microplastics

Review

Toward Circularity in Blended Polyester-Based Textile Waste: Microfiber Pollution, Recycling Technologies, and Implementation Challenges

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Abstract

Blended polyester (PET)-based textiles comprise a significant portion of post-consumer waste, posing substantial challenges to circular economy initiatives while contributing to microfiber (MF) pollution. Despite the considerable recycling potential of PET textiles, no commercially viable technologies currently exist that can efficiently separate and recycle blended PET-based textile waste on an industrial scale. This review provides a comprehensive analysis of recycling strategies for post-consumer blended PET-based textiles and their subsequent valorization pathways. Mechanical, chemical, and biological recycling processes are mostly not yet market-ready, although chemical approaches are considered particularly promising. The findings highlight a critical need for advanced sorting technologies, enhanced material traceability, and robust MF mitigation strategies to foster circularity and contribute to the United Nations Sustainable Development Goals (SDGs). The results further indicate that mechanical recycling of blended PET textiles leads to significant MF release due to fiber fragmentation, whereas chemical recycling offers the potential for improved material recovery, but remains limited by high energy demand and solvent-related challenges. While closed-loop approaches support true circularity by maintaining textile-to-textile material flows, open-loop pathways repurpose textile waste for high-value non-textile applications.

Keywords: textile waste; polyester; polycotton; microfibers; circular economy

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1. Introduction

It was estimated that worldwide thermoplastics production reached 445.25 million metric tons in 2025 [1], of which biobased plastics accounted for 2.31 million tons [2]. It is also estimated that, by 2040, more than 100 Mt of plastic waste will still be mismanaged [3]. Under a business-as-usual scenario, global plastic production is projected to reach 736 Mt, with waste generation of 617 Mt by 2040, driven by accelerated production outpacing waste management infrastructure [3]. This scenario drives a 60% growth in plastic-related greenhouse gas emissions, amounting to 2.8 Gt CO_2e by 2040. Consequently, more than 445,000 metric tons of small plastic particles, known as microplastics, are released annually into the environment by companies across the global plastic supply chain [4]. To address

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this issue, the European Commission, as part of its 2021 Zero Pollution Action Plan, aims to diminish the release of microplastics by 30% by 2030 [5].

The textile industry, which produces garments for people and sportswear [6], fabrics for automotive interior [7], and footwear, accessories, and home décor items, including curtains and carpets [8], similarly contributes to environmental concerns. The fast textile and fashion sector drives a demand for approximately 80 billion new garments each year [9], resulting in per capita textile consumption of 7 to 13 kg [10,11]. By 2030, global textile sales revenues are projected to reach UDS 1320 billion [12]. Notably, approximately two-thirds of the world's textile fibers are petrochemical-based (polyester, polyamide, elastane, and polypropylene), with the remaining one-third consisting mainly of cotton (36%) and wool (2%) [9,13,14]. This growing consumption has intensified the environmental challenges associated with textile production and waste generation [15]. To mitigate these impacts, Directive 2008/98/EC, as amended by Directive (EU) 2018/851, reinforced the waste hierarchy, promotes waste prevention, and mandates the separate collection of textiles by 1 January 2025 [16]. By establishing these requirements, the Directive provides the legal basis for extended producer responsibility (EPR) schemes and higher recycling targets, thereby directly supporting the transition toward circular textile systems. However, Europe still faces significant challenges in textile waste management. Only 15–20% of textile waste is separately collected, and about half of this is exported to developing countries [17]. Most discarded textiles continue to be landfilled or incinerated, while about 1% of garments are effectively recycled into new products [18,19]. These figures highlight the urgent need to transition from the prevailing linear "take–make–dispose" model toward more circular systems. In this context, the United Nations Sustainable Development Goal 12 (SDG 12), "Ensure sustainable consumption and production patterns", emphasizes the need to adopt recycling, reuse, and closed-loop resource management. Aligned with this global objective, the European Union is actively promoting a circular economy for textiles, prioritizing the collection, recycling, and valorization of post-consumer textile waste. This transition is particularly critical for mixed polyester-based textiles, which represent a substantial share of the global market.

Polyethylene terephthalate (PET) is the most widely used thermoplastic polymer, with extensive applications in packaging and textiles due to its durability, versatility, and cost-effectiveness. In the textile industry, polyester fibers, first introduced in the mid-20th century [6], now dominate global fiber production, accounting for approximately 72% of the man-made fibers [14,20,21]. By 2023, 13% of the PET fibers produced worldwide were derived from recycled materials [22]. Notably, Polar Fleece, introduced in 1993, was the first recycled polyester textile made from post-consumer plastic soda bottles [23]. Today, almost all recycled polyester (r-PET) fibers are produced from post-consumer PET bottles [24–27], supporting both material circularity and functional textile design. This predominance can be largely attributed to the well-established collection, sorting, and recycling infrastructure developed for PET bottles, as well as their relatively high purity, uniform composition, and consistent molar mass (15,000 to 27,000 g mol^{-1} of bottle-grade PET) [28,29].

Despite these advances, the recycling rates for polyester remain low. For example, only about 12.5% of PET fibers have been recycled, and just around 1% originate from textile-to-textile recycling, with the majority of recycled PET derived from plastic bottles [25]. To address this gap, both mechanical and chemical recycling approaches for PET textile waste have been developed [12,25,27,28,30–36]. Fiber-to-fiber recycling, which aims to recover high-purity PET from post-consumer textiles, offers considerable environmental advantages over conventional virgin PET production [14,37]. Producing one ton of recycled PET requires less than 17% of the energy needed for virgin PET and significantly reduces emissions of CO_2, CH_4, and other hydrocarbons. Moreover, recycling one ton of PET can save approximately 17.2 tons of water, 0.65 tons of natural gas, 1.28 tons of crude oil, and 0.51 tons of coal [28]. Importantly, recycled PET exhibits properties comparable to those of virgin PET, making it suitable for high-quality textile applications [30].

However, despite the significant recycling potential of PET textiles, no commercially viable technologies currently exist that can efficiently separate and recycle blended polyester-based textile waste at an industrial scale [9,38]. Blended fabrics such as cotton/viscose/lyocell combined with polyester (polycotton), polyester–nylon, wool–polyester, or materials containing elastane consist of fibers with fundamentally different chemical properties. This heterogeneity makes their separation technically challenging and economically unfeasible using existing mechanical or chemical recycling processes [39]. The complexity is further exacerbated by the presence of dyes and finishing chemicals, which complicate fiber separation and reprocessing [9]. Certain additives, such as di-butyl phthalate, may act as initiators of polymer decomposition, accelerating material breakdown [40–42]. Laboratory simulations have estimated that the global annual release of these compounds could range from 1 to 5.5 tons, indicating their potential accumulation in the environment [40]. Mussels (*Mytilus edulis*) exposed to degraded PET nanoparticles (600 nm–3.1 μm) at environmentally relevant concentrations (10–10^5 particles/L) showed concentration and time-dependent cellular responses [43]. Hemocyte subpopulations, especially granulocytes and hyalinocytes, exhibited altered lysosomal stability, oxidative activity, and viability, with partial recovery over time.

Additionally, contaminants including detergents, flame retardants, antibacterial, and anti-mold agents, pesticides, dyes, pigments, catalysts, volatile organic compounds (VOCs), and nanomaterials pose challenges for both recycling processes and the safety and quality of the resulting products [15,29]. For example, PET/cotton blended fibers (60:40 ratio) have been reported to exhibit intermediate degradation levels of up to 20%, reaching a plateau after 30 days [11]. The partial degradation of the biodegradable cotton fraction may, in turn, accelerate the fiber fragmentation, further complicating material recovery and recycling efforts. Consequently, the release of microfibers (MFs), a distinct morphological form of microplastics, is no longer seen merely as a consumer "laundry problem" but as a systemic inefficiency within the textile recycling industry itself [44–48]. These MFs can be generated during the production, use, washing, disposal, and recycling of garments, highlighting an important environmental concern linked to both textile waste management and recycling limitations. The Regulation on the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) (EU 2023/2055) [49] defines MFs as fibers up to 15 mm in length with a length-to-diameter ratio greater than three. In the textile industry, the term "microfiber" usually refers to ultra-fine synthetic fibers with a linear density of less than 1 denier, commonly used in clothing and household items, measuring less than 5 mm in all dimensions and maintaining a length-to-diameter ratio greater than 3 [50]. Fibrils are sub-micrometric fiber derivatives produced through the abrasion of synthetic MFs, with diameters not exceeding 10 μm, and usually failing below 5 μm [23].

Despite many review papers addressing the recycling of PET textile waste and microfiber release during the laundering process, scientific interest has recently accelerated toward the efficient separation and recycling of blended PET-based textile waste, as well as the release of MFs throughout different processing stages. In addition, there is a gap in the clear identification of the technical and environmental barriers that must be overcome to enable sustainable recycling of blended PET textile waste, as well as to better understand the mitigation and release of MFs during the recycling processes. In this context, the paper aims to (i) evaluate the mechanism and prevalence of MF release from blended PET textile waste, (ii) critically assess the recycling technologies currently used for the valorization of post-consumer blended polyester-based textiles, and (iii) identify the bottlenecks and solutions for implementing effective recycling strategies.

2. Research Methodology

This manuscript provides a comprehensive overview of advancements in the recycling and reuse of blended PET-based textile waste over the past decade, supported by a bibliometric analysis of publications indexed in the Web of Science from 2015 to the present. The literature search employed the keywords “microfibers”, “textile waste”, “blended PET textile”, and “blended PET textile waste” to capture the current knowledge on microfiber release and recycling technologies that promote circularity in PET-based blended textiles. A total of 864 publications related to blended PET textiles and blended PET textile waste were retrieved from the Web of Science Core Collection database.

