textiles

Review

A Review on Textile Recycling Practices and Challenges

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Abstract: The expansion of clothing and textile industry and the fast fashion trend among consumers have caused a rapid global increase in textile waste in the municipal solid waste (MSW) stream. Worldwide, 75% of textile waste is landfilled, while 25% is recycled or reused. Landfilling of textile waste is a prevalent option that is deemed unsustainable. Promoting an enhanced diversion of textile waste from landfills demands optimized reuse and recycling technologies. Reuse is the more preferred option compared with recycling. Various textile reuse and recycling technologies are available and progressively innovated to favor blended fabrics. This paper aims to establish reuse and recycling technologies (anaerobic digestion, fermentation, composting, fiber regeneration, and thermal recovery) to manage textile waste. Improved collection systems, automation of sorting, and discovering new technologies for textile recycling remains a challenge. Applying extended producer responsibility (EPR) policy and a circular economy system implies a holistic consensus among major stakeholders.

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

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Citation: Juanga-Labayen, J.P.; Labayen, I.V.; Yuan, Q. A Review on Textile Recycling Practices and Challenges. *Textiles* **2022**, 2, 174–188. https://doi.org/10.3390/textiles2010010

Academic Editor: Philippe Boisse

Received: 6 February 2022
Accepted: 9 March 2022
Published: 16 March 2022

1. Introduction

Population growth, improvement of living standards, an increasing assortment of textile materials, and the decreasing life cycle time of textile products contributed to global fiber consumption that generates a significant amount of post-industrial and post-consumer fiber waste [1,2]. Globalization has made the apparel industry produce more clothing at lower costs, and many consumers have adapted a 'fast fashion' trend that considers clothing to be a disposable product [3]. Fast fashion characterized by mass production, variety, agility, and affordability has brought about a surge of apparel consumption [4].

The rising cost associated with textile manufacturing in terms of energy, raw materials, and waste management is putting pressure on businesses across the globe. The textile industry accounts for about 10% of total carbon emissions [5] and has been identified as the fifth largest contributor of carbon emissions [6,7]. In this regard, it is crucial to understand that 20th-century approaches in meeting 21st-century demands are not affordable for sustainable development [8]. It is essential to consider the efficient use and management of natural resources by reducing the raw material consumption through reuse and recycling of textile products regarded as waste, which would offer a sustainable approach for textile waste management. To improve the current behavior of clothing consumption and waste generation, an environmentally and financially sound long-term national program should be established [9].

Globally, approximately 75% of textile waste is disposed of in landfills, 25% is reused or recycled, and less than 1% of all textile is recycled back into clothing [10,11]. In this respect, advancing reuse and recycling technologies for textile waste in diverting waste from landfill is crucial. More importantly, closed-loop recycling of fabric is highly promoted. There have been several reinforced global actions integrating many expert stakeholders addressing both economic and environmental challenges that the clothing industry faces; among them are the Textile Exchange, Council for Textile Recycling, Sustainable Apparel Coalition, and the Boston Consulting Group, among others. For instance, Textile Exchange commits to reducing CO_2 emissions by 30% from textile fibers and material production by 2030 and fosters the role of the circular economy as a powerful instrument for mitigating impacts and contributing to the urgent need for climate action [11]. Hence, textile reuse and recycling are vital in promoting this innovative act. This paper determines the existing textile waste reuse and recycling technologies and the status of textile waste generation and management in some leading economies.

2. Textile Production

Clothing and textiles contributed 6% to the world exports of manufactured goods in 2017 (Figure 1); China and the European Union (EU) are the two leading regions for clothing and textile exports [12]. The worldwide volume production of textile fibers in 1975 was about 23.9 million metric tons (MMT), in 2017 it reached 98.5 MMT [13], and it increased further to about 111 MMT in 2019 [11]. For many years, cotton fiber demand dominated polyester; however, in 2002, polyester demand surpassed cotton fiber and has continued to grow at a faster rate than cotton fiber [14]. Polyester and cotton are the most common fibers used worldwide [14,15]. Moreover, the global fiber consumption in 2017 consists of 60% synthetic fibers or polyester/cotton blend (polycotton) and 40% cellulosic, which is the typical example of most textiles [16]. Nevertheless, the global fiber market in 2019 was dominated by polyester and cotton (Figure 2). From these figures, it is apparent that textile waste management is a critical issue that presents enormous challenges for the textile industry, policymakers, and consumers.

