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Review

Advances in Recycling and Reuse Technologies for Textile Fiber Material Products

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ABSTRACT: Global industrialization and rising living standards have driven widespread adoption of fiber materials. However, the rapid growth of the textile industry has also caused substantial resource depletion and environmental pollution. Each year, over 92 million tons of textile waste are generated worldwide, most of which is landfilled or incinerated, while only a small proportion is recycled. This paper systematically reviews the latest advancements in the recycling and reuse of fiber-based products, focusing on mechanical, chemical, and biological recycling technologies and the reapplication of recycled fibers. Mechanical recycling is a mature and cost-effective process, but it results in reduced fiber quality. Chemical recycling can produce high-purity raw materials, yielding regenerated fibers with properties close to virgin fibers, but the process is complex and energy-intensive. Biological recycling operates under mild conditions with low energy consumption but is limited by low efficiency and long reaction times. This paper also explores the applications of recycled fibers in regenerated apparel, automotive textiles, construction materials, medical supplies, and eco-friendly filtration materials. Fiber recycling technologies should advance toward greener, more innovative, and circular economy-oriented approaches. Technological innovation, industrial collaboration, and policy guidance can significantly enhance the resource utilization of textile waste.

Keywords: Textile waste; Recycling and reuse; Fiber recycling technologies; Mechanical recycling; Chemical recycling; Biological recycling

1. Introduction

With the continuous advancement of global industrialization and the sustained improvement of human living standards, fiber materials are increasingly widely used in modern society. As shown in Figure 1, fibrous materials can be divided into two categories depending on their sources: natural fibers and chemical fibers. Natural fibers mainly include plant fibers (e.g., cotton, hemp, and bamboo fibers) [1], animal fibers (e.g., silk and wool) [2–4], and mineral fibers (e.g., chrysotile asbestos and crocidolite asbestos) [5,6]. Chemical fibers can be further subdivided into man-made fibers (also known as regenerated fibers, e.g., and acetic acid fibers) [7,8], synthetic fibers (e.g., polyester and nylon) [9,10], and inorganic fibers (e.g., carbon fiber and glass fiber) [11–13].

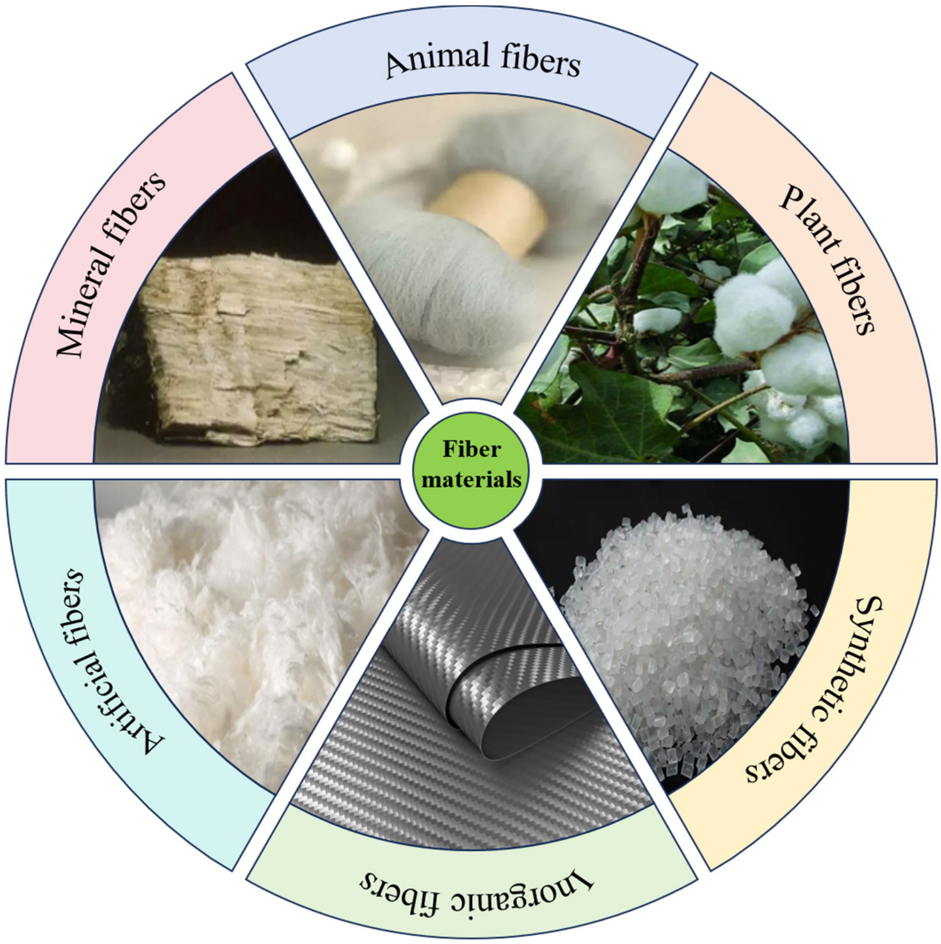


Figure 1. The classification of fiber materials.

With the rapid development of the global textile industry and related sectors, the production and consumption of fiber materials have increased significantly. This growth has led to increasingly severe issues of resource depletion and environmental pollution. Globally, over 92 million tons of textile waste are generated annually, with primary disposal methods including landfilling, incineration, and recycling [14]. Conventional landfilling not only occupies vast amounts of land but also poses environmental risks as synthetic fibers are resistant to degradation and may release harmful chemicals that contaminate soil and groundwater. While incineration can reduce waste volume and recover some energy, the high-temperature combustion process may emit toxic gases, contributing to air pollution and increased carbon emissions. Consequently, recycling technologies have emerged as a more sustainable alternative to landfilling and incineration [15,16]. However, current recycling systems still face many technical and economic challenges that limit their large-scale application, such as low recovery rates, process complexity, and the degradation of recycled product performance.

In the face of resource shortages and environmental pressures, it is critical to improve the recycling rate of fiber material products. First, the production of fiber materials (especially synthetic fibers) involves non-renewable resources such as oil and natural gas, so recycling can effectively reduce dependence on these primary resources and reduce consumption [17]. Second, through efficient recycling and reuse technology, the landfill and incineration of waste fiber materials can be reduced, along with greenhouse gas and pollutant emissions, reducing the impact of this sector on the environment [18,19]. In addition, the construction of a perfect recycling system can help promote the development of a circular economy and improve the sustainability of the textile industry. Meanwhile, policies and regulations also provide impetus for the recycling of fiber materials. For example, the Waste Framework Directive (EU) 2018/851 of the European Union [20], and China's Implementing Opinions on Accelerating the Promotion of Recycling of Used Textiles, released in 2022 [21], call for an increase in the recycling rate of textile waste. Furthermore, the growing consumer demand for sustainable products has prompted companies to actively develop recyclable and renewable fiber materials and promote industrial upgrades and technological innovation.

In recent years, significant progress has been made in fiber material recycling technologies. These technologies can be primarily categorized into mechanical, chemical, and biological recycling methods. However, current recycling systems still face multiple challenges. First, imperfect recycling infrastructure results in immature classification systems, collection channels, and standardized recycling processes for textiles and composite materials, ultimately affecting overall recycling rates. Second, the diversity and contamination of fiber materials present difficulties; many textile products contain blended fibers of different types or multi-layer composite structures, making separation and purification during recycling particularly challenging. Third, some recycling technologies remain costly and energy-intensive, hindering industrial-scale adoption. Fourth, recycled fibers often exhibit reduced mechanical properties such as strength and durability, limiting their applicability in high-end products. Consequently, improving the efficiency of fiber recycling technologies, reducing costs, and enhancing the quality of recycled products have become critical issues requiring urgent solutions in both the research and industrial sectors.

Currently, numerous researchers have conducted studies in the field of fiber material recycling and reuse, covering various dimensions such as technical management, environmental benefits, and economic feasibility, and presenting diverse technological pathways. Irena et al [20]. provided an in-depth analysis of the current status of textile waste treatment from the perspective of waste management systems, detailing the construction of collection, sorting, and recycling systems. They focused on the application of automated sorting technologies such as NIR spectroscopy and systematically reviewed the development status of mechanical and chemical recycling technologies. Abrishami et al [22], systematically outlined the current state of textile recycling technologies from an environmental protection perspective, comprehensively assessed the environmental impact of fast fashion, and conducted a comparative analysis of mechanical, chemical, and biochemical recycling technologies. They also explored methods for resource recovery from non-recyclable textiles. Kamble et al [23] focused on the innovative application of upcycling technologies for textile waste, delving into the technical challenges faced during the recycling process and elaborating on the application prospects of recycled fibers in composite material manufacturing.