As illustrated in Figure 1, research outputs in these areas have grown exponentially over the last ten years. Although the publications specifically addressing MFs have remained relatively stable, approximately 45% (289 publications) of studies on blended PET textiles and 63% (141 publications) of those on blended PET textile waste were published within the past three years, highlighting the increasing scientific and industrial attention devoted to this topic. After the elimination of duplicates and the removal of articles whose abstracts did not align with the research scope, 85 papers were selected for in-depth analysis, of which 25 were review articles.

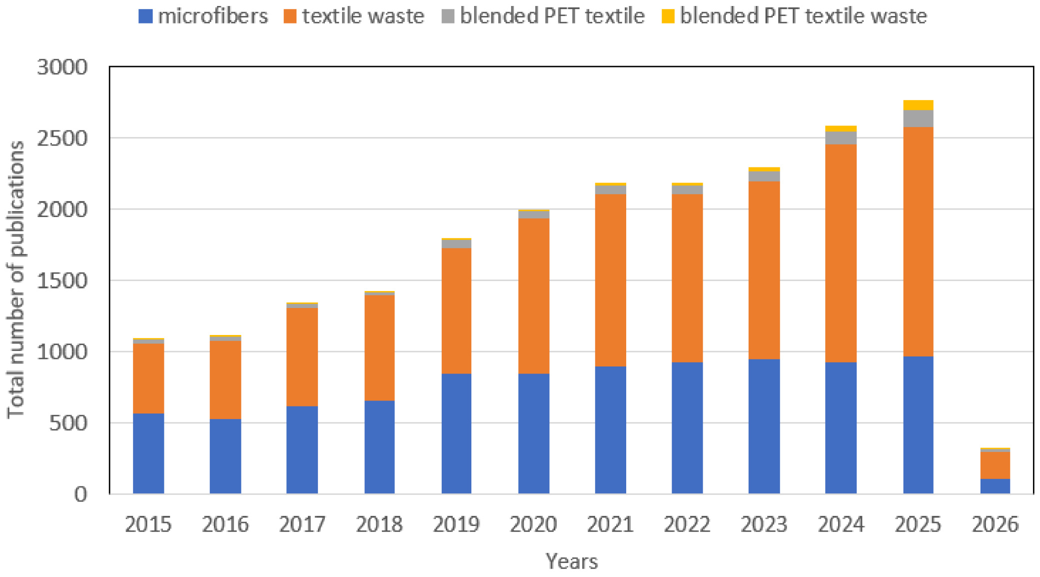
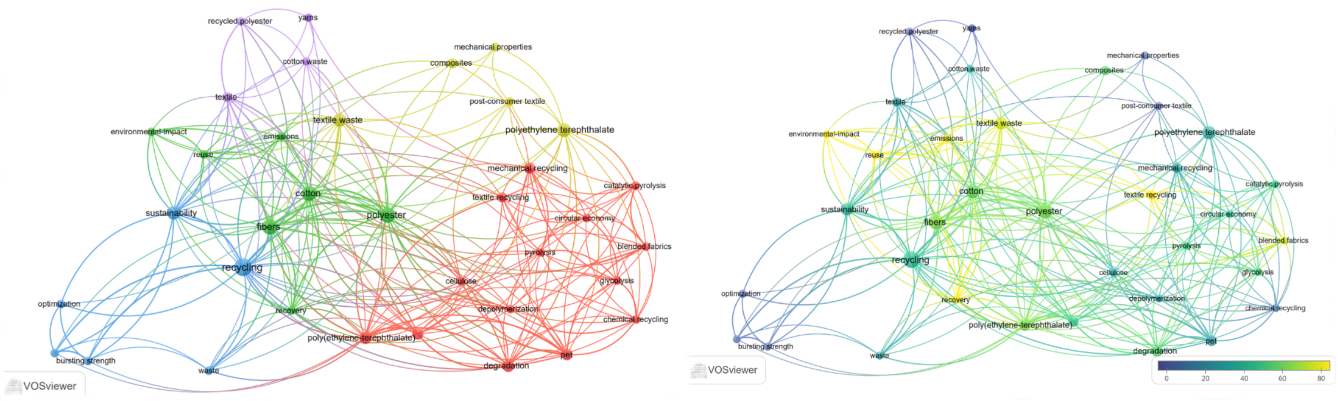


Figure 1. The number of annual publications for “microfibers”, “textile waste”, “blended PET textile”, and “blended PET textile waste” keywords found in Web of Science Core Collection database from 2015 to February 2026.

Figure 2a,b shows the keyword associations and their average citations per year, as analyzed with VOSviewer (version 1.6.20).

A total of 336 keywords were identified in the literature, of which 36 met the minimum co-occurrence threshold of three. The high average citation per year further demonstrates the importance and impact of the identified keyword clusters within this research field.



(**a**) (**b**)

Figure 2. The co-occurrence of the "microfibers", "textile waste", "blended PET textile", and "blended PET textile waste" keywords (**a**) (where colors represent clusters of closely related keywords) and the average citations per year (**b**) (where blue indicates earlier topics and yellow highlights more recent research trends).

3. Blended Polyester-Based Textiles and Mechanisms of Microfiber Release

3.1. Types of Blended Polyester-Based Textiles

The diversity of textile fiber blends can be systematically classified into four primary chemical groups: cellulosic fibers (for example: cotton, jute, linen), synthetic fibers (for example: PET, polyurethane, acrylic, polyamide), protein fibers (for example: wool, silk), and regenerated fibers (for example: viscose, cellulose acetate, lyocell, rayon) [51].

Among these categories, polyester (PET)-based blends are the most extensively studied, particularly in combination with cotton [52–54], nylon (polyamide) [55], and elastane (spandex) [56]. These blends are widely used because they balance performance, cost, and processability. In addition to conventional blends, other polymer systems relevant to textile applications include polycarbonate [7], styrene–butadiene rubber (SBR) [57], and PP/SEBS-g-MA [58].

A prominent example is polycotton (PET/cotton), which combines the advantages of both fiber types. Cotton offers softness, breathability, and moisture absorption, while polyester provides strength, wrinkle resistance, and color fastness [52]. As a result, polyester/cotton blends form a key segment of the global textile market, projected to grow from USD 16.8 billion in 2025 to USD 20.6 billion by 2035 [53].

Another important class of blends involves nylon, particularly polyamide 6 (PA6), which is valued for its high moisture absorption, abrasion, and mechanical properties [55]. These characteristics primarily arise from strong intermolecular hydrogen bonding within the polymer structure [26]. In PET/PA6 blends, the incorporation of a small amount of PA6 ($\leq$10 wt%) into the polyester melt can lead to the formation of a self-compatible copolymer form through the reaction between ester and amide groups [55]. This in situ compatibilization improves interfacial adhesion, enhances crystallization behavior, and increases the crystallization temperature due to heterogeneous nucleation effects. Consequently, the melt exhibits improved spinning stability, and the resulting fibers show improved hydrophilicity.

Blending also influences the functional performance of natural fiber systems. For example, increasing the proportion of recycled PET (r-PET) in r-PET/wool woven fabrics has been shown to enhance the thermal conductivity, air permeability, and moisture vapor transmission, while also influencing surface roughness and overall moisture management behavior [59].

This diversity of textile fibers, chemical structures, and interactions in blended textiles is the primary reason that makes blended fabrics difficult to recycle.

3.2. Mechanism of Microfiber Release During Washing

Domestic laundering of garments is widely recognized as the primary pathway for MFs release into the environment, with households estimated to contribute up to 35% of global emissions. Other sources include wear, abrasion during use, and drying processes [23]. It has been reported that washing 6 kg of mixed garments in real house conditions can generate 18×10^6 MFs per cycle [60]. Along with MFs, fibrils, smaller particles with diameters of less than 10 µm, are usually released into the environment during the washing process [23].

Figure 3 shows the shedding mechanism of MFs during wear, tear, washing, and drying of garments [8].

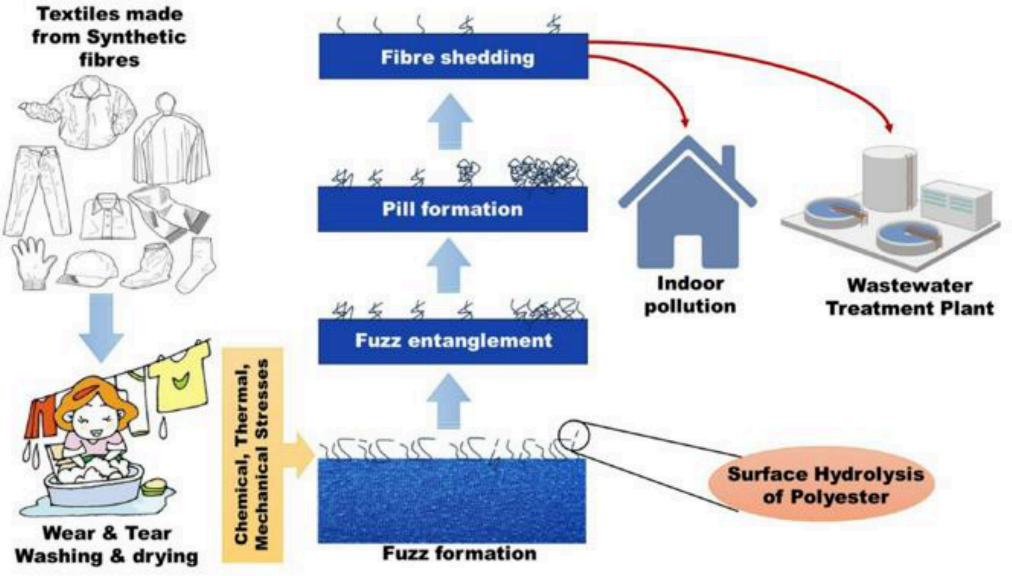


Figure 3. Lifecycle of MFs release from textile garments to environment due to their wear and tear and washing [8] (Open Access).

