textiles

Review

State of the Art in Textile Waste Management: A Review

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Abstract: Textile waste constitutes a significant fraction of municipal solid waste sent to landfill or incinerated. Its innovative management is important to enhance sustainability and circularity. This review aims to present the latest policies and the state-of-the-art technologies in the collection, sorting and recycling of textile waste. Policies at global and regional levels are increasingly made to address the sustainability of the textile industry and integrate the concept of circular economy. They are crucial to driving changes and innovations in current textile waste management. The Internet of Things, big data, blockchain and smart contracts have been proposed to improve transparency, traceability and accountability in the textile waste collection process. They optimize collection routes, and transactions and agreements among stakeholders. The sorting of textile waste using near-infrared spectroscopy, optical sorting and artificial intelligence enables its separation based on composition, color and quality. The mechanical recycling of textiles regenerates fibers with the same or different applications from those of the original fabrics. Fibers have been used for making building and slope protection materials. Chemical recycling depolymerizes waste textiles using chemicals to produce monomers for new textiles or other materials, while biological recycling uses enzymes and microorganisms for this purpose instead of chemicals. Thermal recycling recovers energy and fuels from textile waste through pyrolysis, gasification and hydrothermal liquefaction. These innovations may have the drawbacks of high cost and scalability. This review contributes to decision making by synthesizing the strengths and weaknesses of the innovations in textile waste management.

Keywords: collection; innovations; municipal solid waste; sorting; recycling; policy; textile waste

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1. Introduction

The textile industry produces a substantial amount of waste every year, and currently, most of the waste becomes part of municipal solid waste (MSW) [1,2]. Annually, the world produces approximately 92 million tons of textile waste. The textile industry is also a major contributor of plastic waste, ranking second after the packaging sector with 42 million tons of plastic waste generated per year [3]. In the US, textile waste occupies about 5% of landfill space. China and the US produce the largest quantities of textile waste, at 20 million tons and 17 million tons, respectively [4].

Textile waste can generally be defined as any undesirable or discarded piece of fabric or clothing that is unfit for its original purpose [5]. It can be divided into three large groups depending on the sources, namely, pre-consumer waste, post-consumer waste, and post-industrial waste. Pre-consumer textile waste is generated during the production, manufacturing or processing of textiles and typically comprises fabric scraps, yarns or rejected defective products. Post-consumer textile waste is produced when textile products have been used and are discarded before or at their end of life. Instances of this waste are clothing, bedding or curtains thrown away by households or institutions [5]. Post-industrial textile waste is generated by other industries that use textiles as inputs or outputs, which include discarded medical textiles, automotive textiles or packaging textiles [6].

Textile waste has given rise to negative environmental, economic and social problems. It is a contributor of greenhouse gases, water pollution and soil contamination [7]. The fashion industry alone was reported to produce 10% of the total greenhouse gas emissions and 20% of global wastewater, in addition to consuming large amounts of water, energy and chemicals for the manufacturing of clothes [4,8]. Textile waste is commonly landfilled or incinerated, thus taking up landfill space or adding to the release of toxic substances or microplastics into air, water and soil upon incineration [9]. Economically, textile waste results in revenue loss of the textile industry. An estimated USD 500 billion is lost annually due to underutilization of clothing and lack of recycling. Additionally, the disposal of textile waste incurs expenses [10]. Socially, the disposal of textile waste further widens social inequalities. Used clothing is sent from developed countries to low- and middle-income countries for sorting, categorizing and re-baling prior to being sold in second-hand markets, and these procedures are often performed by low-wage workers [10]. Clothing which fails to make it to the markets is treated as solid waste, thus burdening the MSW systems of low- and middle-income countries while bringing more environmental health hazards [11].

Therefore, the effective management of textile waste could yield positive environmental, economic and social impacts. However, the management of textile waste is faced with multiple challenges. The collection of textile waste is often inadequate, inefficient and unorganized, particularly in developing countries, leading to disrupted and unreliable streams of textile waste for the recycling industry [7]. The heterogeneity and complexity of textile waste due to the diverse blends, dyes, finishes and accessories on textiles render the sorting and separation of waste difficult [12]. The recycling of textile waste faces multiple technical, economic and environmental constraints; for instance, the recycling technologies for natural fibers are not established, whereas the recycling processes for synthetic fibers are usually energy-intensive and polluting [13]. Limitations in the sorting and recycling of textile waste make its disposal the only feasible option in many countries, which is unsustainable, since it occupies valuable landfill space and releases greenhouse gases and leachates [10]. The mismanagement of textile waste, particularly synthetic textiles, aggravates the already alarming plastic pollution, since synthetic textiles constitute a major source of microfibers [14,15].