The aforementioned studies provide insights and guidance for the technology and management of fiber material recycling. However, with increasing resource and environmental pressures and rapid advancements in new technologies, systematic analysis and research are still required in the following aspects: a comprehensive evaluation of the advantages, disadvantages, and application scenarios of existing fiber material recycling technologies; beyond apparel fiber materials, the application of recycled fibers in various fields such as automotive, construction, medical, and environmental protection materials needs further expansion. These fields increasingly use fiber materials, with varying forms and material compositions of fiber-based products. It is essential to analyze the current application status and potential of recycled fibers in these areas. Additionally, policies and regulations related to the ecological environment and sustainable development in various countries significantly influence the innovation of recycling technologies and management mechanisms for fiber-based products, warranting in-depth research.

Based on the above, this paper will systematically summarize the latest technological advances in the recycling of fibrous material products, focusing on the development of mechanical recycling, chemical recycling, and biological recycling technologies, and further analyzing the application potential of recycled fibers. Finally, this paper will examine future development trends of fiber material recycling technology, with a view to providing a scientific basis and reference for promoting the sustainable development of fiber material recycling.

2. Fiber Material Recycling and Reuse Technology

Recycling fiber materials is an important means to achieve resource circulation and reduce environmental pollution. Different forms of fiber recycling and reuse are classified in Figure 2 [22]. Depending on the recycling approach, current fiber material recycling technologies can be primarily categorized into three types: mechanical recycling, chemical recycling, and biological recycling. Due to differences in physical and chemical properties, different types of fiber materials require distinct recycling techniques. A comparison of the advantages and disadvantages of these three recycling technologies is presented in Table 1. A systematic understanding of the principles and application scope of different recycling methods is crucial for promoting the efficient recycling and reuse of fiber materials.

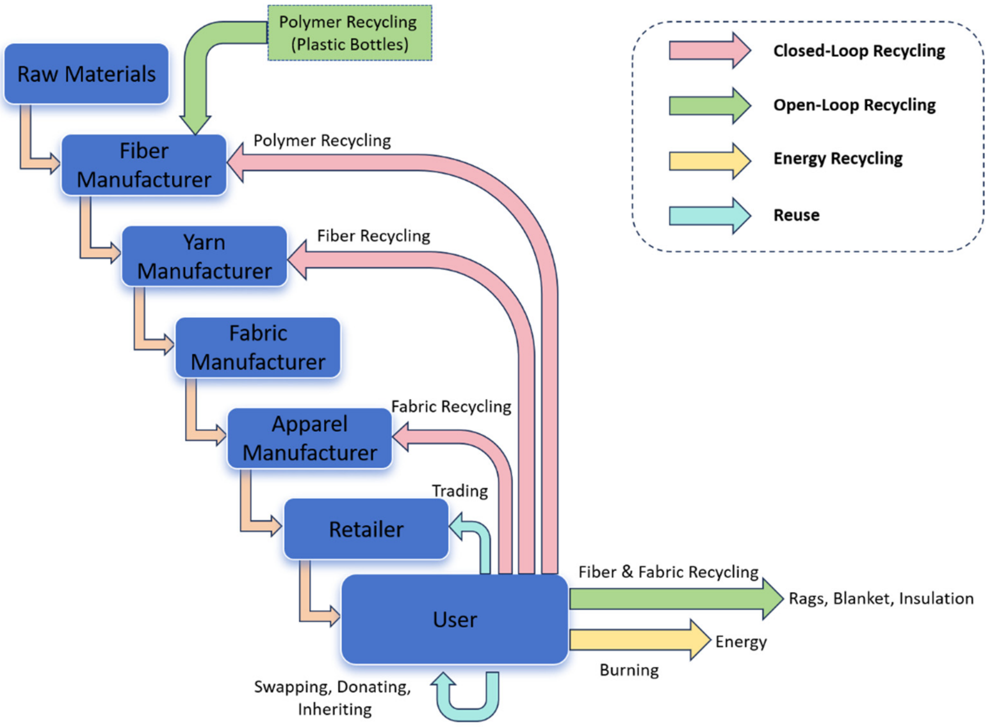


Figure 2. Classification of the available reuse and recycling routes [22].

Table 1. A comparison of the advantages and disadvantages of three recycling technologies.

Recycling Technology	Advantages	Disadvantages
Mechanical recycling	Technologically mature, simple process, low operating costs	Declining quality of recycled fibers and poor treatment of mixed materials
Chemical recycling	High-purity raw materials can be obtained, and the performance of recycled fibers is close to that of virgin fibers (high-quality fibers)	Complex process, high energy consumption, high cost
Biological recycling	Environmentally friendly, gentle process, low energy consumption	Low efficiency, long response time

2.1. Mechanical Recycling

Mechanical recycling technology is currently the most mature and widely used method for fiber material recovery. The core principle involves physically processing waste textiles into fibers or yarns through mechanical means, then reprocessing these fibers into new textile products. As this process involves no chemical reactions, it offers distinct advantages, including operational simplicity and relatively low energy consumption. However, research by Filho [24] has demonstrated that mechanical recycling leads to the progressive degradation of the regenerated fiber quality with each recycling cycle, ultimately affecting yarn and fabric production. This technology is particularly suitable for natural fibers such as cotton, linen, and wool (with the specific recycling process illustrated in Figure 3 [25]) and certain synthetic fibers, including polyester and nylon. The standard mechanical recycling process for post-consumer textiles is shown in Figure 4.

According to statistics, mechanical recycling accounts for approximately 43% of total fiber recovery [26] representing the highest proportion among the three major recycling technologies. The typical process consists of several key steps: sorting, cutting, fiber opening, carding, and re-spinning.

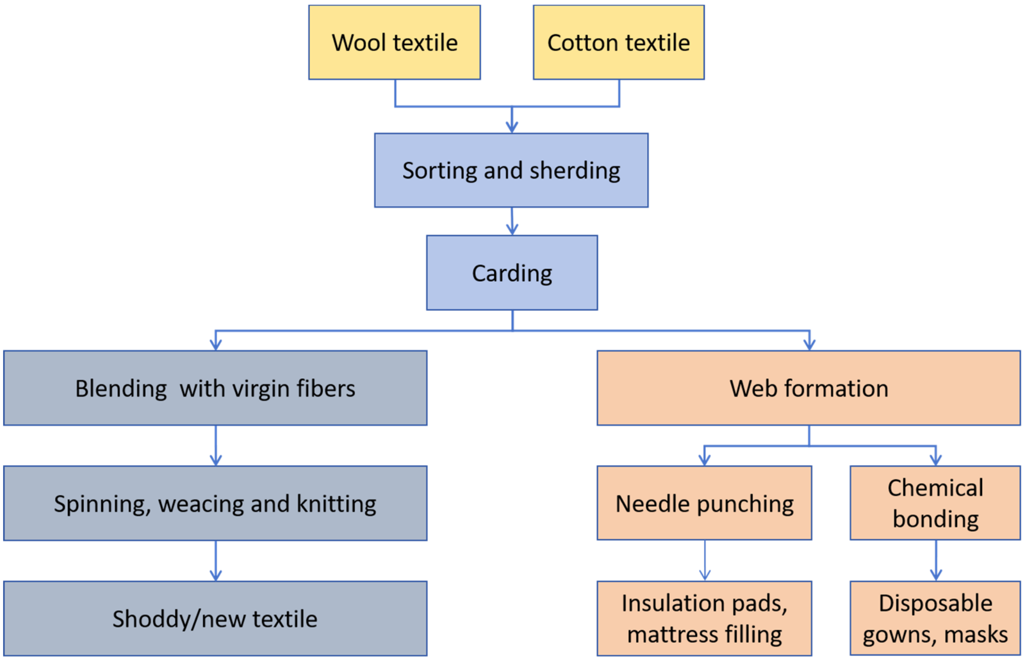


Figure 3. Mechanical recycling of natural fiber textiles [25].

