Textile Recycling

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Textile reuse consists of the various methods of prolonging the useful service life of textile products from one owner to another. Renting, trading, swapping, borrowing, and inheriting are commonly practiced, which are facilitated by second-hand stores, garage sales, online stores and flea markets, and charities. On the other hand, textile recycling refers to reprocessing pre-consumer and post-consumer textile waste for use in new textile or non-textile products. Various textile recycling technologies such as fiber regeneration, conversion of textile waste into insulation/building materials, fermentation, anaerobic digestion, composting, and thermal recovery are available and progressively improved. Textile reuse and recycling offer environmental sustainability and can reduce environmental impact by reducing the use of virgin textile fiber and avoiding processes further downstream in the textile product life cycle.

Keywords: textile waste ; reuse and recycling ; municipal solid waste ; composting ; sustainability

1. Textile Waste Generation and Management in Leading Economies

Textile waste is considered as discarded or unwanted material from the production and use of fiber, textile, and clothing, which can be categorized into three types, pre-consumer, post-consumer, and industrial textile waste [1][2]. The pre-consumer textile waste is viewed as 'clean waste', as a by-product during the manufacturing process of fibrous materials. The post-consumer textile waste consists of discarded garments or household textiles (sheets, towels, and pillowcases) that are worn-out, damaged, and outgrown of no value to consumers after their service life [3]. Industrial textile waste is deemed as 'dirty waste' generated from commercial and industrial textile applications. The expansion of the clothing and textile industry and the consumer's fast fashion trend have caused a rapid global increase in textile waste. The increased consumption of fashion textiles generates a growing amount of waste. Furthermore, more than 60% of all recovered clothes could be reused, 35% could be converted into wipers and fiber recycling, and only 5% would need to be discarded [4]. However, in the real world, a significant portion of textile waste is disposed of in landfills. As a result, it is critical to comprehend the challenges that leading economies face when it comes to textile production and waste management. In terms of textile exports, the leading economies considered are China, The European Union, The United States, and Canada.

China has the largest economy in clothing and textiles exports globally, yet the industry faces unprecedented crises [5][6]. The country's dominance as a textile provider across the globe is challenged by the loss of competitive advantages in terms of low labor costs as wages are rising. China attempts to maintain its dynamic advantage in labor-intensive textile products by encouraging the relocation of Chinese textile production bases to poorer Chinese provinces and neighboring least developed countries (LDCs). Simultaneously, China's global competitiveness was upgraded through technological advancement, implementing sound policies to develop capital-intensive textile goods, launching niche products and international brands [6][7]. The Chinese textile industry sector has experienced consistent economic growth over the last decade and is primarily focused on the production of apparel made of synthetic fabrics. Furthermore, China produces approximately 31% of the global ratio of synthetic fibers required by the modern textile industry [8] and produces nearly 65% of the world's clothing [9]. When China started imposing strict environmental standards on textile production, China's cloth products became more competitive in the United States (US) market [10].

Furthermore, many people in China have easy access to low-cost fashion clothing with short service life. Roughly 45% of the textile produced in China is wasted. Approximately 26 million tons (MT) of garments are left untreated and dumped annually, while only 3.5 MT of the collected textile waste was recycled and reused in 2017 [9]. China's textile waste generation is estimated to range from 20 to 26 MT per year, with a low utilization rate [11]. The Chinese government is encouraging businesses to recycle their own brand clothing through mechanical and chemical recycling. China recognized the two-fold benefits of donating textile waste as it gives clothes a second life while generating revenue for charity. However, in the absence of effective recycling practices, used clothing is sent to waste-to-energy (WTE) incinerators [9]. In 2013, China's State Council mandated that textile manufacturers create a circular value chain to promote environmental sustainability in the disposal of post-consumer textiles [11].