Currently, there are few review papers that present the management of textile waste holistically. A review paper on textile waste valorization techniques focuses on the reusing capability of textile waste and the challenges associated with waste valorization practices without addressing the aspects of textile waste management related to sorting and recycling [16]. Similarly, another review presents reuse and recycling technologies for textile waste with limited discussion on its collection and sorting [17]. Furthermore, a systematic review was conducted on the methods and technologies for recycling fabric waste, encompassing mechanical, chemical and biological recycling, as well as the challenges faced in recycling, such as the compositional complexity of fabric waste, the low quality and value of recycled products, and the environmental impacts of recycling processes [12]. However, it was not extended to the policies, collection and sorting of textile waste. This review, therefore, aims to present the state-of-the-art technologies in the collection, sorting, reusing and recycling of textile waste. It achieves the aim by reviewing recent articles (published in the past 10 years) in these genres to highlight the latest developments in the collection, sorting, reusing and recycling of textile waste.

2. Policies on Textile Waste Management

Policies from governments are essential to driving efforts and innovations in textile waste management. They are indications of global and national commitments which motivate operationalization of and technological development for textile waste management. The UK government, for instance, launched an all-encompassing Waste Prevention Program in March 2021, aiming to reduce environmental and social impacts of textile, as well as other sectors [18]. The program has a list of measures to promote the sustainability of the fashion industry, including encouraging reuse and repair, upscaling circular business models and improving consumer information and education [18]. An Extended Producer

Responsibility scheme for textiles is also in the pipeline to hold the UK fashion industry responsible for the costs of the recycling and disposing of their products [19].

The European Union (EU) rolled out a new Circular Economy Action Plan in March 2020 which covers a comprehensive strategy to enhance the sustainability and circularity of the EU textile sector [20]. The strategy promulgates that the design of textile should consider better durability, reusability and recyclability and that textile production should aim to minimize the associated environmental and social impacts. The strategy also probes the possibility of introducing new rules on textile labelling and traceability to provide consumers with clear and reliable information on the sustainability of textile products [9]. In 2019, the United Nations Environment Program already introduced a Textile Flagship Initiative to bring about systemic change towards sustainability and circularity in the textile sector according to three priorities, namely, changing consumption patterns, improving practices and investing in infrastructure [21]. The initiative complements the operationalization of the UN Alliance for Sustainable Fashion introduced in 2018 to coordinate the efforts of various UN agencies and partners to promote sustainable fashion [22].

In the US, in view that textile waste constituted 5.3% of the total MSW generated in 2018, of which 68.5% was landfilled and only 15.2% was recycled, a white paper was jointly released in April 2022 by the Secondary Materials and Recycled Textiles Association and the Council for Textile Recycling to propose strategies for enhancing textile recovery in the US [4,23]. The two institutions assume important roles in the sale, collection, sorting and processing of textile materials, in addition to educating the public on the environmental and economic benefits of textile reuse and recycling [23]. Increasing emphasis on the sustainability and circularity of the textile sector regionally and globally has spurred research and development of new strategies to collect, sort, recycle and reuse textile waste.

Currently, these policies focus on six major areas, namely, promoting recycling, sustainability, value addition, regulation compliance, innovation encouragement and entrepreneurship [24]. These areas are interrelated. Promoting recycling emphasizes the recycling of textile waste into new textiles with similar or different functions, as well as other products, ideally with value added to enhance the sustainability of fashion industry. Sustainability underscores the reducing, reusing and recycling of textile waste to improve the economic, social and environmental performances of the textile industry [25]. Value addition focuses on textile waste valorization, as well as value-added products in the textile and apparel industries, for long-term benefits [26]. Regulation compliance ensures that harmful waste is properly disposed of, whereas innovative encouragement drives new technologies and methods for dealing with textile waste. Entrepreneurship aims to create new business opportunities in textile waste recycling. These have driven technological innovations and new businesses in the collection, sorting and recycling of textile waste [24]. The most notable innovations have been in the area of sorting with the commercialization of new machines for the more efficient sorting of textile waste, as well as the mechanical and chemical recycling of waste textiles into new textiles with similar or different functions [25].

3. Collection of Textile Waste

The Internet of Things (IoT) and big data have been proposed to enable the efficient identification and collection of textile waste. For example, smart tags or sensors can be attached to textile products to track their location, usage and condition. This can help to optimize the collection routes, reduce transportation costs and increase the recovery rate of textile waste [27]. IoT sensors enable the real-time monitoring of space availability of textile waste containers for optimization of collection routes (Figure 1). Additionally, they contribute to waste collection optimization through the tracking of radio frequency identification as well as the use of sensors and cameras to obtain input on the amount, type and location of textile waste [28]. This helps lower transportation costs, fuel consumption and greenhouse gas emissions associated with waste collection [28]. Big data can also be used to analyze the supply and demand of textile waste and to match waste collectors with recyclers (Figure 1) [29]. Specifically, waste collection efficiency and effectiveness are improved by feeding real-time data on waste generation, collection and disposal to predictive analytics and decision support tools to plan and optimize collection routes, schedules and methods [29].