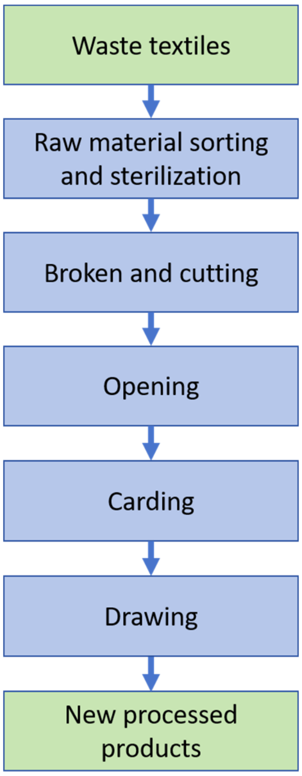


Figure 4. Mechanical recycling process flow chart for waste textiles.

The mechanical recycling process begins with rigorous sorting, which helps ensure a certain level of recycling quality. Modern sorting centers combine manual sorting with automated technologies. First, near-infrared spectroscopy is used to quickly analyze fiber composition [27] followed by color recognition via high-resolution cameras, and finally, manual verification to ensure accuracy. After sorting, the textiles undergo pre-treatment, including the removal of impurities such as plastic components, buttons, and zippers.

Next, cutting and shredding equipment processes large pieces of waste textiles into smaller fragments or fibrous materials. As shown in Figure 5 [28] rotating blades shear the fiber materials as they pass through the cutting device. Subsequently, the fragments undergo fiber opening, carding and drawing to break them down into individual fibers. Finally, the processed fibers are spun into recycled yarn or developed into nonwoven fabric products.

Figure 5. Cloth shredder [28].

Different fiber types exhibit significant variations in recyclability. As the second most commonly recycled fiber after cotton, acrylic fiber possesses unique application value. Ahu et al [29] successfully obtained recycled acrylic fibers by blending acrylic fabric waste with covered yarns and polybutylene terephthalate (PBT) elastic yarns. For mixed-material waste, Hussien and Nachiappan [30] explored separation and recycling techniques for cotton-acrylic blended knitwear. Through mechanical shredding and further refinement using metal pins on feed rollers, they successfully extracted recycled cotton and acrylic fibers for nonwoven fabric development, demonstrating the feasibility of recycling mixed materials.

The diversity of waste types has given rise to innovative recycling solutions. Sanches et al [31] addressed waste materials with different structural characteristics by combining shredded fibers extracted from woven, knitted, and nonwoven waste with virgin cotton fibers and recycled polyester. They employed conventional ring spinning to produce yarns, which were subsequently processed into blended knitted fabrics using small-diameter circular knitting machines. This integrated utilization of waste materials from different sources effectively expands the source of recycled raw materials, provides new ideas for the comprehensive utilization of waste textiles, and enhances the performance diversity of the final product.

In-depth research on the production process of recycled yarn from waste textiles has revealed directions for technological optimization. Yu et al [32] systematically investigated the complete process from waste cotton fibers to yarn-reinforced composites, which sequentially includes opening, carding, drawing, roving, spinning, and final twisting operations, as illustrated in Figure 6. Particularly noteworthy is their finding that twist parameters decisively influence product performance. The optimal twist for single-yarn reinforced composites was determined to be 0.76 times that of conventional single yarns. Furthermore, plied yarns exhibited significant strength variations across different twist ranges: in the low-twist range (550–850 TPM), the tensile strength reached 148.52 MPa, while in the high-twist range (850–1050 TPM), the strength decreased with increasing twist. These precise measurements provide a scientific basis for process parameter optimization.

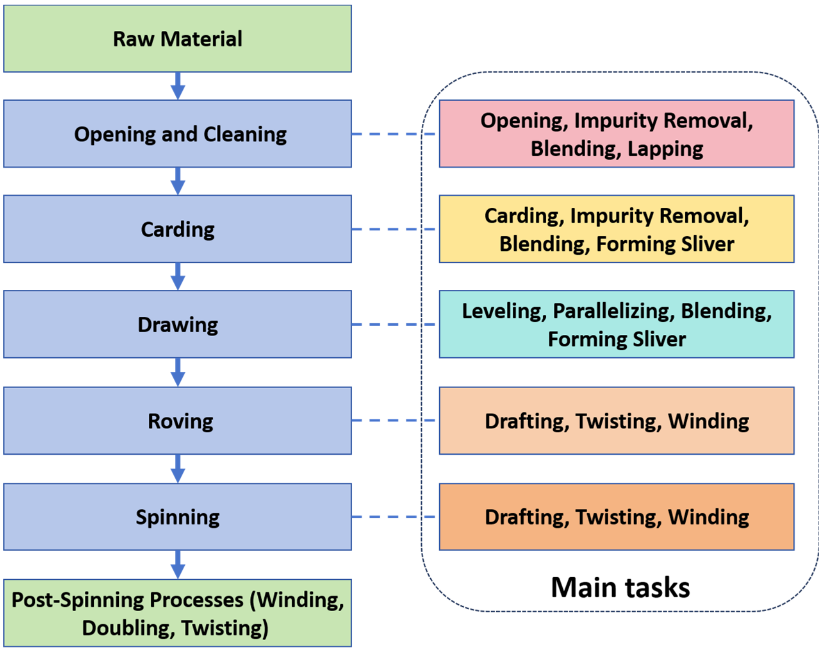


Figure 6. The yarn preparation process flow chart.

Recycled fibers require appropriate blending ratios with virgin materials in practical applications. Wanassi et al [33] produced a blended yarn by mixing waste cotton fibers with virgin cotton fibers in a 50:50 mass ratio, following a manufacturing process that included opening, carding, drawing, roving, and spinning. This blended yarn demonstrated a 33.5% cost reduction compared to 100% virgin cotton yarn. Following this, Arafat et al [34] successfully produced medium-count (30 Ne) yarns suitable for knitwear production by blending pre-consumer and post-consumer recycled cotton fibers with virgin cotton using ring spinning technology. Meanwhile, Ütebay [35] investigated an optimal blend ratio of 50% recycled cotton, 30% virgin cotton, and 20% polyester fibers specifically for pre-consumer cotton knitwear waste, while also confirming the suitability of rotor spinning technology for processing recycled materials. Collectively, these studies provide practical formulations to facilitate the industrial-scale application of recycled fibers.

The mechanical recycling of waste textiles has shown unique value in the development of functional materials. Mohamed et al [36] used needle-punching technology to produce nonwovens from acrylic and wool wastes. The result exhibited thermal insulation properties superior to those of conventional glass and mineral wool, Figure 7 [37] shows a high-speed needle punching machine. Çay [38] converted a variety of textile wastes into biochar through low-temperature carbonization and applied it to cotton fabrics to obtain functional textile materials that provide high thermal and physiological comfort. These studies show that waste textiles have unique advantages in the field of functional materials.

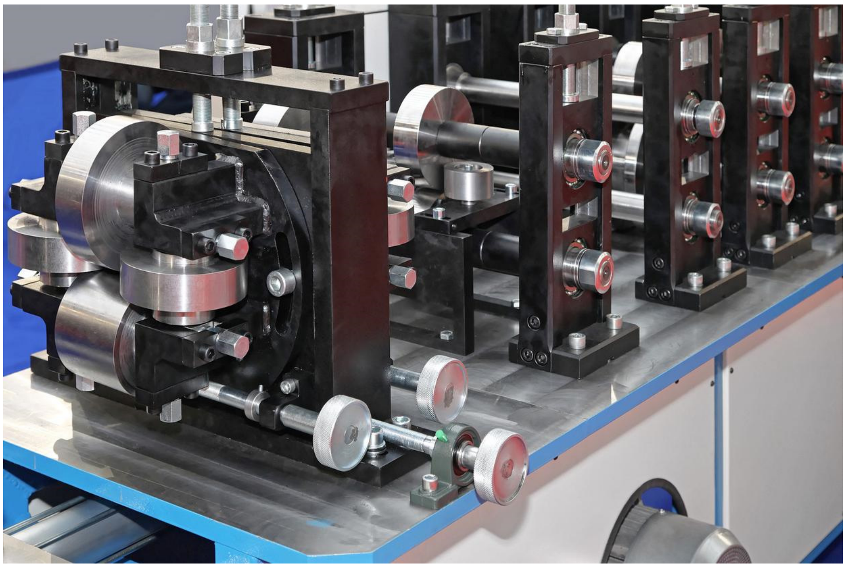


Figure 7. A high-speed needle loom [37].