The EU textile industry generates approximately 16 MT of waste annually. European consumers discard 5.8 MT of textiles per year, where only 26% is recycled, while a significant fraction of this waste is disposed of into landfills or incinerated [12][13]. The disposal cost of textile waste into landfills is about €60/ton in some countries in Europe, including France [14]. The

European Waste Framework Directive (2008/98/EC) established the fundamental waste management principle and requires the EU member states to adopt a waste management hierarchy (prevention, reuse, recycling, and disposal) in waste management plans and waste prevention programs [15]. Furthermore, the European Council (EC) promoted sustainability by substituting the Waste Framework Directive with a Circular Economy Package, which set a target for the municipal solid waste (MSW) recovery to 70% and limits the fraction to be landfilled to 10% by 2030 [16]. The extended producer responsibility (EPR) policy was essential in achieving such targets. The EPR holds the producers responsible for collecting, processing, and treatment, including recycling and disposal of products at the post-consumer stage of a product's life cycle [17]. The EPR policy has led to an average annual increase of 13% in post-consumer textile collection [12]. Furthermore, the EPR policy encourages waste prevention at source, promotes green product design, and encourages public recycling [17]. The financial responsibility of the producer, as well as separate collection and recycling agencies, are critical to the success of EPR-based environmental policies [18].

Furthermore, the EU establishes new waste management rules, with a focus on closed-loop recycling from production to waste management, with the goal of making economies more sustainable and environmentally friendly [19]. The closed-loop system reduces waste by a repeated process of recycling and reusing materials until they become biodegradable waste. The system can address the fashion industry's intensive use of finite land, water, and energy resources in a sustainable manner [20]. The EU member states' reuse and recycling targets for municipal waste have been set at 55% by 2025, 60% by 2030, and 65% by 2035. By January 2025, a separate collection of textiles and hazardous waste from households will be implemented [19]. Across the European countries, only 18% of clothing is reused and recycled, while 30% is incinerated and a significant fraction of 70% goes to landfills [21]. In France, 40% of the post-consumer textiles collected are exported to African countries for reuse. As of 2017, France is the only European country that globally introduced EPR for textiles, household linen, and shoes [12]. European companies are innovative in formulating sustainability targets where the raw materials, design and development, manufacturing, and end-of-use are the priority on the agenda [20].

In the US, the majority of textile waste in the MSW stream is discarded apparel. However, other sources were identified such as furniture, carpets, tires, footwear, as well as other non-durable goods such as towels, sheets, and pillowcases [22][23]. Textile waste generation and the fraction of textile waste in MSW is increasing with time. In 2010, an estimated 13.2 MT of textile waste were generated, which is equivalent to 5.3% of total MSW stream. While in 2015 and 2017, the generated textile waste increased to 16.1 MT and 16.9 MT, accounting to 6.1% and 6.3% of the total MSW generation, respectively. Approximately 85% of all textiles in the US end up in landfills, and only 15% is donated or recycled [24]. The United States Environmental Protection Agency (USEPA) estimated that textile waste occupies nearly 5% of landfill space [24]. Among the leading economies in the textile industry, the US has the highest share of landfilling textile waste, amounting to 29.3 kg/ca in 2016, and the estimated cost of textile waste sent to landfills is $45/ton [25]. Since landfilling keeps the largest share in textile waste management in the US, promoting recycling technologies to many textile industries is crucial. Composting is not a common method of managing textile waste. Nevertheless, incineration and recycling are gaining popularity in textile waste management .

In Canada, an estimated 500,000 tons of apparel waste is disposed of annually [26]. The average Canadian discards between 30 [27] and 55 [28] pounds of textiles annually [29]; almost 95% of those clothes could be reused or recycled [30]. Globally, textile waste has increased dramatically due to the rise in clothing consumption and production [30]. In Ontario, approximately 1.2 million people dispose their unwanted clothes into the waste bin at a rate of roughly 45,000 tons annually [31]. In the Metro Vancouver Regional District, an estimated 30,000 tons of textile waste are annually landfilled, accounting for 5% of the annual total waste volume in 2016 [32]. In Toronto, a survey was conducted to determine if participants donated and/or disposed of their unwanted clothing [31]. According to the findings, 17% of participants consider “disposal” to be the most convenient (10%) and fastest (7%) method of getting rid of unwanted textile waste. In Manitoba, textile and carpet waste materials are under the Canadian Council of Ministers of the Environment (CCME) National Action Plan for EPR of the Waste Management Task Group [33]. Unwanted clothing items that could be donated are usually dropped off at city drop-off bins or collected by non-profit charitable organizations and municipal programs. Due to their poor condition, some donated textiles are frequently discarded in landfills [34].