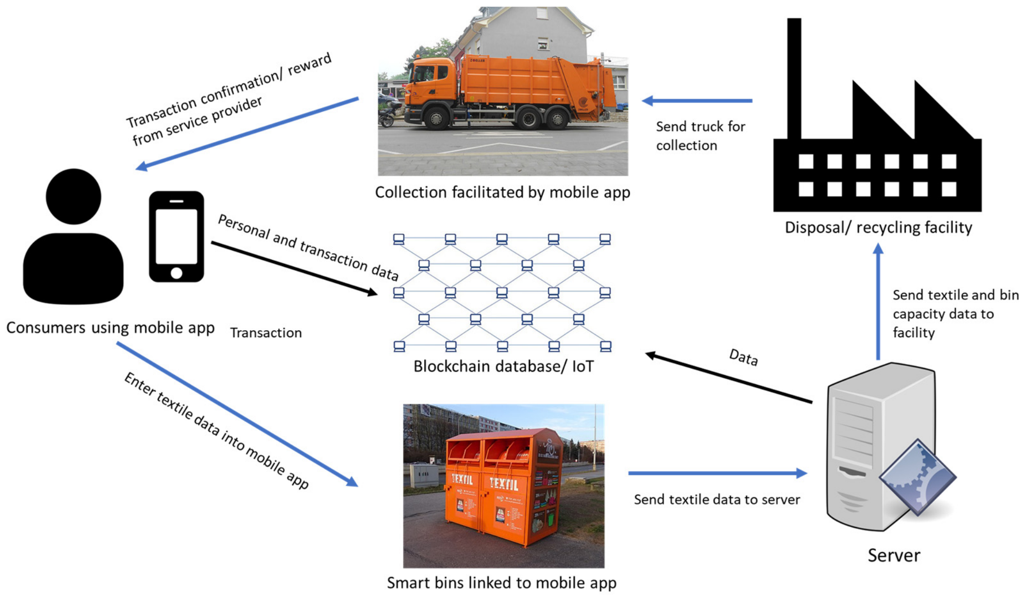

Figure 1. Integration of blockchain, the IoT and mobile applications in textile data collection.

In summary, both the IoT and big data permit the traceability, verification and reporting of textile waste flows and the performance of waste collectors, thus improving the quality and reliability of waste collection services while minimizing illegal dumping. However, the functioning of the IoT and big data requires well-established infrastructure, connectivity and security, whose cost and maintenance could be challenging to developing countries, as the textile industry therein often lacks regulation [28]. The IoT and big data rely on the availability and quality of input data, the accuracy and reliability of algorithms and the feasibility and scalability of solutions, without which their effectiveness in managing textile waste could be compromised [27,29].

Blockchain and smart contracts can also be used to enhance the transparency, traceability and accountability of the textile waste collection process. Blockchain creates a decentralized and secure ledger that records the origin, ownership and destination of textile waste (Figure 1) [30]. The ledger can be accessed by all the stakeholders involved in waste collection. Smart contracts, on the other hand, are used to automate the transactions and agreements between waste collectors and recyclers and to ensure the quality and quantity of waste. This is made possible using self-executing codes triggered by predefined events [31]. Both technologies could render intermediaries, paper-based documentation and manual verification unnecessary, thus reducing transaction costs, risks and errors associated with the textile waste collection process [31]. As with the IoT and big data, their requirements for technical expertise, infrastructure and security are high, and their reliability depends on the quality and accuracy of input data, the design and functionality of the codes and the coordination of the stakeholders [30,31].

Mobile applications and platforms provide valuable channels to facilitate the communication, collaboration and coordination of the textile waste collection process. Mobile applications and platforms connect consumers, waste collectors and recyclers and are used to provide information, incentives and feedback on the textile waste collection process [32]. They enable the stakeholders to request, schedule, track and pay for textile waste management services via smartphones or tablets [32]. Mobile applications and platforms can also be used to educate and raise awareness among consumers about the environmental and social impacts of textile waste and to encourage them to donate or return their unwanted clothes [32]. They employ technologies such as the IoT, artificial intelligence and big data to optimize waste collection routes, methods, frequency and capacity; hence, they experience drawbacks similar to those of the technologies already discussed [33].

The high cost incurred using the IoT, big data, blockchain technology and artificial intelligence can be reduced with the use of open-source technologies, the selection of energy-efficient devices for the IoT and partnerships with other organizations such as fashion companies in the policy-driven quest to make the fashion industry more sustainable through circularity [30]. This also creates new business opportunities. Additionally, incentivization, particularly by governments, is crucial to promoting circularity in the fashion and textile industries. Blockchain technology has, in fact, been used to incentivize waste sorting [30].