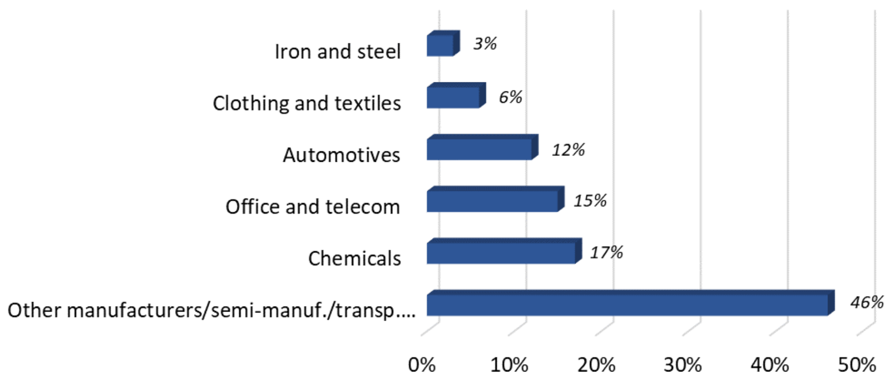

Figure 1. Percentage share of world exports of manufactured goods in 2017 [12].

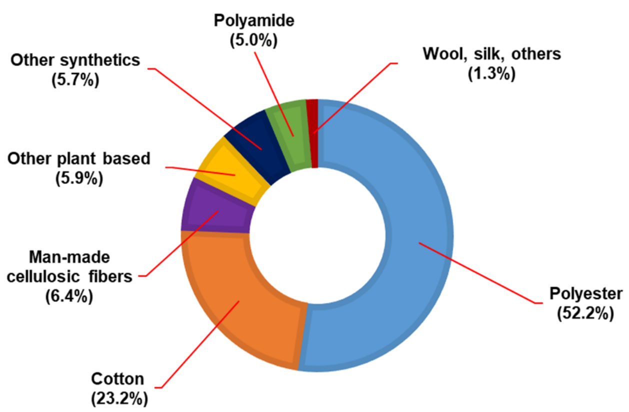

Figure 2. Global fiber production share in 2019 [11].

3. 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 [8,17]. 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 [18]. 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 wastes. The increased consumption of fashion textiles generates a growing amount of waste. As fashion textiles, are almost 100% recyclable, nothing in the textile and apparel industry should be wasted in an ideal scenario. 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 [19]. 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 in this study 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 [20,21]. 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 [21,22]. 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 [23] and produces nearly 65% of the world's clothing [24]. When China started imposing strict environmental standards on textile production, China's cloth products became more competitive in the United States (US) market [25].

Furthermore, many people in China have easy access to low-cost fashion clothing with a 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 [24]. China's textile waste generation is estimated to range from 20 to 26 MT per year, with a low utilization rate [26]. 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 [24]. 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 [26].

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 [4,27]. The disposal cost of textile waste into landfills is about €60/ton in some countries in Europe, including France [28]. 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 [29]. 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 [30]. 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 [31]. The EPR policy has led to an average annual increase of 13% in post-consumer textile collection [4]. Furthermore, the EPR policy encourages waste prevention at source, promotes green product design, and encourages public recycling [31]. The financial responsibility of the producer, as well as separate collection and recycling agencies, are critical to the success of EPR-based environmental policies [32].

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 [33]. 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 [34]. 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 [33]. 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 [16]. 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 [4]. 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 [34].

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 [35,36]. 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 (Figure 3). Approximately 85% of all textiles in the US end up in landfills, and only 15% is donated or recycled [37]. The United States Environmental Protection Agency (USEPA) estimated that textile waste occupies nearly 5% of landfill space [37]. 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 (Figure 4), and the estimated cost of textile waste sent to landfills is $45/ton [38]. 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 (Figure 5).