Mechanically recycled fibers also show good reinforcing effects in construction and composite applications. Patricia et al [39]. added cotton fibers extracted from discarded denim to polyester concrete, then irradiated the concrete with γ-rays. Eventually, the compressive and flexural strengths of the discarded cotton fiber polyester concrete were enhanced. Kamble and Behera [40], meanwhile, used pre-consumer cotton textile waste to develop thermoset composites suitable for furniture and automotive components. Petrucci et al [41] developed polypropylene with moisture-resistant properties by washing, removing impurities, and garneting waste denim to obtain denim fibers, which were added to a polypropylene matrix. Finally, composite panels were obtained by injection molding to develop a polypropylene composite suitable for automotive door panels. These high-value-added applications provide new economic growth points for waste textile recycling.

Quality assessment studies of recycled materials have provided unexpected discoveries. Julia and Anders [42] compared post-consumer waste with different degrees of abrasion. They found that more abraded materials lost less fiber length during the recycling process. This overturned traditional understanding and provided a new perspective for screening recycled materials. Taken together, the mixed application of waste textile fibers with other materials is the mainstream technical route at present. It shows broad application prospects in the fields of yarn production, functional material development, and composite material enhancement, opening up a diversified development path for the recycling of textile resources. The mechanical recycling methods for different types of waste textile materials are shown in Table 2.

Table 2. An overview of the mechanical recovery of different types of waste fiber materials.

Waste Fiber Materials	Recycling Methods	Products	Sources
Cotton fiber/polyester fiber/wool/nylon blend	Using polypropylene textile waste as the matrix phase, mixed with wood chips as a secondary filler, and homogenized	Fiber-reinforced composite for construction applications	Echeverria [43]
Waste cotton fiber/synthetic fiber mixture	The waste is cut into small pieces, shredded, opened, and finally processed using open-end spinning technology	Recycled yarn	Esteve-Turrillas [44]
Denim scraps/waste jute fiber composite	Fibrized through a shredder and carding machine, dried, then compacted by static pressing in molds	Acoustic insulation material for buildings	Raj [45]
Cotton yarn waste from defective dyeing in jeans production	Cotton yarn is first sheared and pulverized by a knife mill, then bleached/acetylated/silanized, melt-blended with PP, and finally extruded and compression molded	Fiber-reinforced composite (FRC)	Araújo [46]
Nylon/spandex blend	Mixed with polyurethane waste in a 3:2 ratio, compression molded using custom dies to produce panels	Thermal insulation material for buildings	Dissanayake [47]

In summary, the advantages of mechanical recycling technology are its simple process, lower cost, and lack of chemical pollution, but its main disadvantage is that the length and strength of recycled fibers are usually reduced. This affects the performance of the final product, and it is difficult to reach the original state, even though the blending of multiple fibers can enhance the performance of the product to a certain extent. Therefore, mechanical recycling is usually used for low-end products, such as building insulation, car interiors, and carpet padding, and is difficult to use for high-end textile production.

2.2. Chemical Recycling

Chemical recycling technology refers to the decomposition of waste fiber materials into monomers, oligomers, or reusable polymers through chemical reactions, which are then re-polymerized to produce new fiber polymers for high-quality recycling [48,49]. Compared with mechanical recycling, chemical recycling can effectively remove impurities such as dyes, auxiliaries, and coatings from textiles and restore the original properties of the fibers to a certain extent, thus producing recycled materials with properties close to or even better than those of virgin fibers. However, the process of chemical recovery usually involves high temperatures, high pressures, or the use of chemical reagents, making it more technically complex and costly.

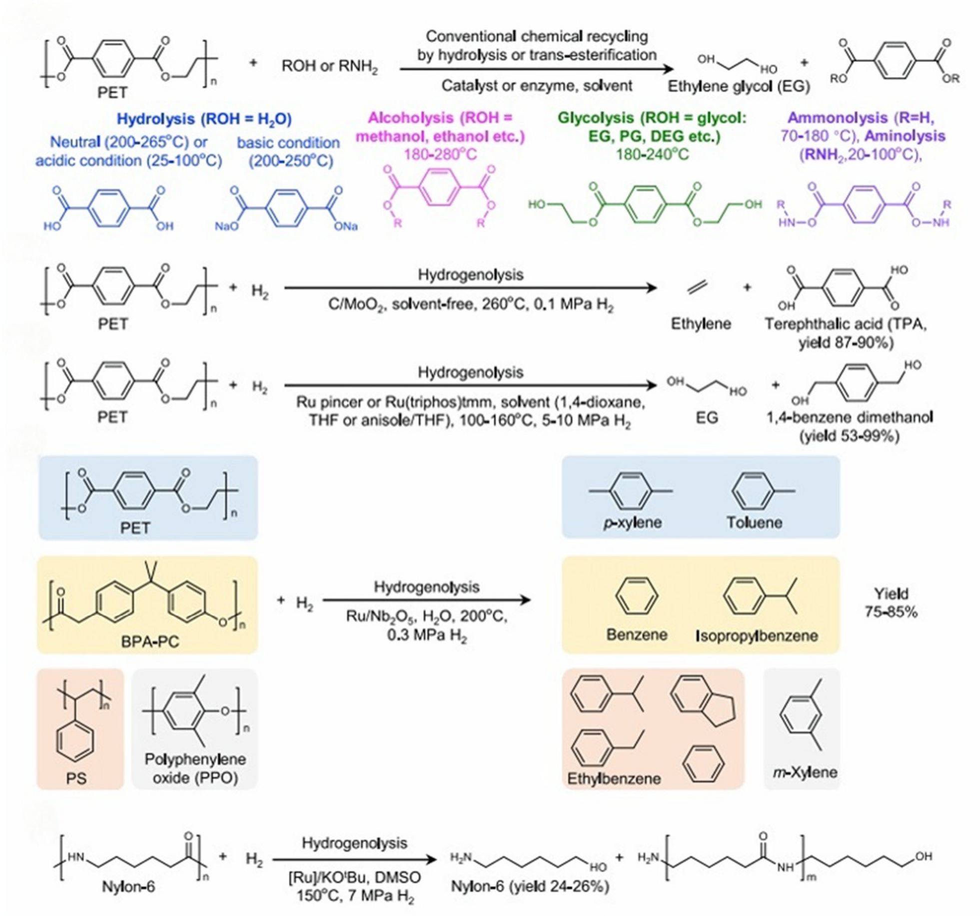
2.2.1. Chemical Recycling Technology for Waste Cotton Fibers

Significant breakthroughs have been made in research on the chemical recycling of waste cotton fibers, especially in environmental management and material regeneration. Researchers have developed a variety of innovative technologies to convert waste cotton fibers into high-value-added materials. Ma et al [50] developed dual network hydrogels (Cellulose/PAM DNHs) based on waste cotton fabrics and polyacrylamide with excellent pore structure and laminar architecture. These can efficiently adsorb a variety of heavy metal ions, such as Cd, Cu, Pb, Zn, and Fe, and offer a new approach for industrial wastewater treatment. Meanwhile, Zeng et al [51] successfully prepared porous, biocompatible, and highly conductive electrode materials through the in situ polymerization and carbonization of common waste cotton textiles. The nitrogen-doped carbon nanoparticles encapsulated on the surface provided a large specific surface area for bacterial growth, which significantly improved the performance of the microbial fuel cell and expanded the application of waste cotton fibers in the energy field.

In the fields of cellulose separation and regeneration, researchers have developed various green solvent systems and catalytic methods. Wang et al [52] developed a deep eutectic solvent (DES) based on choline chloride (ChCl) and p-toluenesulfonic acid (TsOH) to successfully treat waste polyester cotton blend fabrics by simultaneously extracting polyester (PET) and microcrystalline cellulose (MCC) under the optimal conditions (75% DES, 110 °C, and 10 min) with yields of 99.20% and 69.46%, respectively. Yousef et al [53] developed a deep eutectic solvent based on nitric acid and p-toluenesulfonic acid (TTB) to extract polyester and microcrystalline cellulose (MCC) under optimal conditions (75% DES, 110 °C, 10 min) with yields of 99.20% and 69.46%, respectively. In addition, Yousef et al[53] efficiently recovered cotton fibers and polyester from waste denim fabrics by de-dyeing with nitric acid solution and separating the fabrics with switchable hydrophilic solvents, achieving a recovery rate of 96%. In terms of fiber regeneration, Liu et al [54] successfully converted degraded waste cotton fabrics into regenerated fibers with strengths of up to 1.11–1.29 cN/dtex using environmentally friendly alkaline/urea solvent systems (LiOH/urea and NaOH/urea) combined with wet spinning. Hou et al [55] used phosphotungstic acid (HPW) to catalyze the hydrolysis of waste cotton fabrics to prepare microcrystalline cellulose, with a yield of up to 83.4% and a crystallinity of 85.2% under optimal process conditions. Wei, Robinson, Huang et al [56–58] used ionic liquids as catalysts, providing new ideas for the high-value utilization of waste cotton fibers.