4. The Sorting of Textile Waste

The sorting of textile waste is important for successful textile recycling, as it determines the quality and quantity of the recycled fibers and products. It is challenging due to the presence of different types of fabrics, colors, patterns and contaminants in the textile waste streams. Technologies have been developed to facilitate the sorting of textile waste. One of the technologies involves the use of hyperspectral imaging and artificial intelligence. It uses a camera that can capture images of textile waste in different wavelengths and light. The images are then fed to an algorithm for analysis and fabric classification based on fiber composition and the contaminants present. This technology provides high accuracy and speed in sorting textile waste [34].

Another technology combines near-infrared (NIR) spectroscopy and optical sorting, with the former emitting infrared radiation and measuring the radiation reflected by textile waste [35]. The spectral signatures enable different types of fabrics, such as cotton, polyester, wool and silk, to be distinguished, and the presence of dyes, coatings and finishes to be detected. A machine is employed to sort the fabrics based on their spectral signatures [35]. In fact, a device called PICVISA (DFactory Barcelona, Barcelona, Spain), which combines near-infrared spectroscopy and an RGB (red, blue, green) camara, has been developed and commercialized to sort fabrics based on their composition and color [36]. This technology facilitates the efficient sorting of large quantities of textile waste and product textile fractions suitable for different recycling processes [36]. Another example is WASTEX (Wastex, Barcelona, Spain), which uses NIR, RGB, together with artificial intelligence, for the highly efficient sorting of textiles to produce high-quality recycled yarn feedstock [37].

However, these technologies can be costly. The integration of artificial intelligence algorithms to analyze voluminous spectral data requires fast computers, sensitive detectors and large data storage capacity. Hyperspectral and NIR imaging may encounter noise and interference due to brightness non-uniformity and pixel abnormality, among others, which could negatively affect the performance of artificial intelligence algorithms, leading to errors or misclassification [38]. Nonetheless, with successful commercialization of advanced sorting machines integrating these technologies, textile waste sorting is expected to be increasingly efficient and cost-effective.

5. The Recycling of Textile Waste

5.1. Mechanical Recycling

In view of the large amount of textile waste generated by the fashion industry, the recycling of waste promotes efficient use of textile resources and valorization of discarded textiles while reducing the environmental impacts associated with the disposal of waste. Advanced mechanical recycling has been developed to disintegrate waste textiles into discrete fibers and, at the same time, preserve their mechanical properties, such as rigidity and strength, without using chemicals. This process involves shredding and carding to extract the fibers from fabrics, which are subsequently spun to make yarn for woven or knitted fabrics [39]. The type of recycling is largely divided into open-loop and closed-loop processes. The open-loop process, which regenerates fibers for applications different from those of the original fabrics, is the most established form of mechanical recycling. It involves shredding and carding the fabrics to extract the fibers, which are used to make materials for insulation, car seats, industrial wipes, mattress pads, etc. (Figure 2) [40]. The products of the open-loop process, however, are often of lower quality, have reduced functionality and may eventually be rejected [12]. Unlike the open-loop process, the closed-loop process recycles textile fabrics back into fibers used for the same (or similar) applications as those of the original fabrics (Figure 2) [17]. The closed-loop process is largely similar to the open-loop one except for the differences in the recycled products and thus has similar limitations in terms of maintaining the quality, functionality and appearance of the products [7].

Figure 2. Closed-loop and open-loop mechanical recycling of textiles.

A typical example of mechanical recycling of textile waste is its application as building materials. Textile waste has been commercially converted into bricks by compressing it with a natural binder. These bricks can be used as partition walls or for furniture making, since they have good thermal and acoustic properties [41]. However, these bricks currently have limited structural application and require longer to dry before they can be used (Table 1). Technology is also available to regenerate nylon yarn from nylon in textile waste. The yarn can be used to make furniture and carpets [39]. Textile-reinforced concrete has come to be in the limelight, with textiles, often multi-axially oriented textiles, as the reinforcing materials which are combined with fine-grained concrete to confer good load-bearing capacity and ductility, resistance to corrosion and light weight [42]. Textile waste comprising scraps of low-quality wool insulating material and nonwoven recycled fibers has been made into thick ropes for slope protection [43].

The mechanical recycling of textiles is constrained by the availability and quality of waste as feedstock, which are in turn dependent on the collection, sorting and preprocessing of textile waste [40]. Currently, these steps lack efficiency, are expensive and labor-intensive and are in need of technological and infrastructural improvements. This is also complicated by the increasing use of fiber blends, synthetic fibers and elastane in textile products [7]. Additionally, factors such as the type and size of shredding equipment, the number and speed of carding machines, the degree of fiber opening and mixing, as well as the spinning and weaving processes, affect the quality and properties of recycled products, particularly fiber length, strength, fineness, color and appearance [39].

Table 1. Advantages and disadvantages of textile waste recycling technologies.

