, depending on the design of the machine. Beyond these limits, the machine may fail to cut the fabric to the desired size and malfunction. A post-cutting manual size checking is applied to confirm that the correct cutting size is attained (Fig. 4c). A conveyor belt then transports the cut pieces into a rotary tank, where a small amount of softener (usually cationic types) and an anti-static agent are added to ensure the smoothness of the shredding operation as well as to minimize the risk of tearing the fibers and fire owing to vigorous pounding during the subsequent process. The cut pieces are then placed in a designated receptacle to be sent to the shredding process later. Then the cut pieces are delivered to the super mixer through a special feeding system, chute feeding from the storage bin. The purpose of the super mixer is to ensure smooth and homogeneous mixing so that the shredding can produce fibers of homogeneous length. The material is then transferred to the shredding section, which is a single unit consisting of six to seven cylindrical shredding rollers, depending on different machine brands (Fig. 4d). A shredder consists of rotating blades driven by electric motors and a collection bin at the bottom incorporating carding technology to open the fibers. The first four rollers have comparatively long teeth, so they can do extensive shredding and then be delivered to the rest of the rollers, which have gradually small saw-type blades and open the fibers almost similar to its initial stage like in the virgin cotton bale. Once the fibers are open, the frontmost roller delivers the opened fibers into a conveyor belt. This belt is linked to an automated bale-press machine and produces the required bale of recycled fibers ready to use for yarn spinning. All the cut pieces missed to catch by the roller teeth fall through the two rollers and are collected by the bin below the rollers. Later, the pieces are returned to the super mixer to be prepared for re-feeding into the shredding section.

### 4.3.1 Testing of Recycled Fibers

After delivery from the shredding section, several lab tests are carried out to ensure that they meet the customers' requirements. Various test of chemical and physical properties are carried out on recycled fibers, such as average fiber length (Fig. 4e), neps, fiber composition analysis, color fastness, pH, dye bleach, dyeability, and toxicology.

### 4.3.2 Final Product

The fiber composition can be 100% recycled cotton (Fig. 4f) or blended with virgin or recycled polyester fibers. Regarding the product offer, it is possible to produce several varieties of fibers, i.e., solid colors and mixed colors with prescribed ratios to produce mélange effects. Solid colors are possible mostly on greige or bleached fibers, which can be dyed to any desired color later. Mélange fibers do not need to be dyed; with a prescribed ratio to mix with virgin fiber, they create the desired mélange shades, which are comparatively more sustainable recycled fiber than solid colors.

### 4.3.3 Limitations

As this industrial practice has enormous potential in terms of sustainability and resource efficiency, it has some limitations, such as all kinds of terry and fleece products that are heavier in structure (i.e., the average weight per square meter is approximately 300 g or above) having polyester filament yarn inside are not suitable for mechanical shredding. A similar result is also for the fabrics having polyamide (i.e., elastane) inside the structure. During shredding, polyester and polyamide do not open up as cotton but rather entangle with the rotating drum's teeth and impede production efficiency. Polyester and elastane are more suitable for chemical recycling.

## *4.4 Case Study 2—Conversion of Recycled Fibers into Finer Recycled Yarn (Ring Spinning)*

Among the various industrial applications of the resulting recycled fibers from the shredding process, the most widespread industrial application is to spin these recycled fibers into yarn by mixing them with other available fibers (i.e., virgin cotton and virgin/recycled polyester). As yarns are produced by the technology used to create the final fabric, such as woven, knit, heavy knit (sweaters), and denim, the diameter of the yarn is also developed specifically. Often, finer yarns are required for most of the woven (except home textiles) and knit (except towels) items. Due to product production technique and end use, heavier knits and denim typically require coarser yarn (larger diameter). Ring spinning is the oldest technology to produce high-quality finer yarn (Shen & Worrell, 2014a, b) ranging from 60 Ne (~10 Tex) to 30 Ne (~20 Tex), and also, to some extent, coarser yarn up to 20 Ne (~30 Tex). However, a specific range of fiber length, 1.25–1.50 inches (Yin et al., 2021), is required for the ring spinning process; otherwise, short fibers are removed and turned into waste in the blowroom, carding, and combing process. Typically, short fiber contents are 25–30% higher in recycled fibers compared with virgin cotton

(Ütebay et al., 2020); therefore, at present, ring spinning can produce yarn with a maximum of 30% recycled fiber content ranging from 20 to 34 Ne.