First, during washing, both synthetic and natural fibers are mechanically detached from textiles as a result of agitation, friction, and chemical interactions with detergents [8,13,23,60,61]. This process initiates surface damage in the fuzz formation, which represents the initial stage of pilling. At this stage, loose fibers reach the surface of the fabric, rise up from the yarn structure, and create a fluffy appearance. As washing continues, these protruding fibers entangle and form pills [8,62]. Once discharged, a substantial fraction of these fibers enters wastewater streams and is transported to wastewater treatment plants (WWTPs) [8]. It is estimated that the microplastics released into WWTP will increase from 0.017 Mt in 2000 to 0.749 Mt by 2062 [63]. Although WWTPs can retain a large proportion of MFs in sewage sludge, some fibers still bypass treatment due to system inefficiencies or because their small size allows them to pass through conventional filtration systems. Consequently, MFs can be indirectly released into aquatic environments, including rivers, lakes, and coastal waters, contributing to widespread microplastic pollution [46,64–68].

3.3. Microfiber Release from Blended PET-Based Textiles

The release of microfibers (MFs) from textiles is strongly influenced by the fiber type, fabric structure, manufacturing history, and processing conditions. A major limitation in

MF research is the absence of a standardized protocol for quantifying MF release from textiles, which creates significant challenges for both scientific assessment and industrial benchmarking [13,44]. As a result, reported MF shedding rates differ considerably and are expressed using different units and methodologies. This variability arises from differences in experimental conditions, including the type of washing equipment (household machines vs. laboratory simulators), detergent formulations, washing temperatures, cycle durations, and the size and composition of the textile sample, which complicate a direct comparison across studies and limit the reproducibility of results [13,53,69,70].

Regarding the chemical composition of textiles, polyester and natural fibers, such as cotton and wool, have been reported to release relatively high amounts of fibers during washing, with values of 161 ± 173 mg kg^{-1} and 165 ± 44 mg kg^{-1} of textile, respectively. In comparison, polyamide (PA) exhibits substantially lower emissions, releasing approximately six times less material (27 ± 14 mg kg^{-1}) [71]. Cotton fabrics generally emit about four times more MFs compared to synthetic fabrics [54]. Overall, the reported release rates from synthetic textiles span a wide range, from approximately 1600 to 56,000 MFs per gram of fabric [23]. In addition, fiber shedding is strongly influenced by washing history. Initial washing cycles typically result in higher fiber losses than subsequent cycles [71], presumably because of residual loose fibers and particulates remaining from manufacturing processes.

Scientific studies on MFs release from polyester fabrics report conflicting findings, largely due to differences in the specific fabric structure and manufacturing characteristics. For example, Cui et al. [72] found that polyester knitted fabrics release significantly more MFs than woven fabrics. This behavior is attributed to the looser coil string sleeve structure of knitted fabrics, which allows fibers mobility and detachment during washing. Conversely, other studies have reported that woven fabrics can release higher MFs than knitted ones. This discrepancy is often linked to yarn characteristics, particularly when woven fabrics are produced from ply-twisted spun yarns, which have a higher “hairiness” compared to the single-filament yarns commonly used in certain knit structures [61]. In addition, the physical properties of fabrics play a significant role. The increased fabric thickness and mass have been associated with greater MF emissions, likely due to the higher material content and intensified mechanical friction within denser textile structures [61].

Several studies have reported no significant difference in MF shedding between virgin polyester and recycled polyester during key manufacturing stages, including spinning, weaving/knitting/tufting, dyeing, and washing processes [23,73]. In contrast, Persson et al. [45] observed a markedly different trend. After three mechanical recycling cycles of knitted fabrics made from 30% r-PET blended with 70% virgin PET, the MFs shedding under simulated wear and laundering increased by a factor of 6.2 compared to fabrics made entirely of virgin PET. This behavior was attributed to the progressive reduction in the polymer chain length and mechanical strength of r-PET during the successive recycling process. As a result, the reduced structural integrity makes the fibers more susceptible to thermo-mechanical stress during washing, leading to accelerated fiber breakage and increased MF release [74].

Currently, there is limited documented evidence on the release of MFs during the chemical recycling of blended PET-based textiles across processing stages [47]. Recently, Manivannan et al. [47] reported the generation of MFs during the chemical recycling of polycotton textiles, across key processing steps such as dye removal, acid hydrolysis, and alkaline hydrolysis—Figure 4.

Figure 5 illustrates the median length of MFs released from four polycotton fabric wastes compared with virgin PET during the chemical recycling process.

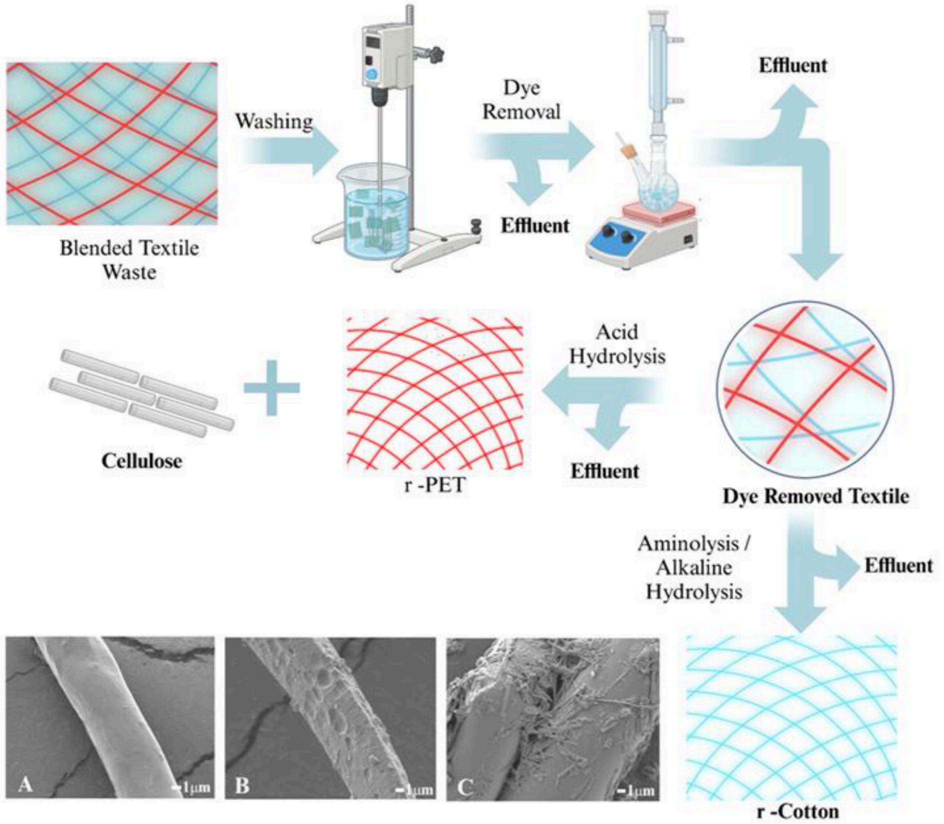


Figure 4. MF extraction methodology from polycotton waste treatment and their surface nature during: dye removal (**A**), acid hydrolysis (**B**), and PET depolymerization (**C**). Reproduced from [47] with permission from Elsevier.

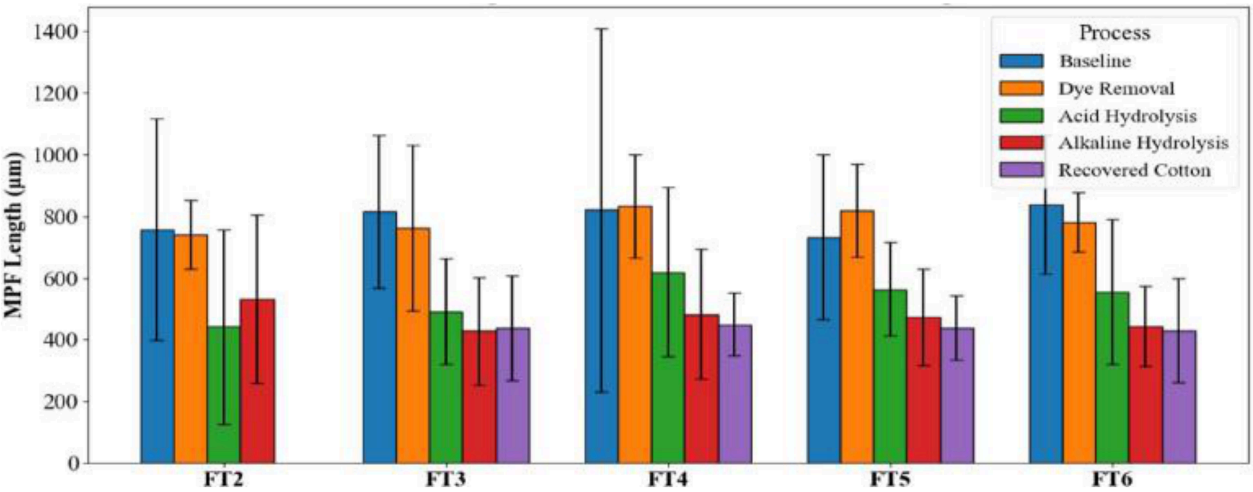


Figure 5. Median length of MFs from fabrics across treatment stages (where the compositions are 100% PET for FT2; 50.03% cotton/49.96% PET for FT3; 59% cotton/41% PET for FT4; 31% cotton/69% PET for FT5; 56% cotton/44% PET for FT6). Reproduced from [47] with permission from Elsevier.