2.2.2. Chemical Recycling of Polyester Fibers

Polyester fiber (PET) is one of the most common synthetic fibers, and its main component is polyethylene terephthalate (PET). The chemical recycling of PET mainly relies on depolymerization reactions, and common processes include hydrolysis, alcoholysis, ammonolysis, and glycolysis, as shown in Figure 8a [59]. The aim is to degrade PET into its monomers or oligomers, then re-synthesize PET through polycondensation reactions to create high-quality recycled polyesters. Different methods of PET chemical recycling and their derived value-added products are shown in Figure 8b.



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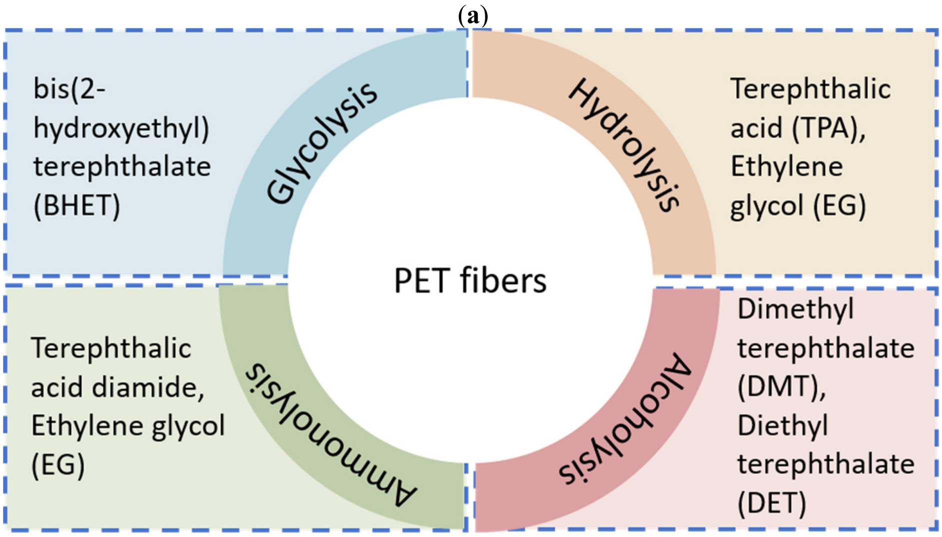

(**b**)

Figure 8. (**a**) Various catalytic reactions [59]; (**b**) Different methods of PET chemical recovery and their derived value-added products.

Hydrolysis is the reaction of PET with water under acidic, neutral, and basic conditions to produce terephthalic acid (TPA) and ethylene glycol (EG), which can then be reused for polymerization by purification [60]. Pereira et al [61]. explored the hydrolysis of PET catalyzed by a variety of acid catalysts (zeolites, inorganic acids, ionic liquids, carboxylic acids, metal salts, and carbon dioxide) at 200 °C for 2 h. Carboxylic acids and metal salts gave greater than 80% TP yields, and zeolite had a negligible effect on the TPA yield. CO_2 as a catalyst did not significantly increase the TPA yield, and its TPA yield was higher when acetic acid was used as a catalyst. Onwucha et al [62] succeeded in hydrolyzing PET in a neutral environment without the use of catalysts, resulting in higher TPA yields. This method avoids the use of acids, toxic solvents, complex TPA purification/recovery processes, and the generation of large amounts of wastewater. However, it requires a long reaction time (6–24 h) and a high PET/water ratio to obtain a TPA yield of 85–98%. Peterson et al [63] performed alkaline hydrolysis of mucilage/PET, pure mucilage, and pure PET samples at a solid-liquid ratio of 1:100 in aqueous NaOH. Yan et al [64] obtained alkaline banana peel extract (PBPE) through the calcination of waste banana peels. Hydrolysis of PET using K_2CO_3 contained in BPE was carried out, and nearly 100% of the content of the TPA was obtained through reactions at 150 °C for 4 h. This method is suitable for the recovery of high-purity PET, but it has high energy consumption and requires the precise control of the reaction conditions in order to prevent the formation of by-products. Li et al [65] proposed a method that combines hydrolysis, reactive processing, and decolorization, which was very effective in converting colored PET fabrics into high-purity TPA under alkaline conditions. The final monomer yield (88.51%) and decolorization rate (94.22–97.65%) were higher than those of TPA produced by conventional hydrolysis.

Alcoholysis refers to the degradation of PET to dimethyl terephthalate (DMT), diethyl terephthalate (DET), or low polyesters through the reaction of alcohols, such as methanol (methanolysis) and ethylene glycol (glycolysis), with PET, which is then further purified and re-polymerized to PET. Ma et al [66] synthesized an ionic liquid using Bronsted–Lewis dibasic acid $[HO_3S(CH_2)_3\text{-}NEt_3]Cl–[ZnCl_2]_{0.67}$, which was then used as a catalyst to efficiently catalyze the methanolysis of PET at atmospheric pressure, 195 °C, and a reaction time of 30 min, with a yield of about 78.4% of DMT. Furthermore, the results showed that two methanol molecules were needed to depolymerize to obtain DMT and ethylene glycol (EG). Lozano-Martinez et al [67] investigated the subdegradation of PET by subcritical ethanol and achieved 94% PET degradation through reaction for 30 min at 275 °C, with a pressure of 40 bar and a 5% weight ratio of PET to ethanol. Tang et al [68] successfully prepared MgO/NaY catalysts with different MgO contents by using the incipient wet impregnation method. The results were used as modified mesoporous catalysts to catalyze the methanolysis of PET. The results showed that the MgO/NaY catalyst had the best catalytic effect when the MgO content was 21%, and the PET conversion and DMT yield were as high as 99% and 91%, respectively, at a methanol-to-PET mass ratio of 6, a catalyst dosage of 4wt%, and a reaction time of 30 min (at 200 °C).

Ammonolysis refers to the reaction of PET with ammonia or amines (such as ammonia gas or ethylene diamine) to produce terephthalic acid diamide and EG. A key feature of amination is its focus on upgrading or functionalizing PET rather than simply recycling it. Liang et al [69] developed an innovative one-step method that does not require catalysts or solvents, enabling PET amination at mild temperatures (40–120°C). This technology can directly recover high yields (>90 mol%) and purity (>95%). Although amination holds great potential for the upcycling and functionalization of PET, it requires large amounts of non-environmentally friendly amines and is prone to side reactions that generate impurities.

The glycolysis method depolymerizes PET into bis(2-hydroxyethyl) terephthalate (BHET) using diols (usually diethanol) as degradation agents [2]. Chen et al [70]. used a combination of $Zn(OAc)_2$/DBU catalysts to depolymerize waste PET to bis(2-hydroxyethyl) terephthalate (BHET). The reaction took 77 min at 180 °C with a weight ratio of PET/EG of 1:3 and a $Zn(OAc)_2$/DBU molar ratio of 1:2. The results showed that the purity of BHET was close to 80%, and the purity of the glycolysis product was 94.85%. When using a DBU molar ratio of 1:2 for 77 min, the BHET purity was nearly 80% and the purity of the glycolysis product was 94.85%. Kim et al [71] used a miniature MgO-doped SiO_2 catalyst to promote the glycolysis of PET, and the final extracted BHET had a purity of more than 99.85%, which indicated that this catalyst has significant benefits for promoting the glycolysis of PET. In addition to the above-mentioned catalysts, other researchers have explored various catalysts, including ionic liquids [72,73], Mn_3O_4 [74], and Fe_2O_4 [75]. Although glycolysis requires relatively high temperatures (close to 200 °C), it possesses the advantage of being less affected by contamination, making it the most widely used method for recycling PET in industry.

Chemical recycling technologies for different types of waste textile materials are shown in Table 3. Overall, chemical recycling technologies can achieve high-quality recycling of fiber materials, but their industrial application still faces several challenges. First, chemical recycling processes usually involve high temperatures, high pressures, or the use of chemical reagents, resulting in high energy consumption and, in some cases, the potential generation of hazardous waste streams or by-products. The question of how to optimize the process to reduce its environmental impact is thus a focus of current research. Second, the recycling of mixed fiber materials remains a difficult issue. For example, blended fabrics contain a variety of components, such as PET, cotton, and nylon. Identifying a method of efficiently separating the different components in order to improve the efficiency and purity of chemical recycling is an important challenge for the industry. In addition, the economic viability of chemical recovery is a key issue. As chemical treatment involves expensive reagents, solvents, and catalysts, which are often more costly than mechanical recovery, the process needs to be further optimized to improve the economics of recovery.