Technology	Advantages	Disadvantages
Mechanical recycling	Recovers polymer from fibers	Reduces the quality and strength of fibers
Mechanical—conversion into insulation/building materials	Utilizes waste fibers as fillers or reinforcements	Limits the end-use applications
Chemical recycling	Retrieves monomers from waste fibers	Requires high capital and chemical inputs
Biochemical recycling—microbial fermentation	Converts waste fibers into biofuels or bioplastics	Depends on the availability of suitable microorganisms
Biochemical recycling—anaerobic digestion	Decomposes waste fibers into biogas or compost	Requires pretreatment of fibers to enhance biodegradability
Biochemical recycling—composting	Transforms waste fibers into organic fertilizer	Only applicable to natural fibers
Chemical and biochemical recycling—fiber regeneration	Produces new fibers from cellulose- or protein-based waste	Involves complex and costly processes
Thermal recycling—pyrolysis	Produces char, oil and gas products	Releases greenhouse gases and toxic emissions; requires high energy input
Thermal recycling—gasification	Converts textile into hydrogen-rich syngas; enhances the conversion of carbon dioxide	Requires high temperatures and oxygen supply; requires high energy input
Thermal recycling—hydrothermal liquefaction	Converts textile into bio-oil or biochar	Requires high pressure and water consumption; requires high energy input

5.2. Chemical Recycling

Chemical recycling involves depolymerizing waste textiles into their monomers or oligomers, which can subsequently be repolymerized into new fibers or other products [7]. Chemical recycling can be applied to synthetic fibers comprising polyester, nylon and acrylic, as well as natural fibers including cotton, wool and silk. It can also segregate and recover different types of fibers from blended fabrics such as cotton–polyester blend [12]. Typical chemical recycling methods are hydrolysis, glycolysis, methanolysis and solvolysis [33]. Hydrolysis has been applied to separate different fibers from blended fabrics by dissolving one type of fiber while leaving another intact through selective use of acid or base at varying concentrations. For instance, hydrochloric acid can selectively dissolve polyester in cotton–polyester blend, and sodium hydroxide can selectively dissolve cotton [44]. Additionally, sulfuric acid can convert cotton into glucose, which can then be transformed into cellulose acetate and sodium carboxymethylcellulose through esterification and etherification, respectively. Both materials are widely used in the textile industry as additives [45]. Sanchis-Sebastiá et al. found that a two-step acid hydrolysis process using concentrated and dilute sulfuric acid enhanced glucose yield from cotton fibers. Nonetheless, hydrolysis has the drawback of being energy- and water-intensive, the latter of which leads to the generation of wastewater containing acid or base residues. Impacts on the quality and purity of the recycled products have also been observed [45].

Different from hydrolysis, which uses acid or alkali in an aqueous environment to break down fabrics into their respective monomers, glycolysis involves the heating of fabrics, particularly polyester fabrics, with ethylene glycol in the presence of a catalyst like zinc acetate or antimony trioxide [46]. Glycolysis of polyester yields bis(2-hydroxyethyl) terephthalate (BHET), which can be purified and condensed to make new polyester fibers or films. This is a closed-loop process which is also exercised in mechanical recycling [46]. Applying glycolysis to the recycling of waste polyester textiles is energy-efficient. It potentially reduces the volume of synthetic textile waste and promotes efficient use of resources. However, it faces technical constraints, especially in relation to decolorization of waste textiles, purification of BHET and recovery of ethylene glycol [46].

Methanolysis is also commonly used for the recycling of polyester textile waste. Waste polyester textiles are shredded into small pieces and fed into a reactor, where they are heated with methanol and a catalyst, typically zinc acetate or antimony trioxide. Methanolysis breaks down the polyester into its monomers, which consist primarily of dimethyl terephthalate and ethylene glycol [47]. The products are then separated from methanol and the catalyst and are purified through distillation or crystallization. They can be used in the synthesis of new polyester materials through polycondensation. In terms of product quality, methanolysis is better than glycolysis in the sense that it can produce high-quality recycled polyester that resembles virgin polyester, while glycolysis may produce recycled polyester of lower molecular weight and viscosity, thus affecting its mechanical properties [47]. Both methods offer the benefits of energy efficiency and lower greenhouse gas emissions. However, their environmental impacts also depend on the ability to recover solvents (ethylene glycol or methanol) and catalysts (zinc acetate or antimony). Both methods incur high capital and operating costs and require sophisticated equipment and technology (Table 1) [48].

In fact, methanolysis is a specific form of solvolysis, which is the general technology of using a solvent and a catalyst to break down polymers into their monomers in a reactor. The monomers are subsequently separated from the solvent and catalyst and are purified through distillation or crystallization. They can be used to produce new polymer materials through polycondensation [33].

5.3. Biochemical Recycling

Dissimilar to chemical recycling, which relies on the use of chemicals to degrade textile waste, biochemical recycling uses biological agents like enzymes or microorganisms to degrade textile waste into simpler molecules for new fibers or materials. Like chemical recycling, biochemical recycling is applicable to natural fibers, synthetic fibers and blended fabrics, depending on the type and specificity of the biological agents [12]. Enzymatic hydrolysis, microbial fermentation and anaerobic digestion are examples of biochemical recycling.