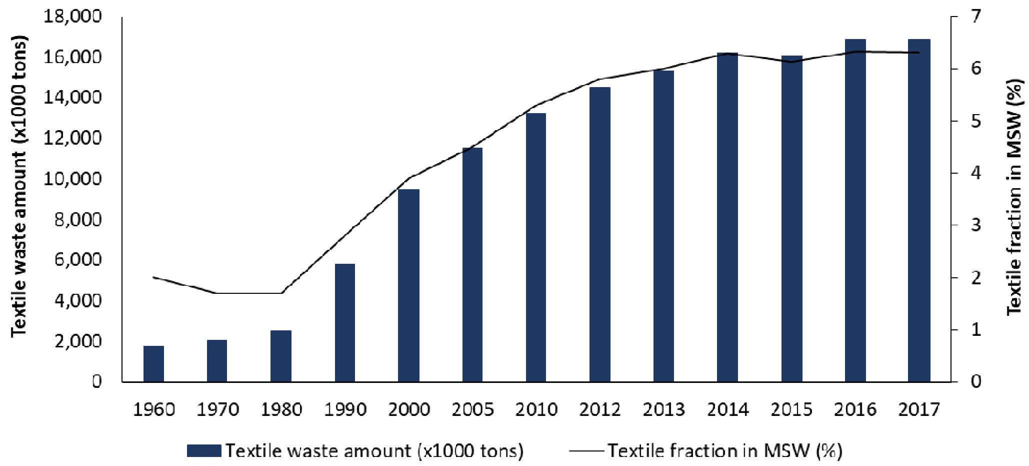

Figure 3. Textile waste generation in the US [39].

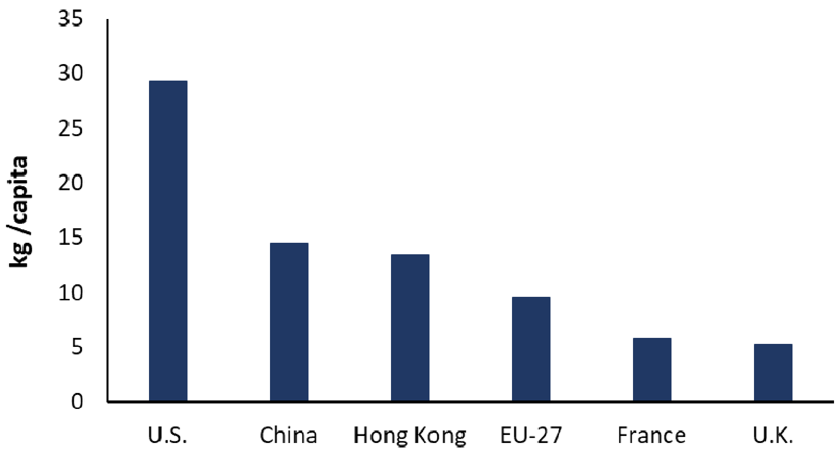

Figure 4. Annual generation of landfilled textiles (in kg/ca) in 2016 [4].

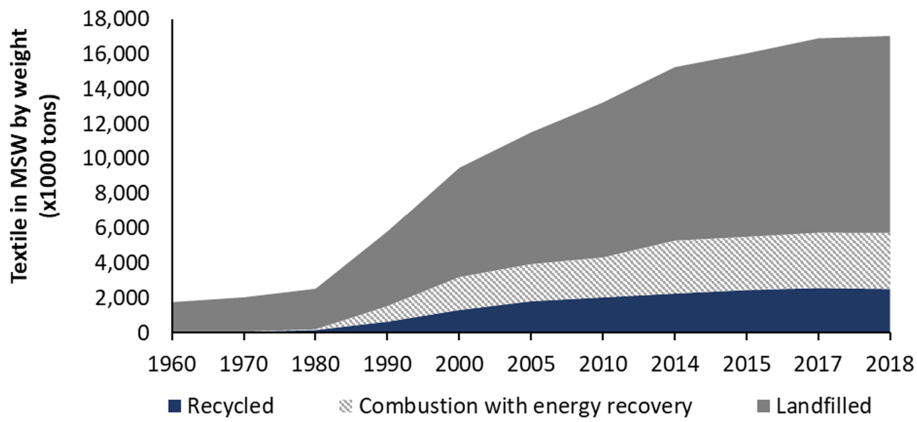

Figure 5. Textile waste management in the US [40].