According to Figure 5, the highest release of MFs was observed during the dye-removal step, ranging from 11,325 ± 2306 MFs g^{-1} for 31% cotton/69% PET blends to 6700 ± 2372 MFs g^{-1} for 56% cotton/44% PET blends, and 6950 ± 1411 MFs g^{-1} was recorded for recovered cotton. During acid hydrolysis, 8350 ± 3295 MFs g^{-1} were generated for 59% cotton/41% PET and 6500 ± 1957 MFs g^{-1} for cotton/49.96% PET. In contrast, alkaline hydrolysis produced the lowest MFs release levels, ranging from

1058 ± 402 MFs g^{-1} for 100% PET to 925 ± 43 MFs g^{-1} for 31% cotton/69% PET blends. Recovered cotton yielded between 36 ± 3 MFs g^{-1} to 74 ± 23 MFs g^{-1}, whereas the recycled cellulose values ranged from 119 MFs g^{-1} for a 59% cotton/41% PET blend to 245 MFs g^{-1} for a 50.03% cotton/49.96% PET composition. The order of MF generation during dye removal and chemical recycling of blended PET-based textiles was dye removal (43.64%) > acid hydrolysis (33.98%) > alkaline hydrolysis (9.6%) (Figure 5) [47].

The process parameters, including reaction duration, mixture composition, and stirring intensity, were found to strongly affect both the quantity and size distribution of MFs, while the temperature had a moderate influence on fiber degradation [47].

Material degradation further amplifies microfiber emissions. A study examining four polyester fabric types (interlock, fleece, single fibers, and single filaments) subjected to artificial aging under ISO 4892-2 [75] demonstrated that degraded textiles released 20–40 times more MFs than those observed during standard washing conditions [17]. This finding suggests potential mitigation strategies, such as pre-washing or industrial pretreatment of new garments, to reduce microfiber emissions to the consumer level.

To address the significant environmental burden associated with MF release during washing, several mitigation strategies have been proposed. Research highlights that equipping washing machines with filters can significantly mitigate MF emissions [13,62,69,76]. For example, a laboratory-scale study reported a separation efficiency of up to 99.6% using a bio-inspired filter designed to mimic the gill arch system of fish [76]. An alternative approach was proposed by Cabigliera et al. [50], who examined eight types of micro- and nano-magnetic particles (MNPs) applied at a concentration of 1.3 g L^{-1} in water for MF mitigation during the laundering of 5 kg of PET and PA-based textiles at 30 °C for approximately 30 min, under both laboratory and industrial washing conditions. The study reported MF removal efficiencies of 66.0% at the laboratory scale and 73% at the industrial scale. These results were attributed to interactions between MNPs and fibers that promote fiber entrainment and their migration toward a magnetized zone via a dragging mechanism. Under the tested washing conditions, the release of MFs was estimated at approximately 7.5×10^5 fibers per washing cycle.

4. Circular Pathways for Blended Polyester-Based Textile Waste

In the literature, secondary and tertiary recycling of post-consumer blended polyester textiles has been documented with the purpose of valorizing the entire or singular component of textile waste [19,21,51,77–87] as new fibers [9,19,55,88], adsorbents [89], fuel [10,90,91], and biocarbon [10,20,92,93], as well as the development of composite materials [7,78,94–96].

Table 1 contains examples of the valorization of blended polyester textile waste by mechanical, chemical, or biological technologies.

Table 1. Technologies for valorization of blended polyester-based textile waste.

Textile Composition	Technology	Circularity	Advantages	Ref.
		Mechanical Recycling		
Decolorized blended cotton/polyester (20/80, 35/65, 50/50) fabric waste	Hot-pressing; Pressing temperature was in the range 260–300 °C; Preheated time of 2–3 min; Pressure of 0.5 MPa; Pressing time of 3–5 min; 40 layers of textile waste	Composites for furniture industry (open-loop)	Adequate mechanical properties, consistent color dispersion, minimal moisture uptake, and enhanced thermal insulation capacity	[94]

Table 1. *Cont.*

Textile Composition	Technology	Circularity	Advantages	Ref.
Mechanical Recycling				
51% Polyester/49% cotton blended fabrics	Cutting mill followed by chemical and density separations	Recovered PET particles reused in different products; recovered cotton particles	Reduce the environmental impact	[77]
Polycarbonate/PET blend	Injection-molding; Processing temperature between 255 °C and 300 °C	Reduce waste and costs of textiles for interior cars	Tensile strength and impact resistance remain within acceptable ranges for interior automotive components	[7]
Knitted fabric of 35% cotton/65% PET textile waste; knitted fabric of 60% cotton/40% PET textile waste	Melt spinning	r-PET recovered for spun fibers	Good stability and mechanical properties	[19]
35% PET/65% cotton textile blend	Open-loop physico-mechanical recycling; two-step NaOH treatment followed by 60% solution of H_2SO_4 at 45 °C for 90 min	Nanocellulose as the reinforcement of the biodegradable film composites based on PVA and silver nanoparticles	Cellulose yield of 65.06 wt%; higher tensile strength of 2.37 MPa and elongation of 214% for the eco-friendly film	[78]
61% pure cotton, 29% cotton/PA blends, and 10% synthetic fibers, including PA, polyester–cotton, PP, and nylon	About 4 wt% of untreated, water-saturated, or NaOH-MFs treated were mixed with cement	Heat-insulating and load-bearing fiber-reinforced cementitious composites	Maximum bending load increased by 320%, toughness improved by 715%, and linear shrinkage reduced by 80%	[95]
90–98 wt% r-PET/2–10 wt% r-PA6 textile bends	Melt reprocessing with in situ reactive modification	r-PET and r-PA6 fiber waste are physically recovered and re-melted into new fibers	Hydrophilicity improved (the 90% r-PET/10% PA6 blend recorded a contact angle value of 80.3°)	[55]
Thermo-Chemical Recycling				
Cotton–polyesters blends	Torrefaction	Fuels and biocarbon	Reduce the energy requirement by 50–85%; Yield of liquid fuel and biocarbon of 35–65 wt% and 10–18 wt%, respectively	[10]
Cotton–polyester blend	Torrefaction; Seven temperature range of 225–375 °C; Four residence times from 1 to 4 h; Nitrogen atmosphere	Sustainable alternative fuel in the energy sector	Higher heating value (HHV) improved from 20.4 MJ kg^{-1} to 31.6 MJ kg^{-1}; Combustion reactivity of 0.8358 μg min^{-1} K^{-1}, comparable to lignite	[90]
Cotton/PET textile (mass ratio of 100:0, 65:35, 50:50, 35:65, and 0:100 wt%)	Co-Pyrolysis; Catalyst of MgO-CaO from oyster shells; 80 mL/min N_2 atmospheric; heating rate of 10 °C/min	Energy conversion by waste valorization	Fuel gas yields on co-pyrolysis and catalytic co-pyrolysis were 13.85 mmol/g blend and 19.66 mmol/g blend, respectively; heating value (HHV) on co-pyrolysis and catalytic co-pyrolysis were 276.87 kJ mol^{-1} and 304.68 kJ mol^{-1}, respectively	[91]
50% Cotton/50% polyester MFs (model sample)	Catalytic hydrothermal carbonization (HTC) (temperature of 200 °C, pressure of 22 bar, Fe-Ni catalyst)	Filamentous solid carbon nanostructures used in potential applications such as separations, electronics, and sensors	Increase in the amorphous phase from 46% to 87%; total heating value of 51,198 J g^{-1}	[20]
Cotton and polyester MFs (model sample)	HTC Optimal processing parameters: temperature of 300 °C, autogenous pressure of 85 bar; heating rate of approximately 5 °C·min^{-1}, residence time of 4 h; ratio between solid to solvent = 0.06:10	Filamentous graphene- and graphite-like nanocarbons (yield of 88%)	Potential applicability for large-scale treatment of textile MFs	[93]