Enzymatic hydrolysis is procedurally similar to chemical hydrolysis, except that shredded textile waste is heated with water and enzymes, such as cellulase, β-glucosidase or cutinase, instead of acid or alkali, in a reactor. Li et al. revealed that chemical pretreatment of textile waste with NaOH/urea actually increased hydrolysis yield, thus suggesting the potential combination of different recycling methods for enhanced efficiency [49]. They observed optimal recovery of glucose and polyester from textile waste when 20 FPU/g cellulase and 10 U/g β-glucosidase were added at 50 °C and pH 5. Moist solid-state enzymatic hydrolysis of PET in mixed PET–cotton textiles using cutinase from *Humicola insolens* yielded 30% of terephthalic acid after 7 days of incubation at 55 °C. With concurrent or sequential cotton depolymerization using Cellic CTec2 (Novozymes A/S, Bagsværd, Denmark) cellulases, up to 83% of glucose was recovered [50]. Cellic CTec2 containing three glycoside hydrolases was also applied in enzymatic hydrolysis of textile and cardboard waste to produce glucose, which was subsequently metabolized by *E. coli* via a mevalonate pathway to synthesize limonene [51].

Microbial fermentation converts the biodegradable fraction of textile waste into valuable products comprising biofuels, biopolymers and organic acids (Table 1) [52]. It utilizes microorganisms such as bacteria, fungi and algae to achieve the purpose, unlike enzymatic hydrolysis, which applies specific enzymes. Having said that, microbial fermentation relies on the enzymes within the microorganisms for bioconversion or biodegradation of textile waste (Table 1) [52]. Microbial fermentation, particularly anaerobic digestion—a type of microbial fermentation conducted in the absence of oxygen—can be used to produce biogas and bioethanol from textile waste. Pretreatment of waste is often required to enhance its biodegradability prior to anaerobic digestion (Table 1) [53]. A study found that waste jeans made of cotton and polyester could be used for biogas and ethanol production after the polyester fraction had been hydrolyzed and the cellulosic fraction had been pretreated with sodium carbonate. The pretreated cellulosic part underwent anaerobic digestion, enzymatic hydrolysis and fermentation, which yielded biogas, sugars and ethanol, respectively. Pretreating pure cotton and jeans with 0.5 M sodium carbonate at 150 °C for 120 min increased the yields of methane, glucose and ethanol significantly [54]. Another study revealed that pretreatment of Scotch mule wool fiber culture with liquid nitrogen resulted in more than 80% increase in methane yield in comparison to non-pretreated culture, mainly because liquid nitrogen could reduce wool particle size, thus increasing its solubility and bioavailability [55]. It is noteworthy that the presence of toxic substances such as dyes and metals, as well as synthetic fibers, in textile waste may inhibit microbial activity, resulting in reduced yield of biogas and bioethanol. These contaminants need to be removed prior to microbial fermentation and anaerobic digestion for optimal efficiency [52].

Microbial fermentation can be used to produce enzymes like cellulases and xylanases from textile waste. Cellulase and xylanases are enzymes that can degrade cellulose and hemicellulose commonly found in natural fibers. Pretreatment of textile waste is also required in the process to expose the cellulose and hemicellulose before inoculating with microorganisms [56]. Hu et al. performed solid-state fermentation of six types of cotton/polyester textiles with different proportions of cotton and polyester which had been modified through autoclaving, alkali pretreatment and milling [57]. Spore suspension of *Aspergillus niger* CKB was used to produce fungal cellulase on textile waste. The cellulase was subsequently extracted and used for textile waste hydrolysis, which gave a sugar recovery yield of 70.2% [57]. In a separate study, *Trichoderma reesei* ATCC 24449 was used in submerged fungal fermentation of textile waste to produce fungal cellulase, which was then used to hydrolyze the textile waste. The glucose recovery yield, however, was 41.6% [56].

Furthermore, microbial fermentation has been used to produce organic acids from textile waste. While studies in this domain are limited, a study by Li et al. involved enzymatic hydrolysis on mixed textile waste to produce hydrolysate rich in glucose but contaminated with dyes [58]. Biochar was used to remove the dyes and was observed to have no adverse effect on subsequent fermentation of the hydrolysate in an in-situ fibrous bed bioreactor to produce succinic acid [58]. It is noteworthy that the production of organic acids from textile waste involves bioconversion of the biodegradable fraction of the waste textiles to glucose, a biomolecule, which is subjected to microbial fermentation for production of organic acids [58]. This is evident in another study, where pretreated cotton fibers underwent enzymatic saccharification to first produce glucose. The glucose was subsequently used as the input for fermentation or hydrogenation to produce bioethanol, sorbitol and lactic acid [59]. The study revealed that pretreatment of colored cotton fibers with a hydrogen peroxide acetic acid–NaOH mixture facilitated removal of dyes and enhanced digestibility of the cellulose therein. NaOH–ethanol pretreatment of cotton–PET textiles also improved glucose yield and contributed to the production of terephthalic acid and ethylene glycol upon enzymatic hydrolysis [59].