Table 3. An Overview of the chemical recovery of different types of waste fiber materials.

Waste Fiber Materials	Recycling Methods	Products	Sources
Waste cotton fabric	(Hydrothermal method) Solid-liquid ratio 1:30, hydrochloric acid concentration 0.6 mol/L, 150 °C, reaction time 100 min	Microcrystalline cellulose (MCC)	Shi [76]
Nylon/cotton blended fabric	WNCFs (3wt%) were added to [AMIM]Cl at 110 °C with continuous mechanical stirring for 80 min	Regenerated cellulose film and nylon 6 fiber	Lv [77]
Colored textile waste	Dissolved in a basic ionic liquid, then processed via dry-jet wet spinning	Artificial cellulose fiber	Haslinger [78]
PET waste (Polyethylene terephthalate waste)	Microwave heating with KOH/methanol as a catalyst	Terephthalic acid (TPA)	Arias [79]
Polyester-spandex blended fabric	First glycolyzed with ethylene glycol (EG) catalyzed by K_2CO_3, then reacted with methanol	Dimethyl terephthalate (DMT) and ethylene glycol (EG)	Xu [80]
Discarded PET	$ZnO/\gamma\text{-}Al_2O_3$ catalyst for waste PET depolymerization in supercritical ethanol (SCE) at 270 °C for 60 min	Diethyl terephthalate (DET)	Yang [81]
Denim waste	Using ionic liquid solvent through dissolution, regeneration, and drying	Cellulose aerogel	Zeng [82]
Waste polyamide 6 (PA6)	Using water as catalyst at 300 °C with a mass ratio (H_2O/PA6) of 11:1 and a reaction time of 60 min	ε-Caprolactam (CPL)	Hu [83]

2.3. Biological Recycling

The biological recycling of waste textiles has emerged as an eco-friendly option in recent years. Compared to traditional mechanical and chemical recycling, biological recycling offers significant advantages such as low energy consumption, mild processing conditions, and environmental friendliness. This technology primarily uses specific enzymes or microorganisms to break down polymer materials in waste textiles, converting them into monomers or other valuable products like cellulose and bioethanol. Unlike chemical recycling, biological recycling typically operates under gentler conditions, consumes less energy, and uses more environmentally friendly reagents. Its high selectivity makes it a promising solution for separating mixed textile waste. However, biological recycling still faces challenges, including high costs and slow reaction rates.

Biological recycling is primarily applied to natural fibers such as cotton, linen, and wool, which can be broken down by enzymes into basic chemical compounds like sugars and amino acids. Enzymes can be used to decompose waste textiles into monomeric building blocks, which can then be utilized to produce various high-value-added products, such as sugars and bioethanol. In biological recycling processes, cellulases are typically employed to break down cellulose-based materials like cotton fibers, while proteases are used to degrade protein-based materials such as wool and silk. Due to the specificity of these enzymes, they enable the separation and recycling of mixed textile waste. Figure 9 illustrates various value-added products extracted from cellulose-based waste using biological recycling technology [25].

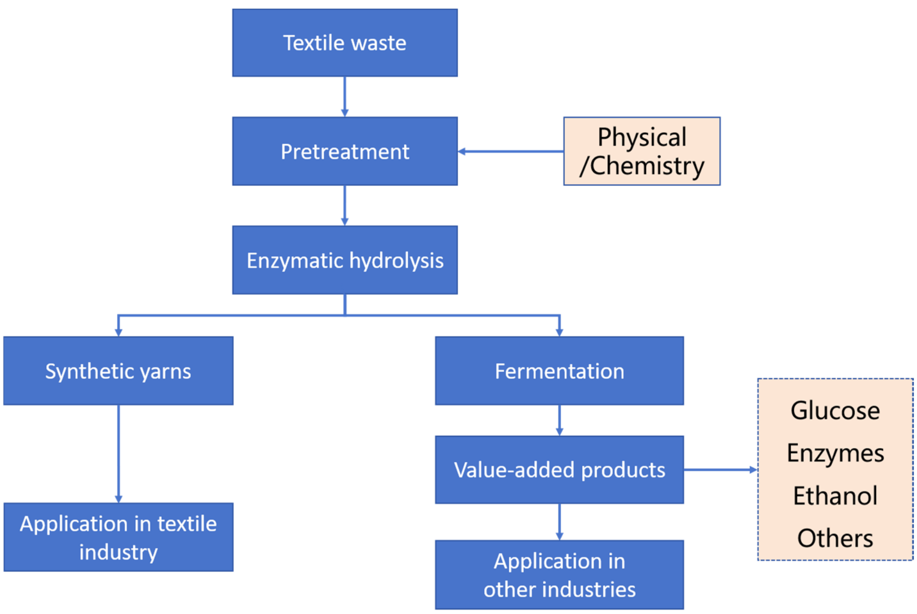

Figure 9. Biological recycling processes and derived value-added products [25].

For the biological recycling technology of textile waste, Hu et al [84] used cellulase enzyme produced by *Aspergillus niger* fungus for the hydrolysis of textile waste, and then obtained glucose with a recovery rate of 70.2% after technological treatments, including autoclaving, freezing alkali/urea treatment, and milling. The resulting glucose can be further used for the production of ethanol or other chemicals. In addition, the PET fibers remaining after hydrolysis can be reused in textile production through melt spinning, forming a closed-loop resource utilization system. For the biological recycling of protein fibers such as wool, this is mainly achieved by keratinases. Navone et al [85] investigated the selective digestion of wool fibers in wool/polyester blends using enzymatic digestion and the recovery of the blends by keratinases, which exclusively degrade the keratin proteins in the wool, and by sodium thioglycolate, a reducing agent used to disrupt disulfide bonds in the wool keratin proteins. The polyester fibers recovered using this method showed no significant difference in elastic modulus or hardness compared to virgin polyester. The recovered wool degradation products can be used to produce biofertilizers, animal feeds, or cosmetic raw materials. Due to the large number of disulfide bonds in wool fibers, it is difficult for ordinary proteases to completely degrade them. Zhang et al [86] investigated this issue and found a green and highly efficient alternative method: a mixture of Es protease, L-cysteine, and urea was used to degrade wool, with a weight loss of up to 99.5%.

Although biological recycling is primarily applied to natural fibers, recent years have seen progress in research on the biodegradation of synthetic and man-made fibers. Yoshida et al [87] reported a bacterium capable of degrading and assimilating PET. Quartinello et al [88] investigated the enzymatic hydrolysis of PET in textile waste. Under neutral aqueous conditions at 250 °C and 40 bar for 60–90 minutes, they utilized *Humicola insolens cutinase* (HiC) to hydrolyze PET. This enzyme specifically cleaves the ester bonds of PET, achieving an 85% recovery rate of terephthalic acid (TA) during the chemical pretreatment stage, which increased to 97% after enzymatic treatment. The recovered TA can serve as a raw material for PET resynthesis. This method offers a new approach to closed-loop recycling of PET textile waste, combining environmental friendliness with economic potential. Kawai et al [89] reviewed the current state of PET enzymatic degradation and its potential applications in waste stream management. While these studies provide new insights for plastic bottle recycling, they have not yet been widely applied to textile fibers. Due to the large molecular size of enzymes, their penetration into the interior of PET materials is limited, confining the hydrolysis reaction primarily to the surface, which significantly restricts the reaction rate. Researchers have explored enzymatic hydrolysis for fibers such as nylon using mixtures of proteases and lipases [90], Nagai et al [91] conducted a study to quantify the reaction rates of nylon hydrolase acting on thin nylon layers. These studies have suggested potential pathways for the biological recycling of polyamide fibers, though practical applications still face challenges. Vecchiato et al [92]. investigated the enzymatic hydrolysis of flame-retardant-pigmented rayon fiber waste. At 50 °C and pH 4.8, with an 8 h reaction time, the waste was decomposed into glucose and flame-retardant pigments, achieving recovery rates as high as 98% and 99%, respectively. The recovered glucose and flame-retardant pigments can be reused in ethanol and rayon fiber production. This demonstrates that biological recycling technology is not only suitable for pure natural fibers but can also be applied to regenerated cellulose fibers with specialized functional treatments.