Table 1. *Cont.*

Textile Composition	Technology	Circularity	Advantages	Ref.
Thermo-Chemical Recycling				
Blended polyester–cotton textile waste	Thermo-chemical process	Biochar; electrode material in supercapacitor	Specific surface area of 548–1106 $m^2\ g^{-1}$; triclosan adsorption capacity of 110.56 $mg\ g^{-1}$; removal efficiency up to five cycles	[92]
50% Cotton–50% polyester	Pyrolysis; Temperature in the range of 700–1000 °C; heating rate of 5 °C/min in N_2 gas; Gas holding time of 30 min	Conductive inks with applications in smart textiles	Good conductive properties (from 1.58×10^2 to $2.08 \times 10^2\ S\ m^{-1}$)	[97]
Chemical Recycling				
Blended cotton/PET textile waste	A superbase-based ionic liquid [DBNH] [OAc]; temperature of 80 °C	Man-made cellulose fibers for wet spinning of textile-grade fibers; recovered PET could be used for packaging applications	Similar performance of recovered cellulose with commercial products	[96]
80% Polyester–20% cotton; 95% Polyester–5% spandex	A mixed solvent of DCM/EtOH and KOH Temperature of 35 °C for 30 min	Recovery PET, cotton, and spandex fractions of waste; solvents can be recycled and reused	98.8% recovery of TPA monomer; Recovery rate of 99% for cotton and spandex	[79]
Blended polyester–cotton textile waste	Glycolysis and aminolysis	Conversion of polyester fraction into a functional hydrogel; closed-loop cellulose recycling	Dye removal efficiencies up to 81.2 ± 0.4% within 3 h for glycolysis and 97.4 ± 0.7% within 15 min via aminolysis	[89]
Polyester–cotton blends	Betain-based deep eutectic solvents (DESs) as catalyst; temperature of ~190 °C, reaction time of 45 min	Complete recycling of PET and cotton	Yield of 85% for bis (2-hydroxyethyl terephthalate) (BHET) monomer; 95% of the cotton was recycled	[80]
53% PET/47% cotton post-business textile waste bedsheets	Hydrophobic DES composed of menthol and benzoic acid (molar ratio of 3:1); Temperature of 216 °C, treatment duration of 5 min	PET fraction can be used for fiber re-spinning and various thermoplastic applications; recovered cotton is recommended for yarn production; environmentally friendly solvent	Recovery efficiency for PET and cotton of 97% and 100%, respectively	[21]
Blended polyester–cotton textile waste	NADES; Temperature of 110 °C for 3 h	Separated polyester and cotton; recovered PET used for filtration membrane fabrication	High recovery efficiencies for cotton and polyester: 98% and 99%, respectively	[81]
65% Polyester–35% cotton blend	Metal-salt-hydrate-based DES based on $ZnCl_2$, H_2O, and H_3PO_4 (molar ratio of 1:3:0.5)	Cellulose fibers can be regenerated through wet spinning; separated polyester fibers after blending and granulating can be regenerated through hot pressing or melt spinning	The rheological properties of the polyester fibers remained largely unchanged after recycling	[82]
80%PET/20% cotton textile, blue color	Binary solvent containing an ionic liquid (IL), 1-butyl-3-methylimidazolium acetate ([Bmim]OAc), and dimethyl sulfoxide (DMSO)	Polyester is recovered; cotton is recovered as regenerated cellulose fibers	Both fibers retain the original dyeing	[83]
52.2% PET/47.8% cotton T-shirt, white color	Aqueous cholinium lysinate ([Ch][Lys]); ratio between polycoton and IL was 1:2; temperature of 180 °C for 2 h	Cotton is entirely recovered; high yield of TPA for valorization	88% conversion of terephthalic acid (TPA)	[87]

Table 1. *Cont.*

Textile Composition	Technology	Circularity	Advantages	Ref.
Chemical Recycling				
Blended 50% PET/50% cotton textile	A switchable DBU/CO_2/DMSO solvent system Optimal conditions: temperature of 40 °C, CO_2 pressure of 5 bar, and 10 wt% amount of DBU	Polyester and cellulose components are recovered separately; precipitated cotton can be reused as regenerated cellulose; DMSO can be recovered	No depolymerization or degradation of PET	[84]
Pink T-shirt containing 47% PET and 53% cotton	Binuclear Zinc complexes (Zn_2L) as catalyst	Separated polyester and cotton	Cotton recovery rate up to 97.5%; effective on textiles regardless of color or cotton proportion; applicable to real-world polycotton garments	[85]
Mixed of PET, cotton, nylon, and elastane textiles	Microwave (MW)-assisted glycolysis; ZnO catalyst	Recovery of BHET precursor for repolymerizing PET; recovery of MDA, which is chemically transformation into methylene diphenyl diisocyanate (MDI), a precursor for spandex polymerization; separation and reuse of nylon and cotton	Avoid the sorting of mixed textiles	[86]
Biological Recycling				
Blended PET/cotton textile waste modified using cellulase enzymes	Microbial nanotechnology	Nano-biofilter	Removal efficiencies higher than 97% for total coliforms, 98% for *E. coli*, and 99.4% for *Salmonella*	[98]
55% PET/45% wool blended fabrics	Enzymatic process	Polyester yarn	New garments	[9]
Blended PET/cotton (50/50%) of fabric waste from H&M	Enzymatic hydrolysis (20 FPU/g commercial cellulase and 10 U/g commercial β-glucosidase)	PET fibers; Cotton is converted into glucose syrup	Applications in textile and other industries	[18]

4.1. Mechanical Recycling

Roungpaisan et al. [19] demonstrated a closed-loop fiber-to-fiber recycling strategy, in which mechanically recycled PET was recovered from blended polyester–cotton textile waste. In this approach, the textile waste was first defibrillated using a recycling machine, followed by pretreatment with a 85% H_3PO_4 solution to selectively dissolve the cotton component. An additional enzymatic treatment was then applied to degrade any residual cotton after acid extraction. Finally, the purified PET was re-melted and re-extruded into fibers, enabling its reintroduction into the textile production cycle. Similarly, r-PET/rPA6 waste fibers can be reprocessed and reintegrated into textile manufacturing, supporting a fiber-to-fiber circularity [55].

In contrast, several studies have explored open-loop material recycling strategies, where the recovered materials are converted into alternative value-added products rather than being reused in textile fiber production, meaning circularity is partial rather than complete. For example, the cellulosic fraction of polyester/cotton textile waste has been transformed into nanocellulose, as a reinforcing agent in biodegradable nanocomposite film based on polyvinyl alcohol (PVA), 5 wt% nanocellulose, and 0.3 wt% AgNPs as a potential alternative to conventional films. This ecofriendly material records a significant mechanical performance, with a tensile strength of 2.37 ± 0.32 MPa and elongation at break of 214.26 ± 44.91% [78]. Similarly, the fibrous textile plastic waste has been directly incorporated into green composite materials for construction applications [95].

Tang et al. [94] converted post-consumer cotton/PET blended textiles into composite material for furniture applications.

Polycotton textile waste has also been used as a precursor for synthesizing carbon black for printed electronic patches [97]. The resulting material exhibited superior electrical conductivity compared to commercial carbon black, attributed to its more ordered graphitic structure. This process is strongly temperature-dependent. Furthermore, the printed patches demonstrated an excellent washing stability, with their conductivity remaining nearly unchanged even after five washing cycles.

4.2. Chemical Recycling

4.2.1. Thermo-Chemical Recycling

Thermochemical conversion technologies offer promising alternatives for managing blended PET-based textile waste that is difficult to recycle through conventional mechanical or chemical methods, which use reagents to achieve depolymerization. Among these, pyrolysis, co-pyrolysis, torrefaction, and hydrothermal carbonization (HTC) have emerged as viable strategies for energy recovery and material valorization.

Pyrolysis provides an effective method for converting mixed waste streams into value-added products under oxygen-limited conditions. For instance, Kar et al. [92] proposed a novel strategy for transforming polyester-based textile fabric waste into surface-modified biochar used for triclosan adsorption. Khan et al. [97] expanded the application spectrum of post-consumer polycotton textiles beyond the textile sector by transforming polycotton waste through pyrolysis into carbon black, which enables high-value applications, particularly in smart textiles and printed electronic systems.

Co-pyrolysis enables the simultaneous thermo-chemical conversion of the natural (cotton) and synthetic (polyester) fibers present in blended textiles. This approach enhances the overall efficiency of waste valorization by exploiting synergistic interactions between biomass and polymer fractions. Oxygen-containing radicals generated from the biomass component facilitate C–H bond cleavage in the synthetic polymer, improving the degradation kinetics. Meanwhile, the higher hydrogen content of PET mitigates the typically high char yield and low volatile fraction associated with biomass alone. These interactions result in improved product distribution and energy recovery efficiency, demonstrating a clear synergistic effect during co-pyrolysis [91]. Wang et al. [91] introduce a novel strategy for valorizing fibers of different compositions from PET-blended textile waste through co-pyrolysis, reaching a maximum fuel gas yield of 19.66 mmol/g.

Torrefaction, a mild thermochemical pretreatment typically conducted at 200–375 °C under inert conditions, represents another promising pathway for textile waste valorization. Aljomah et al. [90] demonstrated that the mixed cotton–polyester shearing waste can be converted into a high-energy, low-emission solid fuel through torrefaction. The optimal biochar sample, obtained at approximately 350 °C for 4 h, exhibited high combustion reactivity (~0.836 μg min^{-1} K^{-1}), comparable to lignite coal, along with low ash (~1.8 wt%) and sulfur (~0.04 wt%) contents. These properties can contribute to SDG 12 (Responsible Consumption and Production) and SDG 7 (Affordable and Clean Energy).

Parrilla-Lahoz et al. [20,93] successfully upcycled model MFs composed of cotton and polyester collected from washing machine filters into high-tech carbonaceous materials via hydrothermal carbonization (HTC). During HTC, the MFs undergo a series of thermochemical transformations in the presence of water, including hydrolysis, dehydration, decarboxylation, aromatization, and deoxygenation reactions. These processes progressively convert the fibrous structures into carbon-rich materials with advanced functional properties. From a process design perspective, water reuse is an important consideration to enhance wastewater management and improve overall energy efficiency. Furthermore, the scalability of HTC is supported by existing industrial facilities that are capable of processing substantial quantities of biomass, indicating its potential applicability for the large-scale treatment and valorization of textile MFs.

4.2.2. Solvent-Based Recycling

A wide range of chemical valorization strategies for blended PET/cotton waste can be identified, including catalytic or switchable solvent systems for mild separation, chemical depolymerization into monomers and functional materials, ionic-liquid-based fiber separation and regeneration, and deep eutectic solvent (DES)-based separation approaches.

The degradation mechanism of PET involves chemical depolymerization (glycolysis) of the polyester chains into the monomer bis(2-hydroxyethyl) terephthalate (BHET). Depolymerization proceeds primarily through an endwise peeling mechanism, in which hydroxide ions attack the ester linkages at the polymer chain ends, leading to stepwise chain scission and the progressive release of monomeric products [99].