Microbial fermentation in the form of composting can be performed on biodegradable textile waste to recover the nutrients therein. Hustvedt et al. added waste wool to a compost mixture consisting of grass clipping and horse stall and reported that a 1:2:1 ratio of waste wool, grass clipping and horse stall provided the optimal results for large-scale composting [60]. It is worth noting that textile waste may take a relatively long time to break down during composting and that synthetic fibers are particularly resistant to biodegradation (Table 1) [17]. As synthetic and blended textiles constitute a large proportion of textile waste, it may be challenging to segregate them from natural fibers for composting, thus potentially contaminating the compost.

In summary, the biochemical recycling of textile waste often involves enzymatic hydrolysis, microbial fermentation and anaerobic digestion sequentially or separately to yield a wide range of products, comprising biofuels, biopolymers, biomolecules, organic acids and enzymes. Organic acids usually result from bioconversion of glucose yielded from enzymatic hydrolysis of textiles. Pretreatment of textile waste increases the efficiency and yields of bioconversion. Nonetheless, biochemical recycling generally incurs high cost due to the use of expensive enzymes, microorganisms and reactors, and it is mainly suitable for natural or cellulosic fibers, as synthetic fibers are more resistant to biodegradation, thus requiring harsher conditions or pretreatment [12].

5.4. Thermal Recycling

Thermal recycling is another major textile recycling technology receiving increasing attention. It converts waste textiles into energy products such as fuel or heat through thermal processes, including pyrolysis, gasification, hydrothermal liquefaction and plasma arc gasification [61]. This technology can handle low-quality or contaminated textiles in addition to non-recyclable materials, such as elastane, polypropylene and polyurethane. Pyrolysis involves thermal decomposition of organic materials in the absence of oxygen to produce syngas, oil and char [61]. Gasification is the partial oxidation of organic materials at high temperature to yield syngas, which can be converted into fuels or chemicals. Both methods are applicable for the recycling of waste cotton, polyester, nylon and other synthetic or natural fibers [61]. Hydrothermal liquefaction converts wet biomass into oil and gas under high pressure and temperature in the presence of water and is suited for the recycling of cotton, wool, silk and other cellulosic or proteinaceous fibers [61]. Plasma arc gasification produces syngas and slag from organic materials using a plasma torch which generates an electric arc that ionizes the gas and creates high-temperature plasma. This method can be used for mixed or contaminated textile waste [12].

A study investigated the effects of pyrolysis and gasification on polyester fibers, cotton and wool under carbon dioxide atmosphere and revealed that their respective kinetic and thermal dynamics were different [62]. Their pyrolysis and gasification activation energies were also different. Gasification of textile waste in a carbon dioxide environment offers much potential for the production of syngas [62]. Kwon et al. conducted catalytic pyrolysis of waste textiles in a carbon dioxide environment and revealed the production of syngas and methane with additional yield of carbon monoxide [63]. The use of a Co-based catalyst increased the production of hydrogen gas and carbon monoxide by three times and eight times, respectively [63]. Yousef et al. performed pyrolysis on lint microfibers using a pilot pyrolysis plant and revealed the potential of generating 13.8 tons of oil, 21.5 tons of gas and 9.7 tons of char from the 45 tons of lint microfibers produced annually [64]. This is translated into USD 120,400 of annual profit and a reduction of 42,039,000 kg CO_2 equivalent per ton of lint microfibers [64]. An attempt was made to produce char-based adsorbents from cotton textile waste through single-step low-temperature pyrolysis [65]. The adsorbents showed good Cr(VI) removal capacity, hence indicating the economic and technical feasibility of low-temperature pyrolysis for conversion of cotton textile waste into adsorbents [65]. Pyrolysis was also demonstrated to be a feasible method for recovering fuels by pyrolyzing waste jeans with and without dye removal in a pilot pyrolysis plant. A total of 82% of the jeans were converted into liquid–gas products, and pyrolysis of jeans without dye removal was found to have high bio-oil yield of up to 37.6% and shorter pyrolysis time [66].

Gasification was suggested as an alternative to incineration of flame-retardant cotton textiles, which can release toxic gases and contaminated ash [67]. Textiles were gasified in a spouted bed gasification plant. The presence of flame retardant in the textiles was found to lower the gasification temperature and syngas production. Removal of flame retardant prior to textile gasification resulted in higher volatile contents and moisture and lower carbon concentrations [67]. Vela et al. performed steam gasification of cotton and polyester using a fluidized bed reactor and found cotton to be more suitable for syngas production [68]. Polyester and blends produced aromatic compounds in addition to syngas. The study highlighted the potential of gasification for recovery of syngas and aromatics from textile waste [68].