### 4.4.1 Recycled Yarn Production Using Recycled Fiber from Post-Industrial Fabric Cutting Waste

According to the GRS (GRS—global recycle standard is an international standard that sets requirements for third-party certification of recycled content, social and environmental practices, and chemical restrictions) guideline, a yarn must include at least 20% recycled fibers by weight throughout the mixing process to be labeled "Recycled" (GRS, 2020). As mentioned earlier, the ring spinning process can handle recycled fiber in the mix up to 30% by weight, which will reduce the average length of the fibers and may result in frequent breakage during the production of slivers and yarn. Depending on the specifications of the final consumer, the remaining 70% could be either 100% virgin cotton, a blend of virgin cotton and virgin polyester, or virgin cotton and recycled polyester. Any mix of recycled fiber would increase hairiness, resulting in more pilling in the final products.

The mixing of recycled fiber with any virgin fiber would take place in the blowroom. During the blowroom and carding processes, along with other foreign materials, such as dust, leaves, and seeds, a small portion of the short recycled fibers is removed, decreasing the recycled fiber percentage relative to the initial mixing (Fig. 5a, b). Combing is not usually used for yarn with recycled fiber mix, as the process will remove a significant portion of the recycled fibers, eventually decreasing overall recycled fiber percentages. For this reason, GRS approved the yarn as "carded" and labeled it as such. Carded slivers are then delivered to the roving frame to impart a slight twist through the rotating flyers and create a bobbin of roving slivers to feed to the ring spinning machine. Then necessary twist is imparted by the ring spinning machine to generate the desired yarn between 20 and 34 Ne.

### 4.4.2 Recycled Yarn Production Using Recycled Fiber from Spinning Waste

Waste produced by various spinning processes is another source of recycled fibers (Fig. 5c). Dust, leaves, seeds, and a small amount of short fibers (approximately 6–8%, depending on the cleaning roller setting parameters) are removed during the blowroom and carding processes. However, short fibers removed during the carding process—often referred to as "noil"—are mostly used to produce recycled yarn due to their superior cleanliness and longer fiber length compared with blowroom waste materials. The combing procedure, however, is the main source of recycled fibers as the process removed higher percentages (approximately 8–10%, depending on the combing rollers setting parameters) of short yarn to produce superior quality yarn. Wasted and leftover yarn and slivers from yarn manufacturing processes are another source of recycled fibers. Particularly, auto-cone machines (approximately 1–1.5%


**Fig. 5** Fiber recovery process from a different section of the spinning industry: (**a**) collection of waste from blowroom and carding process, (**b**) carding "Noil," (**c**) collection of leftover and rejected slivers and yarn, (**d**) feeding the spinning waste into the shredding machine, (**e**) shredding machine for spinning waste (i.e., noil, rejected slivers and yarns), and (**f**) recycled fibers after the shredding of spinning waste. (Author generated)

depending on the "cut length" setting parameters) and vortex spinning generate a lot of waste yarn (approximately 6–8% during auto splicing) that is shredded and used as recycled fibers (Fig. 5d). Spinning manufacturers occasionally buy rejected and leftover yarn from various knitting and weaving production facilities and mix it with waste yarn while shredding to boost the volume of recovered fibers. Due to higher fiber length and fiber uniformity, recycled yarn from spinning waste has some advantages over post-industrial fabric cutting waste. Another benefit is that the percentage of recycled fibers can reach up to 40%, while the remaining 60% could be either 100% virgin cotton, a blend of virgin cotton and virgin polyester, or virgin cotton and recycled polyester.

#### 4.4.3 Laboratory Testing

Following yarn manufacture, several physical tests are carried out in the in-house lab, such as fiber length, mass variation, hairiness, thick and thin places, and neps to ensure that the end user's needs are fully met. The in-house laboratory does not conduct any chemical tests, but final customers occasionally verify the product's fiber content and toxicology before exporting it to the target countries.

#### 4.4.4 Limitations

Even though ring spinning has numerous advantages over other spinning techniques, it has several drawbacks when producing recycled yarn. For instance, the amount of recycled fiber removed during the blowroom and carding processes cannot be accurately measured, leaving the amount of recycled fiber in the finished yarn unknown. Additionally, using more than 30% of recycled fiber is not possible.