In summary, biological recycling technology offers an environmentally friendly approach to textile waste recovery, which is particularly suitable for natural fibers and certain regenerated fibers. Biological recycling techniques for different types of waste textile materials are summarized in Table 4. Compared with chemical recycling, biological recycling typically operates under milder conditions with lower energy requirements, employing benign solvents and chemicals. The high specificity of enzymes makes biological recycling an excellent choice for separating mixed textile waste. However, biological recycling still faces limitations such as restricted applicability, demanding pretreatment requirements, and commercialization challenges. This technology is primarily effective for natural polymers but comes with higher costs and slower reaction rates than chemical recycling. Textile waste often requires pretreatment before biological recycling, as antimicrobial or insect-resistant treatments on fabrics may inhibit enzyme activity.

Table 4. An overview of different types of waste fiber materials for biological recycling.

Waste Fiber Materials	Recycling Methods	Products	Sources
Polyester/cotton blend	The material was dried at 110 °C, cut into small pieces, then ground into granules using a rotary blade mill, and finally subjected to enzymatic hydrolysis using glucosidase and cellulase.	Polyester and ethanol	Gholamzad [93]
Waste denim containing cotton and polyester	Anaerobic digestion, enzymatic hydrolysis, and fermentation	Ethanol	Hasanzadeh [94]
Cotton/polyester mixed waste	Hydrolysis of waste materials using cellulase produced by the Mucor fungus	Glucose and polyester	Wang [95]

Cotton ginning waste	First, pre-treatment with organic acids is used to remove lignin, followed by enzymatic hydrolysis with β-glucosidase and cellulase, and finally fermentation with brewer's yeast and Pichia yeast.	Ethanol	Sahu [96]

3. Fields of Application for Recycled Fiber Textile Materials

With the growing global emphasis on sustainable development and the circular economy, the application of recycled fiber materials has become a crucial direction for the textile industry and related sectors. Through technologies such as mechanical recycling, chemical recycling, and biological recycling, regenerated fiber materials can be widely used in various fields, including apparel manufacturing, the automotive industry, construction materials, healthcare, and eco-friendly materials. These applications not only effectively reduce reliance on virgin resources but also mitigate environmental pollution, providing economically viable and environmentally sustainable material solutions for diverse industries.

3.1. Recycled Fiber Clothing

The most direct application of recycled fiber materials is in the production of regenerated textiles. Utilizing recycled fibers such as polyester (rPET), nylon (rPA), and cotton (rCotton) to manufacture new clothing, home textiles, and functional fabrics not only reduces resource waste but also meets consumer demand for sustainable fashion.

Recycled polyester fiber (rPET) [97,98]: rPET, obtained through chemical or mechanical recycling, has been widely used in the apparel industry, such as sportswear, functional outerwear, and swimwear. Brands like Nike and Adidas have launched sportswear made from rPET to reduce reliance on virgin polyester [99]. rPET is also used to produce home textiles, such as carpets and curtains.

Recycled cotton fiber (rCotton) [34,44]: After processes such as sorting, spinning, and weaving, recycled cotton fibers can be used to manufacture everyday textiles like T-shirts, jeans, and towels. The production of recycled cotton fiber reduces the demand for new cotton, thereby decreasing agricultural water consumption and pesticide use.

Recycled nylon (rPA): Recycled nylon can be used to produce high-end sportswear, yoga apparel, and regenerated fabrics from fishing nets, among other applications. For instance, Zhejiang Jiahua Special Nylon Co., Ltd [100] processes discarded nylon yarn into ski jackets, windbreakers, and similar products, as shown in Figure 10. The company has collaborated with various apparel brands such as Decathlon, Li-Ning, Semir, and Anta to launch multiple sportswear lines made from recycled nylon.

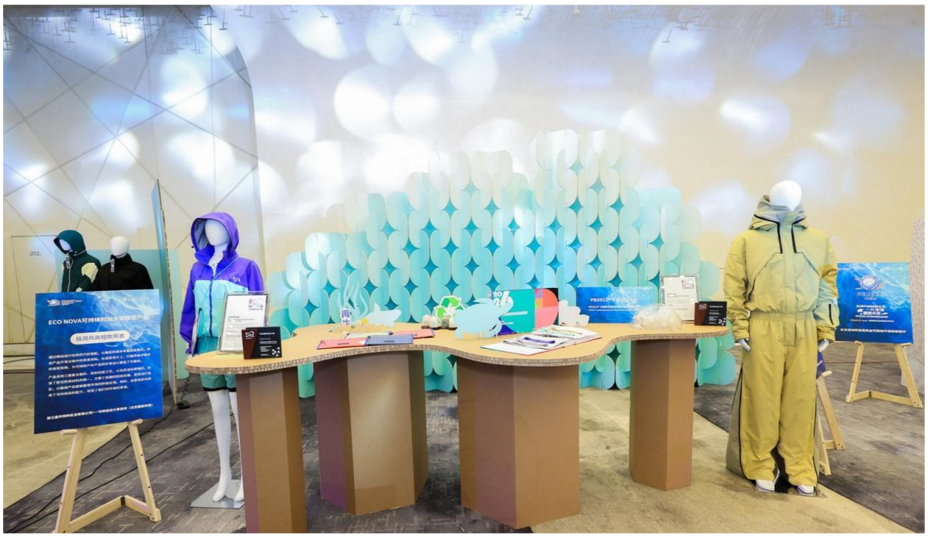

Figure 10. windbreakers and ski jackets [101].

3.2. Textiles for Automotive Applications

Recycled fiber materials are increasingly being used in the automotive industry, particularly in interior trims, acoustic insulation materials, and lightweight structural components. These materials not only reduce the carbon footprint of automobile manufacturing but also meet industry demand for high-performance and sustainable materials.

Interior trim materials: Many automakers have begun using recycled PET fibers to produce seat fabrics, door panels, and carpets. For instance, brands like BMW and Tesla have adopted premium interior seat fabrics made from rPET to reduce reliance on petroleum-based textile materials.

Soundproofing and noise-reduction materials [102]: Recycled fiber materials are widely used in automotive soundproofing cotton and noise-damping pads due to their excellent acoustic absorption properties. For example, recycled cotton and polyester fibers can be processed into eco-friendly sound insulation materials, which are applied in components such as engine hood liners and door fillers.

Fiber composite structural components [41,103]: Recycled fibers combined with resin can be used to manufacture automotive interior structural parts, such as dashboard brackets and seat frames. These materials not only reduce weight but also meet automotive industry requirements for high strength and wear resistance.

3.3. Building and Home Materials

The application of recycled fiber materials in the construction and home furnishing sectors mainly covers environmentally friendly carpets, soundproofing panels, insulation materials, and wall decoration materials [43]. These applications not only improve the sustainability of building materials but also enhance comfort.

Eco-friendly carpets [104]: Carpets made from recycled PET or nylon fibers, featuring durability, stain resistance, and antibacterial properties, have been widely adopted in residential spaces, commercial office spaces, and hotels. For example, the EcoWorx® carpet launched by the Shaw Corporation in the United States is made from recyclable materials.

Soundproofing and sound-absorbing panels [45]: Soundproofing panels made from recycled fibers are used in meeting rooms, recording studios, cinemas, and other venues to reduce noise pollution. For example, compressed panels made from recycled cotton fibers are often used as wall soundproofing materials due to their high sound absorption performance.

Insulation materials [47,105,106]: Recycled polyester fiber and insulating cotton can be used for building insulation layers. It not only provides low thermal conductivity and excellent thermal insulation but also does not release harmful substances, making it suitable for green buildings and eco-friendly residences.

3.4. Medical and Hygiene Products

Recycled fiber materials also have significant applications in the medical and hygiene sectors, including in the production of medical protective clothing, masks, surgical gowns, and sanitary napkins [107–109]. Under the premise of ensuring safety and hygiene, the recycling and reuse of these materials can effectively reduce the generation of medical waste.

Medical textiles: Through high-temperature sterilization and special treatment, certain recycled fibers can be used to produce medical sheets, masks, surgical gowns, and protective clothing. These products not only meet hygiene standards but also reduce the medical industry's reliance on disposable textiles.

Nonwoven materials: Recycled polyester and polypropylene fibers can be used to manufacture biodegradable masks, wet wipes, nursing pads, and other nonwoven products. In recent years, eco-friendly biodegradable nonwoven materials have become a key development trend in the hygiene products market.

3.5. Environmental and Filtration Materials

Recycled fiber materials are also widely used in eco-friendly bags, filtration materials, ecological restoration products, and other fields, offering greater potential for sustainable development.