Using 25 g of ethylene glycol (EG) and 5 wt% [Betaine]$Zn(OAc)_2$ catalyst at 190 °C, 5 g of PET fiber were completely converted into bis(2-hydroxyethyl) terephthalate (BHET) within 45 min, achieving a BHET yield of 82.3% [80]. Concurrently, 95% of the cotton fraction was recovered, demonstrating an efficient and selective separation of both polymeric components. The betaine-based deep eutectic solvent (DES) acts as a catalyst in a mild glycolysis reaction, enhancing bond cleavage in the PET backbone under EG treatment conditions and converting the depolymerization of PET into BHET, while preserving cotton integrity.

Similarly, Zhang et al. [79] proposed a selective depolymerization approach to break down PET from textile blend waste into its monomers (terephthalic acid (TPA)) and EG at ambient temperature using a tailored solvent system consisting of dichloromethane (DCM) and ethanol (EtOH). This method eliminates the requirement for laborious pre-sorting and complex separation processes of PET blends, while also reducing the environmental impact, with an energy factor of 3697 °C x min and emissions of 1169.4 kg CO_2 equiv., which is less than one-third of that associated with traditional chemical hydrolysis. However, for industrial scalability, chemical safety concerns related to the use of volatile chlorinated solvent DCM must be addressed.

To prevent the degradation of individual components and enable the recovery and reuse of both fiber types, specialized solvent systems have been developed to selectively dissolve one component of polycotton textile waste. Using this approach, the cellulosic fraction can be recovered [96], while the PET component is depolymerized. For instance, chemical recycling of PET/viscose blends via alkaline hydrolysis has been demonstrated to effectively depolymerize PET, while preserving the cellulose fraction [99,100].

Building on this concept, an advanced valorization strategy for polycotton textile waste uses aqueous ionic liquids (IL) to selectively depolymerize polyester into TPA with yields up to 88%, while maintaining the integrity of the cotton fibers, allowing for the recycling of colored, mixed-textile streams [87]. This process also exhibits high biocompatibility and allows a one-pot approach for either conventional monomer recovery or direct biological upgrading.

In another study [82], a green and efficient method for separating polyester–cotton blends without damaging the polyester fiber was developed using a low eutectic solvent synthesized from $ZnCl_2$, H_3PO_4, and H_2O—Figure 6.

The experimental procedure (Figure 6a) entails immersing chopped polyester–cotton-blended textiles in a prepared $ZnCl_2/H_3PO_4/H_2O$ ternary cosolvent [82]. At ambient temperature, the cotton dissolves selectively, separating from the intact polyester fibers. The isolated polyester fibers, once cleaned and dried, are regenerated through melt spinning.

The resulting cellulose solution is subsequently coagulated in deionized water, filtered, and dried to produce regenerated cellulose powder suitable for wet spinning. This approach allows for efficient component separation and fiber-to-fiber circular recycling of polyester–cotton blends at the laboratory scale (Figure 6b). Observations of the solvent system (Figure 6c) indicate that the metal salt hydrate solvent is initially a colorless, transparent liquid. During dissolution, cotton fibers form a light brown, viscous cellulose solution, while polyester fibers retain their original shape and color.

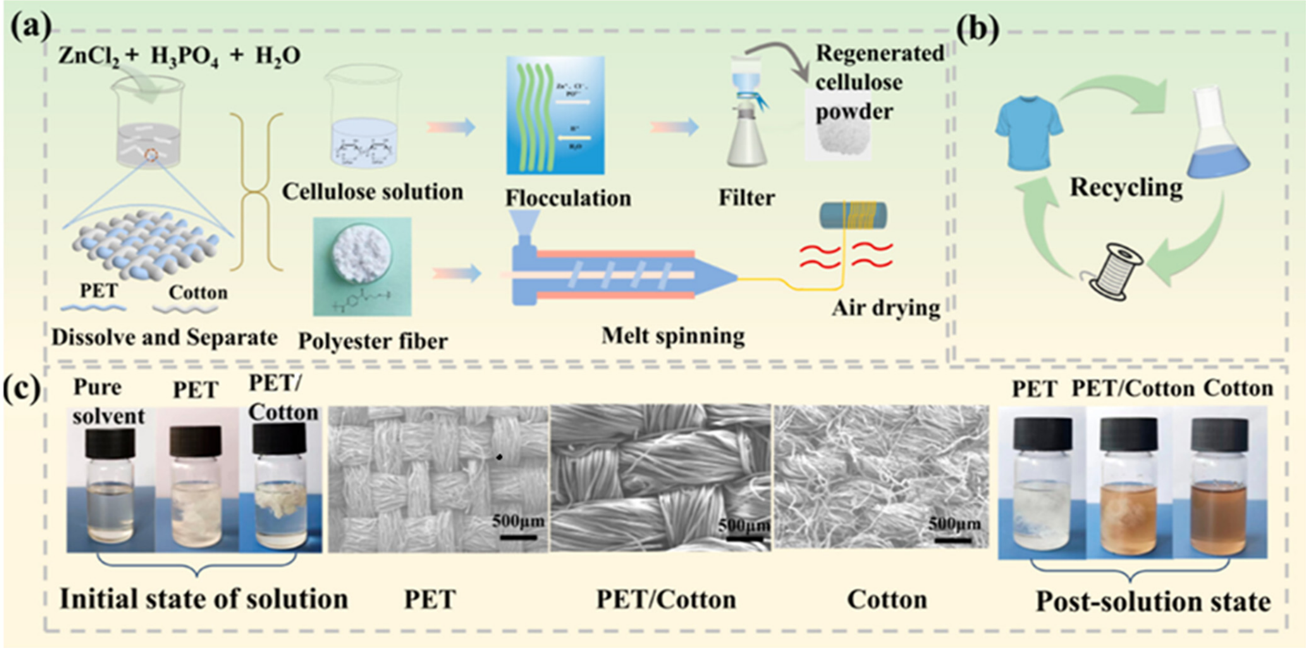


Figure 6. Controlled separation and reutilization of PET and cotton fractions from polycotton blended textiles (**a**); reprocessing and reutilization of the separated components (**b**); comparative study of textile dissolution in the $ZnCl_2/H_3PO_4/H_2O$ ternary solvent medium (**c**). Reproduced from [82] with permission from Elsevier.

A recent valorization strategy proposed by Jungbluth [84] used a switchable solvent system composed of 1,8−diazabicyclo [5.4.0] undec−7−ene (DBU), dimethyl sulfoxide (DMSO), and CO_2 to selectively dissolve and precipitate cellulose from polycotton textile blends without degrading the PET component. This innovative approach enables the intact recovery of both fibers. This method has the potential to increase recycling rates for mixed textile waste while reducing reliance on the hazardous solvents commonly used in conventional separation processes. DMSO is marked as flammable, an irritant, and a health hazard [25]. Different types of ILs have different toxicities and ecological footprints. The most relevant factor to their toxicity is the alkyl chain length of the cations. The longer the alkyl chain length of the cation, the more toxic the ionic liquids are.

The transition toward a circular economy for mixed PET/cotton garment waste was also demonstrated by a chemical separation and recycling process that used the superbase-based ionic liquid [DBNH][OAc] to selectively dissolve the cellulose component and transform it to new high-value fibers with fineness, strength, and elongation properties comparable to commercial Lyocell fibers [96].

Rosson et al. [83] developed a recycling-friendly coloration approach to treat both polyester and cotton from polycotton blends, in which the dye color is retained as a critical performance indicator of chemical separation. The difference in color (ΔE) between the original materials and the recovered materials was 3.7 for recovered polyester and 8.3 for regenerated cellulose.

Ara et al. [81] introduced a green and sustainable extraction method using natural deep eutectic solvents (NADES) to selectively dissolve and separate cellulosic cotton fibers from polyester in blended textile waste.

A significant advance in the chemical recycling of blended textile waste, offering a more efficient, less destructive, and widely applicable route toward circular textile materials, was presented by Wu et al. [85]. They proposed a mild alkaline hydrolysis process catalyzed by a binuclear zinc complex (Zn_2L) to separate cotton from polyester in polycotton blends. Unlike many recycling methods that degrade cotton fibers, this approach preserves the cotton's degree of polymerization and crystalline structure, resulting in recycled cotton with a quality nearly identical to the original material. Moreover, the use of the Zn_2L catalyst improved the separation efficiency by approximately sevenfold compared with traditional alkaline hydrolysis.

A highly promising approach to addressing the complex challenge of polycotton waste valorization is the integration of chemical and enzymatic processes, which allows for the selective deconstruction of cotton and polyester components [101]. This enables the recovery of high-purity PET monomers alongside fermentable sugars from the cellulosic fraction. For instance, Abdel-Gawad et al. [98] activated polycotton post-consumer with biosynthesized copper oxide nanoparticles in the presence of *Chlorella* microalgae in an ecofriendly process. This transforms waste into "smart" functional materials rather than low-value recycling outputs. Activation of the textile waste using cellulase enzymes increases surface carboxyl and hydroxyl groups, significantly improving the binding and durability of nanoparticle immobilization, even after multiple washing cycles. The *Chlorella*-CuO-NP-loaded textile waste functions as a nano-biofilter, capable of significantly reducing microbial contamination in wastewater. Such a dual recovery strategy not only maximizes material utilization but also provides versatile feedstocks for polymer repolymerization and bio-based chemical production, thereby supporting a closed-loop, circular economy for textile waste.