2. Textile Reuse and Recycling

Generally, textile reuse and recycling could reduce environmental impact because it could potentially reduce virgin textile fiber production and avoid processes further downstream in the textile product life cycle. Moreover, textile reuse and recycling are more sustainable when compared to incineration and landfilling. However, reuse is considered more beneficial than recycling, mainly when sufficiently prolonging the reusing phase [35]. Textile reuse encompasses various means for extending the useful service life of textile products from the first owner to another [36]. This is commonly practiced by renting, trading, swapping, borrowing, and inheriting, facilitated by second-hand stores, garage sales, online and flea markets, and charities. On the other hand, textile recycling refers to reprocessing pre-consumer and post-consumer textile waste for use in new textile or non-textile products.

Textile recycling is typically classified as mechanical or chemical recycling. Mechanical recycling degrades waste into a decoration, construction, agricultural, and gardening use. Chemical recycling involves a process where polymers are depolymerized (polyester) or dissolved (cotton and viscose). Chemical recycling can produce fibers of equal quality compared to virgin materials [9][35]. The sorted textile waste could be chemically treated to extract resources such as protein-based fibers to produce wood panel adhesives; and cellulosic fibers for bioethanol production [13].

The textile recycling route can be classified based on the nature of the processes involved or the level of disassembly of the recovered materials [35]. Fabric recycling consists in recovering and reusing of a fabric into new products. Meanwhile, fiber recycling involves disassembling of fabric but preserving the original fibers. Polymer/oligomer recycling consists of disassembling of fibers while preserving the polymers or oligomers. Moreover, monomer recycling consists of disassembling of polymers or oligomers, while preserving the monomers [35].

Moreover, textile recycling can be classified into upcycling, downcycling, closed-loop, and open-loop recycling. If the product made from recycled material is of higher quality or value than the original product, it is termed ‘upcycling’; the opposite of this is known as ‘downcycling’. Closed-loop recycling involves recycling of a material from a product and reusing it in a more or less identical product. In contrast, open-loop recycling consists of recycling of a material from a product and reusing it in another product. The closed-loop recycling approach recovers the raw material used to produce a polymer product and then reprocess it into the same product of equivalent quality as that from the virgin material [35][37].

Furthermore, recycling technologies for fibers can be typically divided into primary, secondary, tertiary, and quaternary approaches. Primary approaches involve recycling industrial scraps. Secondary recycling involves the mechanical processing of a post-consumer product. Tertiary recycling involves pyrolysis and hydrolysis, converting plastic waste into chemicals, monomers, or fuels. Quaternary recycling refers to burning the fibrous solid waste and utilizing the heat generated [38].

3. Textile Recycling and Recovery Technology

Nowadays, various technologies can be chosen to promote textile waste recycling and recovery. Technologies such as anaerobic digestion, fermentation, and composting are among the biotechnology available for textile waste. The following sections also discuss thermal recovery and conversion of textile waste into insulation/building materials.

3.1. Fiber Regeneration from Textile Waste

Since the ‘export for reuse option’ is no longer a sustainable option for second-hand clothing in many developing countries, virgin cotton fiber production demands the use of extensive resources. Fiber regeneration by recycling cotton waste garments is a closed-loop upcycling technology for cotton waste garments [39]. Fiber regeneration involves transforming the waste cotton fabrics into pulp, dissolving the pulp using a solvent, and spinning into fibers. The N-methylmorpholine N-oxide (NMMO) solvent can dissolve cellulose completely without any degradation and is environmentally safe to use. Pulp reclaimed from cotton-based waste garments can be blended with wood pulp to make fibers similar to lyocell [40].