In Canada, an estimated 500,000 tons of apparel waste is disposed of annually [41]. The average Canadian discards between 30 [42] and 55 [43] pounds of textiles annually [44]; almost 95% of those clothes could be reused or recycled [45]. Globally, textile waste has increased dramatically due to the rise in clothing consumption and production [45]. In Ontario, approximately 1.2 million people dispose their unwanted clothes into the waste bin at a rate of roughly 45,000 tons annually [46]. 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 [47]. In Toronto, a survey was conducted to determine if participants donated and/or disposed of their unwanted clothing [46]. 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 [48]. 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 [49].

4. 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 [50]. Textile reuse encompasses various means for extending the useful service life of textile products from the first owner to another [51]. 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 [24,50]. 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 [27].

The textile recycling route can be classified based on the nature of the processes involved or the level of disassembly of the recovered materials [50]. 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 [50].

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. Figure 6 shows the classification of various forms of reuse and recycling. 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 [50,52].

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 [53].

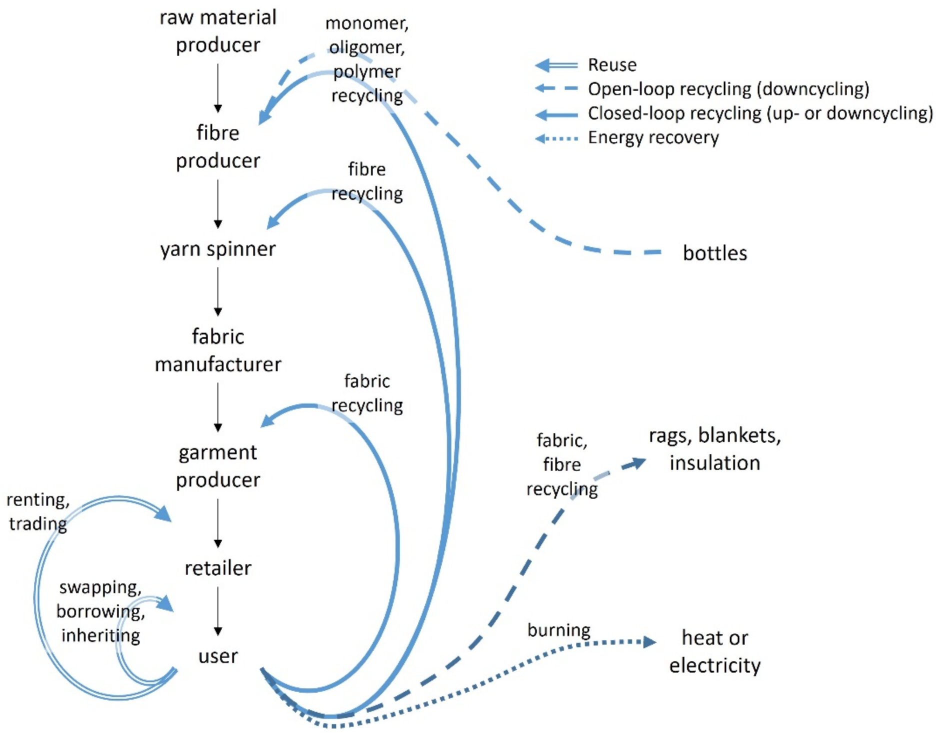

Figure 6. Classification of textile reuse and recycling routes, reprinted with permission from [50]. Copyright 2018 Elsevier.

5. Environmental Sustainability in Textile Recycling

Reuse and recycling of textile waste offers environmental sustainability. Upcycling and closed-loop recycling are the potential recycling routes that maximize conservation of resources such as raw materials, water, and energy, with minimal environmental impact [8]. Moreover, textile reuse and recycling reduce environmental impact compared to incineration and landfilling, and reuse is more beneficial than recycling [50]. Applying ecological footprint in a textile tailoring plant revealed that the resources category has the highest ecological footprint, followed by the energy consumed [54]. Resources recovery can provide significant environmental gains by replacing products from primary resources [55]. For every kilogram of virgin cotton displaced by second-hand clothing and polyester could save approximately 65 kWh and 95 kWh, respectively [56].

6. 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.