Manivannan et al. [89] developed a novel valorization route for transforming post-consumer polyester–cotton blended textile waste into functional hydrogels with strong adsorption capacity (up to ~379 mg g^{-1}) for anionic dyes, while simultaneously recovering cotton fibers as a second high-value product. The resulting hydrogels demonstrate rapid and efficient dye removal, achieving high removal rates within minutes to hours, and retain over 80% efficiency after multiple reuse cycles, highlighting their practical potential for wastewater treatment. Furthermore, the hydrogel exhibits pH-responsive behavior, with functional properties optimized through aminolysis, crosslinking, and the inclusion of activated carbon, enabling enhanced performance under realistic wastewater conditions.

Andini et al. [86] proposed another strategy for chemical recycling of mixed textile waste that contains polyester, cotton, nylon, and spandex, which typically cannot be recycled effectively by mechanical means. In a microwave-assisted glycolysis process, the mixed textile waste is treated with EG in the presence of a ZnO catalyst (Figure 7). Under optimized conditions, polyester can be selectively depolymerized within ~15 min to form bis(2-hydroxyethyl) terephthalate (BHET). Simultaneously, spandex is chemically broken down, yielding 4,4′-methylenedianiline (MDA). The remaining solid fraction primarily consisted of cotton (cellulose) and nylon (polyamide), which can then be separated by solvent dissolution based on their different solubility behaviors. Nylon can be dissolved in 90% formic acid while cotton remains insoluble, allowing efficient fractionation and recovery with different degrees of polymerization (DP). This approach leads to a textile circularity rate of 88%, avoiding the sorting of waste.

Thanks to advances in chemical recycling, textile waste valorization has evolved from simple separation processes into a multi-pathway circular economy framework, encompassing closed-loop fiber regeneration, selective solvent-based separation, chemical upcycling into monomers and functional materials, and integrated multi-component recycling systems.

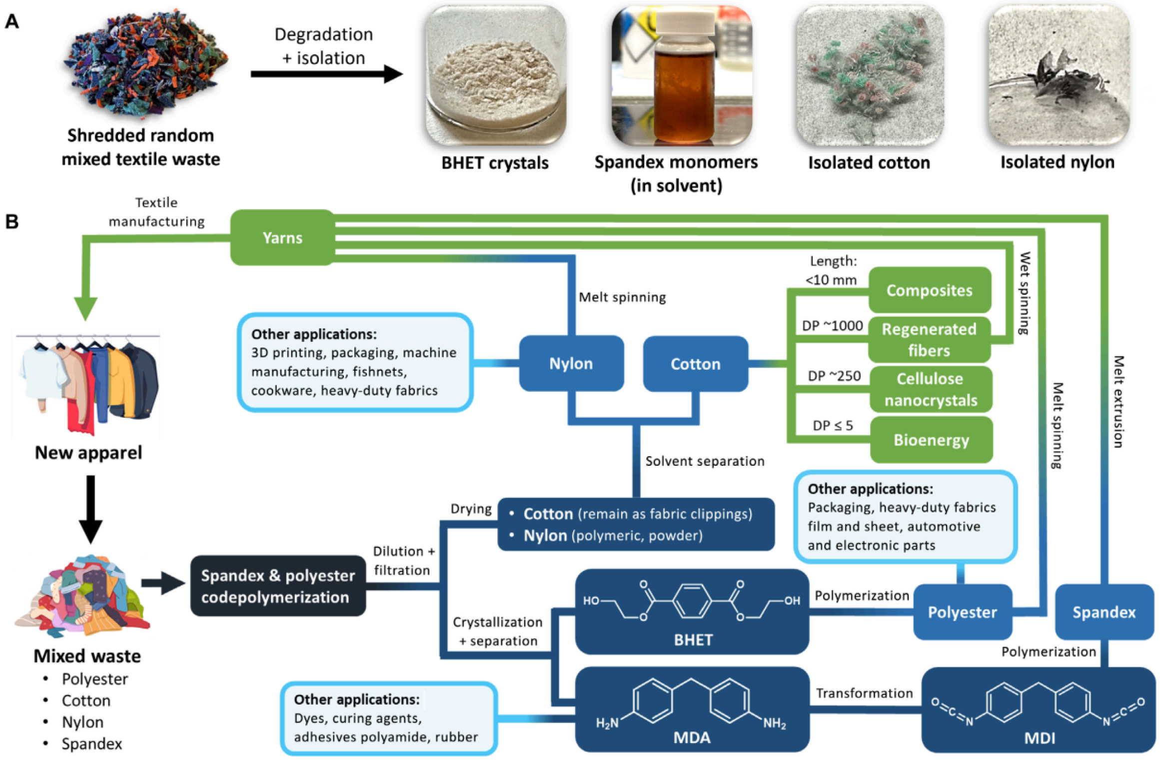


Figure 7. Recycling strategy of mixed textile waste with unknown composition. Isolated components (**A**); textile to textile and open-loop recycling (**B**) [86]. (Open Access).

4.3. Biological Recycling

Biological recycling of blended PET/cotton and PET/wool textile waste allows for valorization that ranges from functional environmental applications to fiber recovery and biochemical conversion.

To separate polyester from mixed polyester–textile materials, enzymatic and microbial nanobiotechnology [9,98] approaches have been used. Thus, PET MFs from blended polyester/wool fabrics can be recycled into yarn and reused in new garments or other products by using a keratinase, while nutrient-rich keratin hydrolysates derived from protein-based fibers may serve as microbial growth media, bio-fertilizers, or animal feed, supporting circular economy strategies [9]. Cellulase-treated PET/cotton textile waste is integrated into a microbial nanotechnology-based nano-biofilter system, where the modified textile structure serves as a functional filtration medium [98]. Rather than recovering fibers or monomers, valorization is achieved through functional upcycling, enabling wastewater treatment with very high removal efficiencies (>97% for total coliforms, 98% for *E. coli*, and 99.4% for *Salmonella*).

Subramanian et al. [18] conducted a systematic LCA of a 50/50 cotton/PET blended fabric waste sourced from H&M and subjected to a biological recycling process that simultaneously recovers PET fibers and glucose syrup. The bio-recycling process consists of three main steps: (i) pre-treatment of textile waste, during which the cotton fraction is prepared for enzymatic breakdown while the polyester component remains intact; (ii) enzymatic hydrolysis, in which the cellulosic cotton is hydrolyzed to produce glucose syrup; and (iii) melt-spinning of the remaining PET, whereby the recovered PET is melted and re-spun into new polyester fibers. The LCA results, based on a functional unit of 1 kg of recovered PET, indicate that pre-treatment is the most energy-intensive stage (207 MJ kg^{-1} PET recovered), followed by melt-spinning (98.5 MJ kg^{-1}), while enzymatic hydrolysis accounts for 44.8 MJ kg^{-1}. This approach represents a hybrid valorization strategy, combining partial closed-loop PET recovery with open-loop biochemical conversion of cellulose into platform chemicals.

Zangelmi et al. [102] developed an integrated green biorefinery strategy for valorizing polycotton textile waste (70% PET/30% cotton) through a sequential combination of mechanical pre-treatment, enzymatic hydrolysis, thermal processing, and microbial upgrading. Cotton was fully converted into glucose, while PET was efficiently depolymerized into TPA and EG, achieving a 98 ± 1% conversion. The recovered TPA was further upgraded via engineered *E. coli* into the high-value aromatic compound protocatechuic acid (PCA), demonstrating a strong potential for cascading valorization of both textile fractions. Overall, from 1 g of polycotton fabric, 500 mg of PCA are generated. Despite high product yields and process integration, the approach is currently limited by slow enzymatic kinetics, scalability challenges, sensitivity to real textile contaminants, and the need for improved enzyme efficiency and byproduct utilization.

4.4. Other Applications

Another direction for the valorization of blended polyester-based textile waste is its upcycling into high-performance rubber microfibrillar composites [57]. This cascade recycling avoids complex chemical separation processes, reducing additional chemical inputs and energy demand compared to depolymerization-based recycling routes.

A novel and facile chemo-thermo-mechanical approach was employed to produce extrudable pellets via a one-pot, TEMPO-mediated oxidation of post-consumer polycotton textiles. This was followed by a mild mechanical treatment without separating the individual constituents of the polycotton blend [103]. The resulting filaments showcase an innovative route for the upcycling of textile waste while leveraging the advantages of additive manufacturing. Furthermore, 3D-printed filters with tunable porosity were fabricated and evaluated for their efficacy in water treatment applications.

5. Prospects and Challenges

Post-consumer textile waste can be valorized through multiple recycling strategies, each offering distinct advantages, limitations, and performance outcomes.

Table 2 presents the advantages and disadvantages of blended polyester textile recycling.

Table 2. Advantages versus disadvantages of circular approaches of blended polyester-based textile Waste.