### *4.5 Case Study: 3—Conversion of Recycled Fibers into Coarser Recycled Yarn (Rotor Spinning)*

As indicated in Case Study 2, recycled fibers are used in ring spinning to create finer yarn, which is required to manufacture knit and woven fabrics. However, the amount of recovered fiber used in ring spinning is restricted to a maximum of 40%. On the other hand, heavy knits (sweaters and jeans) have a great demand for coarser yarn (6–24 Ne). To address this demand, rotor spinning is extensively employed as an alternative to ring spinning, which is unsuitable for production in this range. Another benefit of rotor spinning is that it can utilize up to 95% recycled fiber in a specific mixture, ensuring the greatest usage of recycled fibers and a significant step toward circularity.

#### 4.5.1 Shredding

There is no need for a particular shredding method for rotor spinning. Similar shredding procedures are used as they are for ring and fiber recycling. On the other hand, rotor spinning is designed to accomplish spinning with relatively short fibers compared with ring spinning. Thus, it can produce yarn from fibers made from a fabric cut piece length of 50 mm compared with ring spinning, which requires at least 80 mm and above.

### 4.5.2 Fiber Mixing and Blending

Fiber mixing and blending take place in the blowroom, similar to the ring spinning. The blending is done in a machine called "blendomat," placed before the blowroom (Fig. 6b). To produce a coarser count from 6 to 10 Ne, the percentages of recycled fiber can be up to 95%, which can be used in heavy-knit products. The remaining amount can be virgin cotton or polyester, sometimes recycled polyester to increase circularity. In most cases, these recycled polyester are outsourced, as most cotton spinning mills are not well-equipped to manufacture recycled polyester fibers from PET (polyethylene terephthalate) bottles. Combining organic cotton and regenerated cellulose, such as viscose and Tencel, is also feasible, usually sourced from China, India, and others (Fig. 6a).

### 4.5.3 Manufacturing of Rotor Yarn

Similar operations are carried out in blowroom and carding (Fig. 6c) for rotor spinning, as explained in Case Study 2. However, in rotor spinning, blowroom and carding opening and cleaning rollers are set to prevent the removal of short fibers on a significant scale (i.e., not more than 6–8% of the initial weight). As usual, the combing process is skipped. In addition to the spinning method, rotor spinning and ring spinning have different process routes. Compared with ring spinning, which requires roving after carding, rotor spinning does not. Carded slivers (Fig. 6d) are transferred directly to the rotor spinning machine, which makes yarns by adding the necessary twist (Fig. 6e).

Similar to the fiber recycling manufacturing unit, the rotor spinning unit features at least four distinct color-based production lines to prevent unintended color mixing. Another purpose is to shorten the time required to clean the machinery after the color changeover resulting in more production time. These four colors are typically grouped according to market demand. Black, greige (white), blue, and mélange are the top four colors in market demand.

### 4.5.4 Manufacturing of Heavy Knit (Sweater) Yarn

For the production of recycled yarn for woven, knit, and denim, there is no need for doubling operations, but for heavy knit (sweater), the doubling operation is necessary. Doubling is a unique procedure in which two yarns are joined and twisted together to make a single yarn so that the finished sweater items become flappier and more insulated (Fig. 6f). Double yarn is used in sweater knitting machines with a finer gauge (GG 10 to GG 14) to produce yarn of 16/2 Ne to Ne 30/2 Ne count. In some cases, instead of using doubled yarn, more ply of yarn are used to make the fabric more flappy, especially when using a coarser gauge sweater knitting machine (GG 3 to GG 7), which requires yarn counts from 6 to 10 Ne.


**Fig. 6** Different sections of rotor spinning industry: (**a**) collection of recycled polyester and organic cotton fiber for mixing, (**b**) Blendomat, (**c**) carding machine for rotor spinning to handle short fibers, (**d**) carded slivers, (**e**) rotor spinning machine, and (**f**) doubling and twisting of sweater yarn. (Author generated)

After the yarn is produced, numerous physical tests are carried out in the lab, such as mass variation, hairiness, thick and thin place, and neps, to ensure that the end user's requirements are fully respected. Although the final customer occasionally checks the fiber content and toxicology before exporting to the destination counties, the in-house laboratory does not conduct chemical tests.