Furthermore, phosphoric acid pretreatment was applied to waste textiles to recover polyester and glucose. The four pretreatment conditions investigated were the phosphoric acid concentration, pretreatment temperature, time, and the textiles to phosphoric acid ratio. The results showed that 100% polyester recovery was achieved with a maximum sugar recovery of 79.2% at the optimized conditions of 85% phosphoric acid at 50 °C for 7 h and the ratio of textiles and phosphoric acid of 1:15 [41]. The feasibility of cellulase production and textile hydrolysis using fungal cellulase vs. commercial cellulase via submerged fungal fermentation (SmF) using textile waste was investigated. It was demonstrated that glucose recovery yields of 41.6% and 44.6% were obtained using fungal cellulase and commercial cellulase, respectively. Thus, the proposed process has great potential in treating textile waste for the recovery of glucose and polyester as value-added products [37].

3.2. Building/Construction Material from Textile Waste

Textile waste represents a source of raw materials for typical application in construction, such as insulation materials for noise and temperature and fillers or reinforcements of concrete [42]. The conversion of fibrous carpet waste into a value-added product as soil reinforcement demonstrated that fibrous inclusions derived from carpet wastes improve the shear strength of silty sands [43]. Moreover, textile reinforced concrete (TRC) is a composite concrete material that uses textile as reinforcement material used in various applications, including precast constructions, repair, rehabilitation, and structural strengthening of existing structures. This is innovated by the construction industry, which promotes sustainability in building material by utilizing waste from the textile industry. It combines fine-grained concrete and multi-axially oriented textiles which offers advantages such as thin size, good load-bearing capacity, resistance to corrosion, excellent ductility, no magnetic disturbances, and lightweight [44][45]. Furthermore, textile waste is used to produce thick ropes designed for slope protection against sliding and erosion. Scraps of insulating materials produced from poor quality wool and scraps of nonwoven produced from a blend of recycled fibers were used to produce ropes. The results confirmed the usefulness of the technology for the protection of steep slopes [46].

3.3. Fermentation of Textile Waste for Ethanol Production

Investigation of cotton gin waste as feedstock for ethanol production started in 1979 at Texas Tech University; however, limited studies investigated the efficacy of textile waste for ethanol production [47]. The effect of alkali pretreatment to enhance ethanol production was evaluated using polyester/cotton blend (polycotton) textile. The maximum ethanol yield by simultaneous saccharification and fermentation was 70% after the pretreatment with NaOH/urea at −20 °C, which was considered the most desirable [48]. Moreover, the cotton part of the waste blue jeans (40% polyester/60% cotton) was investigated for ethanol production, which involves the process of enzymatic hydrolysis and fermentation [49]. Enzymatic hydrolysis converts cellulose to fermentable sugars [50]. The effect of corona pretreatment of non-mercerized and mercerized cotton fabrics enhanced the glucose and ethanol yields. The cotton fabric demonstrated its potential as an alternative feedstock for bioethanol production [51].

3.4. Anaerobic Digestion of Textile Waste

Anaerobic digestion (AD) is widely used to treat a biodegradable fraction of organic waste for biogas production. Cotton was characterized by more than 50% cellulose, a potential substrate for biological conversion. Over the last decade, studies have been conducted on AD using cotton waste to produce methane-rich biogas. Cotton wastes (cotton stalks, cottonseed hull, and cotton oil cake) can be treated anaerobically to produce biogas [52]. Cotton waste from spinning mills is a potential substrate for AD [50]. The AD of medical cotton industry waste under thermophilic condition with the use of cattle manure as inoculum demonstrated an improved biogas yield of approximately 92% [53]. Pretreatment methods enhance the biodegradation of complex organic matter in AD systems, resulting in an increase in biogas quality and production and improved biosolids quality in reduced production [54][55]. Various pre-treatment technologies mainly mechanical, thermal, chemical, biological, and their integration can be chosen to enhance the digestion process [56][54]. Pretreatment prior to AD of waste jeans (60% cotton, 40% polyester) and pure cotton waste substrates using 0.5 M Na_2CO_3 at 150 °C for 120 min generates a maximum methane yield of 328.9 and 361.1 mL CH_4/g VS, respectively [49]. Furthermore, a comparable maximum methane production rate of 80% was obtained using single-stage and two-stage digestions in batch reactors utilizing viscose/polyester or cotton/polyester textiles with 20 g/L cellulose loading [57].