6.1. 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 (Table 1). 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 [57]. Cotton waste from spinning mills is a potential substrate for AD [58]. 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% [59]. 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 [60,61]. Various pre-treatment technologies mainly mechanical, thermal, chemical, biological, and their integration can be chosen to enhance the digestion process [60,62]. 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 [63]. 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 [64]. Table 2 summarizes the optimum operating conditions using batch process of anaerobic digestion from the reviewed literature.

Table 1. Characteristics of cotton waste [58].

Contents	Percentage
Cellulose	54.00
Non-cellulose	16.00
Ether extractive	12.00
Moisture	8.80
Ash	7.20
Metals and others	3.20

Table 2. Optimum operating conditions for biogas production using cotton wastes

Cotton Waste Stream	Pretreatment	Inoculum	Operating Temperature (°C)	Digestion Time (Days)	CH_4 Yield (mL/g VS)	CH_4 (%)	Reference
Cotton waste (cotton stalks, cottonseed hull, cotton oil cake)	-	Effluent from WWTP anaerobic digester	35 ± 2	23	65 (cotton stalks); 86 (cotton seed hull); 78 (cotton oil cake)	60	[57]
Cotton waste from spinning mills	-	5–7.5% cow dung/pig dung	30–32	50	-	77	[58]
Medical cotton waste	Alkaline (Na_2CO_3)	Cattle manure	55	90	37.57	60–70	[59]
Waste jeans (60% cotton) Cotton waste (100%)	0.5 M Na_2CO_3 at 150 °C for 120 min	Effluent from municipal WWTP anaerobic digester	37	40	328.9 (60% cotton); 361.08 (pure cotton)	-	[63]
Cotton textile waste (100% cotton)	0.5 M Na_2CO_3 at 150 °C for 3 h	Digested sludge from municipal WWTP anaerobic digester	37	15	306.73	>50	[65]

6.2. 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 [66]. 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 [67]. 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 [63]. Enzymatic hydrolysis converts cellulose to fermentable sugars [58]. 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 [68]. Table 3 summarizes the optimum operating conditions for ethanol production based on the reviewed literature.

Table 3. Optimum operating conditions for ethanol production using cotton wastes.

Cotton Waste Stream	Pretreatment	Enzymatic Hydrolysis	Fermentation Condition	Glucose Yield	Ethanol Yield	Reference
Cotton part from polyester-cotton textile	NaOH/urea, −20 °C, 72 h	Cellulase and β-glucosidase enzyme, pH 4.8, 45 °C, 72 h	*S. cerevisiae*, 36 °C, 72 h	91%	70%	[67]
Bleached and mercerized cotton fabric (100% cellulose)	Corona pretreatment of mercerized cotton fabrics	Celluclast enzyme, 50 °C, 8 days	*S. cerevisiae* var *ellipsoideus*, pH 5, 30 °C, 100 rpm	0.94 g/g	0.9 g/L·h	[68]
Waste jeans (60% cotton) Cotton (pure)	1 M Na_2CO_3, 150 °C, 120 min	Cellulase and β-glucosidase, 45 °C, 72 h, 120 rpm	*S. cerevisiae*, 36 °C, 72 h	81.7% (60% cotton) 88% (pure cotton)	59.5% (60% cotton) 69.4% (pure cotton)	[63]

6.3. 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 [66]. 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 [69].

Vermicomposting is a biotechnological composting process that uses earthworms to convert waste into compost with improved soil fertility that significantly exceeds conventional compost [69]. 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 [70].

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 [71].

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 [66]. 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 [72]. This study 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 [73]. 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 [73]. 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 [74]. 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 [74].

6.4. 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 [75]. 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 [76].

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 [77]. The feasibility of cellulase production and textile hydrolysis using fungal cellulase vs. commercial cellulase via submerged fungal fermentation (SmF) using textile waste was investigated. The study 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 [52].

6.5. 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 [78]. 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 [79]. 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 [80,81]. 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 [82].

6.6. 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 [1]. 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 [83]. Incineration of 1 ton of household textile waste can recover 15,800 MJ of energy, and 27 kg of ash is generated [84,85].