### 4.5.5 Prototype Fabric Production (Sweater)

As heavy knit manufacturers (sweaters) are the primary customers for rotor yarn, the firm has prototype automatic sweater manufacturing machines to test the feasibility and efficacy of the produced yarns. A center specifically dedicated to studying different sweater knitting structures with recycled yarn is sometimes available. Its goal is to provide clients with recycled yarn and offer attractive, trendy sweater designs.

### 4.5.6 Circular Economy in Bangladesh Textile Supply Chain

Post-industrial textile waste represents the textile–apparel manufacturing part of the entire textile supply chain. The circular economy in the textile–apparel manufacturing chain in Bangladesh perspective encompasses the entire formal manufacturing factories to the informal markets trading the textile wastes and the formal textile recycling factories. Establishing the textile waste recycling strategy in Bangladesh can mitigate the environmental burden of textile waste, supporting sustainable practices in the long run in textile production. Recycling and reusing textiles could reduce the production and consumption of virgin materials, which would be positive for the environment (Sandin & Peters, 2018). Bangladesh has 100% export-oriented apparel factories and does not sell the products directly to the consumer, having a huge opportunity to co-create a CE model where factories are ready to look for circularity in their business (Uddin, 2018). The textile and apparel sector has long practiced recycling and material reuse. There are many benefits to it, including the availability of the raw materials needed to create new products, new employment opportunities, a reduction in waste and the use of natural resources, the need for less energy to produce virgin goods, the prevention of global warming and water pollution, the preservation of wildlife, and economic benefits (Uyanık, 2019).

Waste recycling in the textile sector greatly impacts Bangladesh's economy in terms of employment generation. Many people are engaged in textile and apparel waste recycling activities for their income. If the textile and apparel waste are recycled nationally in Bangladesh, the industry's revenue may increase by USD 4 billion, adding to the economy and generating new job possibilities (Ahmed et al., 2022). Two forms of apparel waste processing stores are currently prevailing in Bangladesh. The small shops contain three to five workers, allocating a monthly salary of 25–30 USD, processing 3–3.5 tons of waste monthly. Large businesses employ 10–15 people paying 35–60 USD monthly to process 10–15 tons of waste monthly. The waste processed here is woven, net, and shirting fabric pricing

0.25–2.5 USD/kg depending on the waste's size and quality, while the recycled fiber's selling price is 0.4–3.5 USD/kg (Quazi, 2017). A study reports that Filotex Ltd. is the first factory in Bangladesh to work with the "Circular Fashion" implementing the recycling concept (Team, 2018). Simco Spinning and Textiles Ltd. in Bangladesh has been recycling 200 tons of textile waste each month for the last 3 years. It produces yarn from discarded cotton clips. It uses 95% recycled fiber instead of virgin fiber (fresh or unused fiber) in production. Simco collects textile waste for a specific buyer to recycle and then upcycles (reuses) it into raw materials (Jui, 2022). After background analysis and considering the current state, it is predictable that, with proper infrastructure, stakeholder collaboration (Saha et al., 2021), and policies (Hartley et al., 2020), Bangladesh can harness the potential of textile material recycling as a sustainable solution for managing textile waste and promoting CE in the textile supply chain.

### 4.5.7 Conclusion

Recycling pre-consumer and post-consumer waste has enormous potential, yet implementing waste recycling poses a unique set of challenges. The increasing consumption of fibers, increasing demand for fiber mix, often more than two fibers, increasing use of performance finishes, and color pellet used in different seasons all create a scenario that is difficult for processing further. The second challenge remains for the collection of textiles and sorting these various mixes in subsequent recycling processes. However, various technological breakthroughs appeared in various parts of the world, although this is still a long way to go. On the other hand, chemical recycling of synthetic fibers or their mixtures based on textiles has yet to be in the mainstream. The third challenge is more future-oriented, as what will happen to the recycling of recycled textiles. In recent studies, it has been found that garments made of recycled fibers are more responsible for microplastic pollution than that of virgin fibers. The final challenge remains due to the nature of business, which, in many countries, is not straightforward and may be due to policy issues or the stakeholders involved in the waste supply chain. As a result, the transparency of these waste generation, collection, and subsequent business operations remained clandestine. It is expected that, with an increasing focus on the circular textile supply chain, these challenges could be overcome in a short period to build a sustainable textile sector.