3.5. Composting of Textile Waste

Composting is a natural phenomenon of biodegradation of organic waste, such as cotton waste, into a valuable soil supplement. Composting is a low technology, bio-oxidative process that reduces the volume of organic waste by up to 50% over the active phase of composting [47]. Composting utilized various microorganisms, including bacteria and fungi, to convert complex organic matter into simpler substances in the presence of air. Cotton waste poses a significant waste disposal problem nowadays, and composting was viewed as an alternative in preventing the direct landfill disposal of cotton trash. Composted and vermicomposted cotton trash could be an excellent long-term nutrient source [58].

Vermicomposting is a biotechnological composting process that uses earthworms to convert waste into compost with improved soil fertility that significantly exceeds conventional compost [58]. Using cotton waste substrate, the number of bacterial diversity in compost and vermicompost samples was similar. However, the vermicompost samples contain a rich density of bacterial isolates when compared with compost samples which produce better humus [59] .

Vermicomposting of cotton textile waste in the form of willow waste from ginning factories was investigated. Willow waste is undesirable for textile application and is just disposed into landfill. The collected willow waste was mixed with cow dung slurry, cellulase, and amylase enzymes (isolated from cow dung), and an effective microorganism solution. The mixture was turned and sprinkled with water periodically. After 20 days, the waste was wholly decomposed, and earthworms were introduced. The vermicomposting process was ended when the waste mixture turned light brown or dark brown after 14 days. The resulting vermicompost was then used to grow plants in pots and revealed that the plants grown using the vermicompost made from willow waste had an excellent growth rate in root length, shoot length, and leaf area index compared to the control pot [60].

Furthermore, cotton gin waste cannot be directly reused on-farm due to farm hygiene risks, and composting of cotton gin waste is an accepted method [47]. Cotton gin waste was used as a bulking agent for pig manure composting under two different proportions of 4:3 and 3:4 of pig slurry:cotton gin waste [61]. It was concluded that the thermal properties of the bulking agent were responsible for the temperature development and aeration demand. The gaseous emissions were related to the organic matter degradation process. The compost with the higher proportion of pig slurry (4:3) had greater organic matter humification and higher nutrient concentrations.

Furthermore, since the 1980s, the waste cotton substrate was utilized for oyster mushroom cultivation. More than 90% of oyster mushroom growers utilized waste cotton substrate for cultivation [62]. Cotton waste with fermented poplar sawdust exhibited the highest yield on fruit bodies of oyster mushroom, equivalent to 742 g per 4 kg of substrate [62]. A new cotton waste composting technology to cultivate oyster mushrooms shows a higher mushroom yield of 65.1% over substrate dry weight when compared to a traditional natural fermentation technology with a 43.6% yield [63]. The process involves adjusting cotton waste moisture content to 65%, after which it was pre-composted for two days by soaking in a lime solution. Then, the cotton substrate was sprayed with the previously prepared Ctec2 enzyme under optimal enzymatic activity conditions (pH 5, 50 °C, 60 h, and enzyme to substrate ratio of 0.45%) and then inoculated in pure culture of fungus. Then spawning, caring of the bed, and harvesting was conducted [63].

3.6. Thermal Recovery

Incineration with the thermal recovery of unwanted textiles not suited for recycling (carpets or textiles with unknown fibers) is considered a viable alternative to landfilling. Carpet fibers have a high calorific value that can reduce the need for fuels, and the resulting ash becomes raw material for cement [64]. The advantage of the incineration option is that it can handle the most significant part of unsorted textile waste, and energy can be recovered from combustion. However, burning textiles alone can cause irregular temperature behavior, ignition rate, and weight loss percentage in the ignition propagation stage. For this, textile waste should be mixed with waste cardboard upon incineration to maintain a uniform burning behavior of textiles [65]. Incineration of 1 ton of household textile waste can recover 15,800 MJ of energy, and 27 kg of ash is generated [66][67].

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