Biodegradable shopping bags [110,111]: Eco-friendly bags made from recycled fibers can replace traditional plastic bags, helping reduce white pollution. For instance, some brands have introduced shopping bags made from rPET (recycled polyethylene terephthalate), which are reusable and ultimately recyclable.

Air and water filtration materials [112,113]: Recycled polyester and nylon fibers can be used to produce functional materials such as air filters and water treatment screens. For example, some HEPA air filters now incorporate recycled fibers to minimize resource consumption [114,115].

Ecological restoration materials: Recycled fiber materials can be utilized in marine pollution remediation, where discarded fishing nets, ropes, plastic bottles, and bags are reprocessed into yarn for new products. For instance, Veolia Huafei Polymer Technology Co., Ltd. transforms ocean-recovered plastics into T-shirts [116]. Additionally, nylon fibers reclaimed from abandoned fishing nets can be incorporated into fiber-reinforced mortar [117].

In summary, the application of recycled fiber materials has expanded from the traditional textile industry to multiple other fields, such as the automotive, construction, healthcare, and environmental protection sectors. This development will play a significant role in promoting the circular economy and sustainable development. With advancements in technology and increasing consumer awareness of environmental issues, the market demand for recycled fiber materials is expected to continue growing. However, to achieve more widespread application, further optimization of recycling processes is needed to enhance the quality and performance of recycled materials, alongside policy support and market incentive mechanisms to promote industrialization. In the future, by integrating smart sorting technology, advanced recycling processes, and new types of regenerated materials, recycled fiber materials will provide more environmentally friendly and efficient solutions for global sustainable development.

4. Development Trends

With the advancement of global sustainable development goals, fiber material recycling and reuse technologies are gradually evolving toward greater efficiency, intelligence, and industrialization [118]. However, the field still faces technological, economic, and policy challenges during practical application. Therefore, future research and development efforts should focus on multiple levels, including innovations in recycling technology, the optimization of recycling systems, policy support, and market promotion, to drive the comprehensive implementation of a circular economy.

4.1. Upgrading and Innovation of Recycling Technologies

Fiber recycling technologies are expected to further develop toward higher efficiency, lower energy consumption, and greater environmental sustainability. For instance, in mechanical recycling, advancements in automated sorting and high-efficiency crushing technologies will reduce energy consumption while improving fiber quality. In chemical recycling, the development of novel green solvents and catalysts will minimize environmental pollution and enhance the purity and utilization rate of recovered monomers. For biological recycling, genetically engineered microorganisms and enzyme technologies will accelerate the degradation efficiency of synthetic fibers, promoting the widespread application of biodegradable fiber materials.

4.2. Development of Intelligent and Automated Recycling Systems

Future fibre recycling systems will become increasingly intelligent with advancements in artificial intelligence, big data, and Internet of Things (IoT) technologies. For example, machine vision and AI-based automated sorting systems can identify different types of fibers, improving sorting accuracy and efficiency. IoT technology can enable full lifecycle management of textiles, from production and consumption to recycling, making traceable recycling systems more robust. Additionally, blockchain technology can be employed to record textile recycling data, enhancing supply chain transparency and trustworthiness.

4.3. In-Depth Application of Circular Design Concepts

Future textile design will increasingly prioritize convenience in recycling, advancing the circular design philosophy of "optimization from the source." For instance, adopting detachable and recyclable material designs will reduce the use of mixed fiber structures and lower separation difficulty; utilizing biodegradable fibers or reversible cross-linked polymers will enhance material degradation performance; and developing recyclable dyes and eco-friendly additives will minimize the impact on recycled fiber quality during chemical processing. This "design equals recycling" concept will become a crucial direction for sustainable textile development in the future.

4.4. Cross-Industry Integration and Expanded Applications

Looking ahead, recycled fiber materials will find broader applications across industries through increasing cross-sector integration. For instance, the construction sector may utilize recycled polyester fibers in thermal insulation materials, acoustic panels, and eco-friendly carpeting. Automotive manufacturers could apply recycled nylon fibers in interior trims, seat fabrics, and lightweight composite materials. In healthcare, biodegradable recycled fibers may be adopted for medical protective equipment and sustainable hygiene products. Such interdisciplinary collaboration will significantly enhance the value proposition of recycled materials while accelerating their commercial adoption across diverse fields.

4.5. Policy Support and Standardization System Construction

Globally, governments and international organizations are gradually strengthening their policy support and regulatory framework for the textile recycling industry. In China, the Implementing Opinions on Accelerating the Recycling of Used Textiles document, jointly issued by the Ministry of Industry and Information Technology (MIIT), the Ministry of Commerce (MOFCOM), and the Development and Reform Commission (DRC), sets a clear target: by

2025, the recycling rate of used textiles should reach 25%, with an output of 2 million tons of regenerated fibers; and by 2030, the recycling rate should be further increased to 30%, with an output of 3 million tons of regenerated fibers [21]. At the same time, the EU has introduced even stricter requirements through its Sustainable and Recycled Textiles Strategy 2024, which stipulates that all textiles must be durable, recyclable, non-hazardous, and made from recycled fibers by 2030. This strategy also introduces the innovative mechanism of 'product digital passports' for tracking textile content and potential hazards throughout the life cycle, and explicitly prohibits the incineration of unsold garments [119]. Japan enacted the Basic Law for Promoting the Formation of a Recycling-based Society and its accompanying regulations as early as 2000, providing a complete legal framework for the recycling of used textiles and setting a goal of decomposing household discarded clothing and using a large proportion of recycled fibers in the production of new garments by 2030. Other countries have also taken specific measures. France followed the EU policy to ban the incineration of unsold clothing [120]. The U.S. federal government introduced the Solid Waste Disposal Act, which would ban the incineration of unused clothes and establish a 'Used Clothes Recycling Day' and other forms of publicity and educational activities [121]. Germany and the Netherlands focus on the promotion of textile recycling through redesign and innovative processes. The establishment of these policies, regulations, and standardization systems has provided the waste textile recycling industry with a clear development direction and compliance requirements, which have strongly promoted the development of the global textile circular economy.

5. Conclusions

This paper has systematically outlined three major recycling technologies for waste textiles: mechanical recycling, chemical recycling, and biological recycling. Although mechanical recycling will decrease the quality of recycled fibers, this problem can be mitigated to a certain extent by blended spinning technology. In terms of chemical recycling, this paper has focused on the recycling technology of waste cotton textiles and PET fibers. As a new, environmentally friendly method, biological recycling is still faced with technological challenges, such as high recycling costs and long reaction times, despite its significant environmental advantages.

From an application perspective, recycled fibers are not only utilized in traditional textile sectors but have also expanded into multiple industries, including the automotive, construction, medical, and environmental protection sectors. These regenerated fibers can be transformed into diverse products such as sportswear, automotive interiors, acoustic insulation materials, and medical protective clothing, providing crucial support for the development of a circular economy.

Fiber recycling technologies will evolve toward greater efficiency, intelligence, and industrialization. Achieving this goal requires multi-stakeholder collaboration: technological innovation to enhance efficiency, the establishment of intelligent recycling systems, the application of circular design principles, cross-industry integration, and policy support. Countries and regions, including China and the EU, have set clear recycling targets. For instance, China aims to achieve a 25% recycling rate for waste textiles by 2025.

In summary, recycling fiber-based products is not merely a technological challenge but a comprehensive economic and social systemic project. Only through coordinated efforts in policy guidance, technological innovation, industrial collaboration, and consumer awareness, we can achieve truly sustainable circular utilization of fiber materials, thereby contributing to the development of a resource-efficient and environmentally friendly society.

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Author Contributions

Conceptualization, S.M. and J.C.; Methodology, J.C.; Software, B.X.; Validation, Z.H. and Q.Z.; Formal Analysis, G.F. and X.D.; Investigation, X.D. and Q.Z.; Resources, Q.X.; Data Curation, B.X.; Writing—Original Draft Preparation, J.C.; Writing—Review & Editing, S.M.; Visualization, S.M. and J.C.; Supervision, Z.Z.; Project Administration, Z.C.; Funding Acquisition, S.M.

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Not applicable.

Informed Consent Statement

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Data Availability Statement

The data involved in this article can be found in the corresponding references.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Statement of the Use of Generative AI and AI-assisted technologies in the Writing Process

During the preparation of this manuscript, the author(s) used DeepL translator in order to paraphrasing sentences. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the article.

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