## References

Ackerman, F. (1997). *Why do we recycle? Markets, values, and public policy*. Island Press.

Ahmed, Z., Mahmud, S., & Acet, D. H. (2022). Circular economy model for developing countries: Evidence from Bangladesh. *Heliyon, 8*(5), e09530. https://doi.org/10.1016/j.heliyon.2022.e09530

Alom, M. M. (2016). Effects on environment and health by Garments factory waste in Narayanganj City, Dhaka. *American Journal of Civil Engineering, 4*(3), 64–67.

Anguelov, N. (2015). *The dirty side of the garment industry: Fast fashion and its negative impact on environment and society* (pp. 1–220). CRC Press. https://doi.org/10.1201/b18902

Atta, A. M., Abdel-Raouf, M. E., Elsaeed, S. M., & Abdel-Azim, A. A. A. (2006). Curable resins based on recycled poly(ethylene terephthalate) for coating applications. *Progress in Organic Coatings, 55*(1), 50–59. https://doi.org/10.1016/J.PORGCOAT.2005.11.004

BTMA. (2020). *Basic data of primary textile industry*. Dhaka [Online]. Available: http://www.btmadhaka.com/wp-content/uploads/2020/01/Basic-Data-of-BTMA-2019.pdf. Accessed June 9, 2021.

Dobilaite, V., Mileriene, G., Juciene, M., & Saceviciene, V. (2017). Investigation of current state of pre-consumer textile waste generated at Lithuanian enterprises. *International Journal of Clothing Science and Technology, 29*, 491–503.

Egan, J., Wang, S., Shen, J., Baars, O., Moxley, G., & Salmon, S. (2023). Enzymatic textile fiber separation for sustainable waste processing. *Resources, Environment and Sustainability, 13*, 100118. https://doi.org/10.1016/j.resenv.2023.100118

George, N., & Kurian, T. (2014). Recent developments in the chemical recycling of postconsumer poly(ethylene terephthalate) waste. *Industrial and Engineering Chemistry Research, 53*(37), 14185–14198. https://doi.org/10.1021/IE501995M/ASSET/IMAGES/LARGE/IE-2014-01995M_0008.JPEG

GRS. (2020). *Global Recycled Standard*. Accessed from https://certifications.controlunion.com/en/certification-programs/certification-programs/grs-global-recycle-standard

Guha, A. K., & Sadi, M. S. (2016). Using cotton cutting waste and knitting waste for bio gas production. *Bangladesh Textile Today, 9*(7), 1–6.

Gui, L. (2020). Recycling infrastructure development under extended producer responsibility in developing economies. *Production and Operations Management, 29*(8), 1858–1877. https://doi.org/10.1111/poms.13202

Hamidul Bari, Q., Mahmudur Rahman, M., & Moniruzzaman, S. M. (2017). Garments waste recycling in Dhaka: A case study of Mirpur area. In *Proceedings of the WasteSafe 2017 – 5th international conference on solid waste management in South Asian countries*. https://www.researchgate.net/publication/314256821

Harmsen, P., Scheffer, M., & Bos, H. (2021). Textiles for circular fashion: The logic behind recycling options. *Sustainability, 13*(17), 9714.

Hartley, K., van Santen, R., & Kirchherr, J. (2020). Policies for transitioning towards a circular economy: Expectations from the European Union (EU). *Resources, Conservation and Recycling, 155*, 104634. https://doi.org/10.1016/j.resconrec.2019.104634

Ishfaq, M. (2015). *Infrared technology and its applications in textile recycling technology: Improving sustainability in clothing industry* (Master's thesis). Lahti University of Applied Sciences. https://www.theseus.fi/bitstream/handle/10024/103950/Ishfaq_Muhammad.pdf?sequence=2

Islam, M. S. (2021). Ready-made garments exports earning and its contribution to economic growth in Bangladesh. *GeoJournal, 86*(3), 1301–1309.

Islam, S., & Khan, F. H. (2021). *Why moving to a circular economic model makes sense for the textile industry*. LightCastle Analytics Wing.