7. Textile Waste Management Challenges

The global increase in clothing consumption and production has resulted in a significant increase in textile waste generation, posing alarming challenges in many leading countries. Textile waste is recognized as the fastest-growing waste stream in MSW across the globe. However, waste collection and economically viable sorting infrastructure remain a challenge. Sorting of textile waste involves intensive time and labor and complications by arising from variations in fiber blends pose a significant challenge. Automation for sorting and innovations in textile recycling are growing interests [4]. Textile reuse, the most preferred option, suffers a shrinking market due to banning imported used clothing in some countries. Textile reuse and recycling to produce new products should be driven by economic incentives to make it feasible for the operating industry. Sustainable blended materials made from recycled fibers are innovative to reduce environmental impact. Further work on the characterization of the structure and properties of cellulosic fibers regenerated from cotton-based waste is essential. Moreover, recycling technologies to sustainably manage other textile waste, such as man-made cellulosic fiber (MMCF) and other fibers (polyamide, wool, rayon, silk, acrylic, etc.), need to be investigated. MMCFs are a group of fibers derived primarily from wood and in other sources of cellulose, which constitute the third most commonly used fiber in the world, behind polyester and cotton. MMCF accounts for approximately 6.4% of total fiber production, with an annual production equivalent of about 7.1 MT [11,86].

Moreover, developing non-conventional fibers—such as bast fibers—and a chemical-free binding technology promote sustainability. Natural fibers—such as bast fibers (among them hemp, flex, nettle, and jute)—can yield significant benefits due to a smaller environmental footprint when compared to conventional plant-based fibers. Innovations supporting the circular economy and closed-loop recycling systems include recycling technologies that can produce new fibers comparable to virgin fibers. Shifting from a current linear economy into a circular economy yields tremendous environmental benefits for the fashion industry while mitigating the effects of greater demand for garments due to a rising world population [34].

8. Conclusions

The global rise in population, industrial growth, and improved living standards have caused a global fiber consumption that generates an alarming amount of unwanted textiles. Economic and environmental sustainability should be incorporated into the long-term textile waste management program. Though the application of EPR policy in textile waste is still limited, it is considered essential in promoting a circular economy system. EPR makes the producers responsible for the overall textile waste management from the collection to the disposal at the end of the product's life cycle. Besides EPR, there is a holistic approach involving major stakeholders (industry, government, private agencies, and consumers) who must work in unity to promote a dynamic circular system. The emerging economies in textile manufacturing should take the lead in shifting from a linear economy to a circular economy.

Textile reuse and recycling are more sustainable than incineration and landfilling, but reuse is more beneficial than recycling. For this, designing a textile product by prolonging the service life quality could promote reuse. In addition, it is essential to promote consumer awareness to foster an environmentally friendly consumption behavior on textile products. Leading economies should manage their textile waste in a closed-loop circular approach, mainly when exporting textile waste to developing countries is being outlawed. Various streams of textile recycling technologies are available and continue to innovate new ideas with biotechnology advancement. Applying holistic technologies, and not relying upon a single technology, to manage a complex textile waste is deemed essential.

Author Contributions: Conceptualization, Q.Y., J.P.J.-L.; Literature review, J.P.J.-L. and Q.Y.; Methodology, J.P.J.-L. and Q.Y.; Writing—original draft preparation, J.P.J.-L. and Q.Y.; Writing—review and editing, Q.Y., J.P.J.-L. and I.V.L.; Supervision, Q.Y.; Funding acquisition, Q.Y. All authors have read and agreed to the published version of the manuscript.

Funding: The research support was provided by the federal funds appropriated to the Graduate Enhancement of Tri-Council Stipends (GETS), the University of Manitoba and the Natural Sciences and Engineering Research Council of Canada (NSERC RGPIN-2014-05510).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

AD, anaerobic digestion; CCME, Canadian Council of Ministers of the Environment; EC, European Council; EU, European Union; EPR, extended producer responsibility; LDCs, least developed countries; MMCF, man-made cellulosic fiber; MMT, million metric tons; MT, million tons; MSW, municipal solid waste; NMMO, N-Methylmorpholine N-oxide; SmF, submerged fungal fermentation; TRC, textile reinforced concrete; US, United States; VS, volatile solids; WTE, waste-to-energy.

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