Hydrothermal liquefaction of textile waste provides an avenue for recovering bio-oil and monomers without the need for sorting or color removal. Hydrothermal liquefaction was performed on post-consumer polyester and cotton textiles, and it was revealed that 95% cotton/5% polyester blend gave the highest bio-oil yield, 26%, at 325 °C under alkali conditions. However, 50% cotton/ 50% polyester blend produced more terephthalic acid [69]. The hydrothermal approach can also be employed as pretreatment for textile waste. In a study, waste cotton textiles pretreated hydrothermally at 320 °C for 60 min resulted in 23.3% bio-crude oil yield [70]. Additionally, biochar rich in carbon was obtained and could be used as alternative solid biofuels or electrocatalytic carbon material [70]. Hongthong found that hydrothermal liquefaction of *Fucus serratus* at 350 °C in the presence of various nylon polymers in different proportions resulted in the complete degradation of nylon 6 into caprolactam and partial degradation of nylon 6/6 into cyclopentanone, indicating the potential of certain nylon textiles to be broken down, with their monomers being recovered, when added to the hydrothermal liquefaction of macroalgae for biofuel production [71].

Plasma arc gasification has been employed to gasify municipal solid waste for energy recovery. The gasification of municipal solid waste in the presence and absence of steam and oxygen in a plasma reactor resulted in the production of methane, ethane, hydrogen, carbon dioxide and carbon monoxide. The presence of oxygen and steam enhanced carbon monoxide formation [72]. While studies on plasma arc gasification of textile waste are currently limited, this method provides an alternative to thermally recycling waste.

The thermal recycling of textile waste offers the benefit of recovering energy and fuels from waste. However, it could also generate harmful emissions, such as nitrogen oxides, sulfur oxides, dioxins, furans and heavy metals, which may harm human health and the environment if not sufficiently treated. Thermal recycling has high energy and resource requirements, particularly electricity, natural gas, catalysts and water, which could offset the benefits of recycling. The lack of scalable technologies could limit its full-scale cost-effective application, thus limiting its feasibility. A summary of the advantages and disadvantages of thermal recycling technologies is also presented in Table 1.

6. Conclusions

The emphasis on sustainability and circular economy has catalyzed the roll-out of regional and global policies on the sustainable design, reuse and recycling of waste, including textile waste, which constitutes a significant part of MSW. Numerous innovations have been proposed in relation to the collection, sorting and recycling of waste. Innovations in the collection of textile waste encompass the deployment of the IoT, blockchain and big data, involving the use of smart tags and sensors to improve the traceability, verification and reporting of textile waste flows and optimize its collection routes. The sorting of textile waste can be facilitated with machine vision integrating spectroscopy, cameras, sensors and algorithms to identify and classify textile waste more efficiently. Innovations in the recycling of textile waste are commonly divided into mechanical recycling, chemical recycling, biochemical recycling and thermal recycling. Mechanical recycling regenerates fibers for applications similar to or different from those of the original fabrics without using chemicals. Chemical recycling involves depolymerizing waste textiles into monomers using chemicals, followed by subsequent repolymerization to produce new fibers or other products. Biochemical recycling is similar to chemical recycling but instead uses enzymes and microorganisms for depolymerization. Thermal recycling converts waste textiles into energy products through pyrolysis, gasification, hydrothermal liquefaction and plasma arc gasification. Mechanical recycling may downgrade the recycled products and limit their marketability, while chemical recycling may have high capital requirement and chemical inputs. The performance of biochemical recycling is highly variable, depending on the microorganisms used and the biodegradability of waste textiles. Pretreatment of the textiles is often required. Thermal recycling has high cost, energy and infrastructural requirements, making recycled products less cost-effective. Nonetheless, certain technologies, particularly the mechanical ones, to regenerate fibers from waste textiles and to recycle waste textiles as building materials have been successfully commercialized. Significant advances have also been achieved in the commercial sorting of textile waste. While increasing the reuse and recycling of textile waste may reduce the amount of textile waste heading to landfills and incinerators, a long-term solution to reduce the production and consumption of fast fashion may be crucial. This may involve customers adopting more sustainable and ethical shopping habits, such as buying less, choosing quality over quantity, and preferring natural and organic materials. Producers can also adopt more responsible and transparent business practices, such as using recycled and low-impact materials, reducing packaging and transportation and disclosing their environmental and social performances. This review aims to inform consumers, producers and policymakers on the innovations of textile waste management, as well as sustainable and circular approaches in managing textile waste, so that responsible decisions and actions on textile production and consumption can be promoted. It is hoped that innovations can reduce textile waste generation, minimize its environmental impacts and create new value and opportunities for its products and materials. Prior to this, further studies to improve the cost effectiveness and efficiency of new technologies are needed to address their high cost, high energy demand, pollution and lack of marketability.

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