Jamshaid, H., Hussain, U., Mishra, R., Tichy, M., & Muller, M. (2021). Turning textile waste into valuable yarn. *Cleaner Engineering and Technology, 5*, 100341.

Jui, U. M. (2022). Reverse resources: Turning textile waste into raw material. *The Business Standard*.

Kazancoglu, I., Kazancoglu, Y., Yarimoglu, E., & Kahraman, A. (2020). A conceptual framework for barriers of circular supply chains for sustainability in the textile industry. *Sustainable Development, 28*(5), 1477–1492. https://doi.org/10.1002/SD.2100

Khairul Akter, M. M., Haq, U. N., Islam, M. M., & Uddin, M. A. (2022). Textile-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh. *Cleaner Environmental Systems, 4*, 100070. https://doi.org/10.1016/J.CESYS.2022.100070

Kim, S., & Jeong, B. (2016). Closed-loop supply chain planning model for a photovoltaic system manufacturer with internal and external recycling. *Sustainability, 8*(7), 596. https://doi.org/10.3390/SU8070596

Leal Filho, W., Ellams, D., Han, S., Tyler, D., Boiten, V. J., Paco, A., Moora, H., & Balogun, A. L. (2019). A review of the socio-economic advantages of textile recycling. *Journal of Cleaner Production, 218*, 10–20). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.01.210

Leonas, K. K. (2017). The use of recycled fibers in fashion and home products. In *Textiles and clothing sustainability. Textile science and clothing technology* (pp. 55–77). Springer. https://doi.org/10.1007/978-981-10-2146-6_2

Li, X., Wang, L., & Ding, X. (2021). Textile supply chain waste management in China. *Journal of Cleaner Production, 289*, 125147. https://doi.org/10.1016/J.JCLEPRO.2020.125147

MacArthur Foundation. (2017). *A new textiles economy: Redesigning fashion's future*. Ellen MacArthur Foundation.

Majumdar, A., Shukla, S., Singh, A. A., & Arora, S. (2020). Circular fashion: Properties of fabrics made from mechanically recycled poly-ethylene terephthalate (PET) bottles. *Resources, Conservation and Recycling, 161*, 104915. https://doi.org/10.1016/J.RESCONREC.2020.104915

Matayeva, A., & Biller, P. (2022). Hydrothermal liquefaction of post-consumer mixed textile waste for recovery of bio-oil and terephthalic acid. *Resources, Conservation and Recycling, 185*, 106502. https://doi.org/10.1016/j.resconrec.2022.106502

Mishra, S., Jain, S., & Malhotra, G. (2020). The anatomy of circular economy transition in the fashion industry. *Social Responsibility Journal, 17*(4), 524–542. https://doi.org/10.1108/SRJ-06-2019-0216/FULL/PDF

Patwary, S. (2020). Clothing and textile sustainability: Current state of environmental challenges and the ways forward. *Textile & Leather Review, 3*(3), 158–173. https://doi.org/10.31881/TLR.2020.16

Pavarini, M. C. (2021). The Materials: How Bangladesh could benefit from recycling cotton waste. *Spin-Off*. https://www.the-spin-off.com/news/stories/The-Materials-How-Bangladesh-could-benefit-from-recycling-cotton-waste-15973

Textile Exchange (2020). *Preferred Fiber and Materials Market Report 2020.*

Quazi, B. (2017, March). *Garments waste recycling in Dhaka: A case study of Mirpur area*.

Ranjithkumar, M., Uthandi, S., Kumar, P. S., Muniraj, I., Thanabal, V., & Rajarathinam, R. (2022). Highly crystalline cotton spinning wastes utilization: Pretreatment, optimized hydrolysis and fermentation using Pleurotus florida for bioethanol production. *Fuel, 308*, 122052.

Rashid, M. E., Khan, M. R., Haque, R. U., & Hasanuzzaman, M. (2023). Challenges of textile waste composite products and its prospects of recycling. *Journal of Material Cycles and Waste Management, 25*, 1267–1287. https://doi.org/10.1007/s10163-023-01614-x

Ruuth, E., Sanchis-Sebastiá, M., Larsson, P. T., Teleman, A., Jiménez-Quero, A., Delestig, S., Sahlberg, V., Salén, P., Sanchez Ortiz, M., Vadher, S., & Wallberg, O. (2022). Reclaiming the value of cotton waste textiles: A new improved method to recycle cotton waste textiles via acid hydrolysis. *Recycling, 7*(4), 57. https://doi.org/10.3390/recycling7040057

Saha, K., Dey, P. K., & Papagiannaki, E. (2021). Implementing circular economy in the textile and clothing industry. *Business Strategy and the Environment, 30*(4), 1497–1530.

Sandin, G., & Peters, G. M. (2018). Environmental impact of textile reuse and recycling – A review. *Journal of Cleaner Production, 184*, 353–365. https://doi.org/10.1016/j.jclepro.2018.02.266

Sembiring, E., & Nitivattananon, V. (2010). Sustainable solid waste management toward an inclusive society: Integration of the informal sector. *Resources, Conservation and Recycling, 54*(11), 802–809. https://doi.org/10.1016/J.RESCONREC.2009.12.010

Shamsuzzaman, M., Islam, M. M., Hasan, H. R. U., Khan, A. M., & Sayem, A. S. M. (2023). Mapping environmental sustainability of knitted textile production facilities. *Journal of Cleaner Production, 405*, 136900.

Shen, L., & Worrell, E. (2014a). Plastic recycling. In *Handbook of recycling* (pp. 179–190). Elsevier.

Shen, L., & Worrell, E. (2014b). Plastic recycling. In *Handbook of recycling: State–of–the–art for practitioners, analysts, and scientists* (pp. 179–190). Elsevier. https://doi.org/10.1016/B978-0-12-396459-5.00013-1

Skvarciany, V., Lapinskaitė, I., & Volskyte, G. (2021). Circular economy as assistance for sustainable development in OECD countries. *Oeconomia Copernicana, 12*(1), 11–34.

Swazan, I. S., & Das, D. (2022). Bangladesh's emergence as a ready-made garment export leader: An examination of the competitive advantages of the garment industry. *International Journal of Global Business and Competitiveness, 17*(2), 162–174.

Team, F. R. (2018). FILOTEX Ltd. model of recycling "cutting waste" is replicable globally. *Textile Today*. Retrieved from https://www.textiletoday.com.bd/filotex-ltd-model-of-recycling-cutting-waste-is-replicable-globally/

Uddin, M. (2018). Circular fashion: Why and how Bangladesh could take the lead? *DailyStar*. Retrieved from https://www.thedailystar.net/opinion/perspective/circular-fashion-why-and-how-bangladesh-could-take-the-lead-1610374

Uddin, F. (2019). *Textile manufacturing processes*. InTech.

Ütebay, B., Çelik, P., & Çay, A. (2019). Effects of cotton textile waste properties on recycled fiber quality. *Journal of Cleaner Production, 222*, 29–35. https://doi.org/10.1016/J.JCLEPRO.2019.03.033

Ütebay, B., Çelik, P., & Çay, A. (2020). Waste in textile and leather sectors. In *Textile wastes: Status and perspective* (pp. 39–58). IntechOpen.

Uyanık, S. (2019). A study on the suitability of which yarn number to use for recycle polyester fiber. *The Journal of the Textile Institute, 110*(7), 1012–1031.

Ventura, H., Álvarez, M. D., Gonzalez-Lopez, L., Claramunt, J., & Ardanuy, M. (2022). Cement composite plates reinforced with nonwoven fabrics from technical textile waste fibers: Mechanical and environmental assessment. *Journal of Cleaner Production, 372*, 133652. https://doi.org/10.1016/j.jclepro.2022.133652

Yalcin-Enis, I., Kucukali-Ozturk, M., & Sezgin, H. (2019). Risks and management of textile waste. In *Nanoscience and biotechnology for environmental applications* (pp. 29–53). Springer.

Yin, R., Ling, Y. L., Fisher, R., Chen, Y., Li, M. J., Mu, W. L., & Huang, X. X. (2021). Viable approaches to increase the throughput of ring spinning: A critical review. *Journal of Cleaner Production, 323*, 129116.

Zhao, J., Yan, P., & Wang, D. (2017). Research on mineral characteristics of converter steel slag and its comprehensive utilization of internal and external recycle. *Journal of Cleaner Production, 156*, 50–61. https://doi.org/10.1016/J.JCLEPRO.2017.04.029