Recycling Type	Advantages	Limitations/Challenges	Quantitative/Notable Metrics	References
Mechanical Recycling	Readily available infrastructure; low operational cost; reduces energy, water use, and environmental impact	Limited fiber separation efficiency; low mechanical integrity of recycled fibers; fiber leaching during processing; polymer contamination and degradation; insufficient traceability and automated segregation; requires preliminary sorting	Up to 60% material retrieval efficiency; ~30% mitigation of GHG emissions	[12,32,35,52,76,104,105]
Chemical Recycling	Achieves >90% resource recovery; more suitable for blended textiles	High cost of solvents and requirement for high-purity solvent recovery; strict pollution control needed	High recovery efficiency of feedstock	[32,47,52,105]
Thermo-chemical Recycling (Pyrolysis/Torrefaction/HTC)	Processing unsorted textiles; produces bio-oil, syngas, or hydrochar; converts blended fibers into energy and/or carbon materials	Potential formation of hazardous by-products; high temperatures and energy input required; water management and scalability considerations	Energy valorization via bio-oil, syngas, or HTC; high combustion reactivity and low ash content of HTC	[10,91,106]

Table 2. *Cont.*

Recycling Type	Advantages	Limitations/Challenges	Quantitative/Notable Metrics	References
Biological recycling	Environmentally friendly, low chemical use; selectively depolymerization of PET using enzymes	High crystallinity of PET hinders enzymatic degradation; requires moderate-to-high temperatures for efficiency; high operational costs and long reaction times	Enzymatic PET hydrolysis yields vary depending on polymer crystallinity and enzyme type	[47,52]

Mechanical recycling benefits from established infrastructure, low operational costs, and reduced energy and water consumption compared to virgin material production, thereby lowering the overall environmental impact. It can achieve up to 60% material retrieval efficiency and mitigate approximately 30% of greenhouse gas (GHG) emissions. Replacing of virgin PET and PA with their recycled types directly supports SDG 12 on sustainable consumption and production, while also contributing to other interconnected goals, including clean water (SDG 6), affordable energy (SDG 7), sustainable cities (SDG 11), climate action (SDG 13), life on land (SDG 15), decent work and economic growth (SDG 8), zero hunger (SDG 2), and good health and well-being (SDG 3) [35,39]. By substituting virgin resources, recycling lowers carbon and wastewater emissions, decreases solid waste generation, and reduces the consumption of water, energy, chemicals, and arable land.

However, mechanical recycling's effectiveness is significantly constrained by several technical limitations [12,32,35,52,77,104,105]. These include low efficiency in separating blended fibers, progressive degradation of polymer and fiber quality, and reduced mechanical integrity of recycled fibers. These lead to contamination, inefficient processing, and reduced recycling yields. Polycotton is the least identifiable fraction because it is prone to moisture noise, oily buildup, and the spectral obscurity of small, dark, and grey items [107].

These bottlenecks are prevented by emphasizing the implementation of improved separate collection systems, which ensure higher purity of input materials and reduce the need for intensive downstream sorting. The findings indicate that enhancing the separate collection of textile waste from 14% to 40%, coupled with the implementation of recycling, can substantially mitigate environmental impacts. Notably, reductions of up to 24% in fossil resource depletion are observed, along with significant decreases in climate change potential and freshwater ecotoxicity, largely driven by the reduced demand for virgin material [108].

To improve recycling process efficiency and reduce the losses associated with mixed-material treatment, a fiber-specific waste routing has been proposed, where cotton and polyester streams are directed toward dedicated recycling or reuse pathways.

Energy-demanding separation processes, expensive functionalization steps, and dependence on additional resins constitute major challenges in textile waste valorization and composite manufacturing [94]. To overcome these limitations, a resin-free processing approach has been introduced, utilizing direct hot-pressing under optimized thermal conditions to produce high-performance composites without chemical binders or functional additives. To ensure good dispersion of the recovered cellulose in nanocomposite materials, a two-step alkaline and acid hydrolysis process applied to polyester–cotton textile waste enables selective cellulose recovery for nanocellulose production, resulting in improved reinforcement performance and higher-value composite film applications [78].

To avoid the high temperatures required for PET melting, Hou et al. [77] proposed a feasible approach for separating cotton and polyester from mixed textile particles after size reduction, thereby facilitating subsequent material recovery.

Other critical challenges include insufficient traceability of textile compositions and the lack of automated sorting and segregation systems. The proposed solution is the development of an enhanced sorting infrastructure and better waste management logistics, including improved identification and pre-treatment of textile fractions before recycling [108].

In addition, the degradation of fiber quality during recycling is addressed indirectly through a strategic shift toward reuse prioritization over recycling, which extends product lifetime and reduces the frequency of fiber processing cycles. This approach minimizes the mechanical and chemical degradation associated with repeated recycling steps.

This study reveals that, if MF emissions contribute to the broader environmental problem of textile waste, only a small fraction of garments is collected for reuse or recycling. Owing to the mechanical characteristics of the recycling process, MFs are expected to form during the shredding stage. These particles can subsequently be discharged into the environment via effluent streams generated during washing procedures. Reported production rates of microplastics within the 0.212–1.18 mm size fraction range from 1.1 to 5.8 g per kg of processed plastic material [109]. The absence of standardized procedures not only hampers the reliable quantification of MF emissions but also limits the development of mitigation strategies, regulatory frameworks, and life cycle assessments. Establishing uniform testing protocols, including controlled washing conditions, fiber identification, and reporting units, is therefore critical to generate reproducible and comparable data across laboratories, textile types, and washing conditions, ultimately supporting evidence-based solutions to microfiber pollution.

Finally, conducting a life cycle assessment (LCA) study could ensure that reuse and recycling strategies are evaluated based on their overall environmental performance, rather than isolated technical efficiency. A life cycle assessment (LCA) assessing the environmental impact of r-PET textiles manufacturing in Pakistan reported a relatively high human carcinogenic toxicity potential of 105.36 kg 1,4-DCB eq., together with a relatively low global warming potential (GWP) of 3.43 kg CO_2e [24]. The corresponding life cycle costing (LCC) analysis estimated the total production costs at approximately USD 28,000 per ton, of which 39.5% was linked to dyeing and finishing processes [24]. The study further demonstrated that substituting electricity generated from heavy fuel oil with solar energy could reduce GWP by 5–6%. In addition, adopting a 50:50 blend of r-PET and virgin cotton fibers significantly lowered the environmental burdens across all evaluated impact categories, including a 14% decrease in water consumption.

A comparison between 100% cotton and 50/50 polyester–cotton textile waste conducted by Morizet-Davis et al. [110] using modular bioenergy with carbon capture and storage (BECCS) technology showed that the polycotton achieved a higher energy output and a lower average cost of electricity (LCOE), approximately USD 0.17/kWh. In contrast, 100% cotton is more advantageous for carbon sequestration, achieving a carbon removal efficiency of about 91%, compared with 59% for polycotton. This result is due to the fully biogenic origin of carbon from cotton. However, the environmental performance of both textile compositions exceeded that of landfill disposal across most assessed impact categories.

Key bottlenecks identified in the thermo-chemical conversion of the polyester blended textile waste, such as pyrolysis, torrefaction, and HTC, include feedstock complexity, separation technical barriers, elevated temperature requirements, significant energy input, and the potential formation of hazardous byproducts. These thermal strategies enable the transformation of degraded, mixed fibers into high-value energy products like syngas, bio-oils, and char, while offering decentralized processing options [106]. These strategies, often combined with pretreatment, allow for the valorization of heterogeneous, post-consumer textile mixtures into chemical feedstock. Hydrochar produced via HTC can exhibit high combustion reactivity and low ash and sulfur contents, supporting energy recovery and circular economy objectives [90].

Chemical recycling provides high resource recovery rates exceeding 90%, making it particularly suitable for blended textiles. Its main challenges include high solvent costs, the need for high-purity solvent recovery, and strict pollution control measures. The extraction parameters need to be optimized with respect to temperature, CO_2 pressure, and the purity of the reused chemicals. The solution to avoid highly corrosive or toxic chemicals typically used in textile recycling is to use natural deep eutectic (NADES) solvents, a cutting-edge green solution for separating polycotton [81]. NADES are eco-friendly, biodegradable, and often derived from natural, non-toxic components, making them a more sustainable alternative to conventional chemical solvents [111]. This approach has achieved recovery rates of up to 98% for cotton and 99% for polyester, with the recovered PET maintaining its structural integrity for reuse in new products like filtration membranes [81]. Beyond separation, betaine-based NADES have been used to catalyze the selective degradation of PET into its monomer, BHET, with yields around 85%, while keeping the cotton fraction structurally sound [80].

In addition, the influence of impurities introduced by textile waste on the extraction process must be addressed. A limited number of plasticizers, specifically bis(2-ethylhexyl) phthalate (DEHP) and dibutyl phthalate (DBP) at concentrations of 5 $\mu g\ g^{-1}$ (under the European Union regulatory limits), were identified in cellulose nanoparticles derived from post-consumer cotton [112]. Conversely, the recovered polyester sequestered 829 significant chemical features, 65% of which occurred at markedly higher levels in the polyester residue [112]. Consequently, this fraction may be precluded from sensitive applications (such as food-grade packaging or medical textiles) due to the elevated risk of hazardous leaching.

With respect to a highly sustainable process, the amount of chemicals required for dissolution and precipitation must be minimized. In the long run, the use of bio-based alternatives for DMSO is advised [84].

Biological recycling leverages enzymatic depolymerization for selective PET breakdown, offering an environmentally friendly route with minimal chemical use. Its application is challenged by the high crystallinity of PET, which limits enzymatic efficiency, as well as high temperature requirements, extended reaction times, and elevated operational costs.

Recent regulations reflect an increasing political commitment to addressing textile sustainability and microfiber (MF) pollution, yet significant technical gaps remain. While the EU's Strategy for Sustainable and Circular Textiles (2022) mandates durability, reparability, and recyclability, and jurisdictions such as California and France require labeling or filtration to curb MF emissions, these measures largely manage impacts downstream [13]. In contrast, effective upstream solutions, such as scalable textile redesign, low-shedding materials, and commercially viable recycling technologies for blended fabrics, remain technically immature or unavailable, highlighting a persistent disconnect between regulatory goals and technological readiness [8].

While several pilot and pre-commercial solutions are under development, recycling has not yet demonstrated scalability or consistent fiber-to-fiber outcomes. As a result, blended textiles continue to represent a significant barrier to circularity in the fashion and textile system.

Furthermore, the implementation of a new recycling infrastructure can create employment opportunities, promoting socio-economic development alongside environmental sustainability. For example, innovative catalytic approaches, including photocatalysis, advanced oxidation processes, and biotechnological methods, could be promising and environmentally sustainable strategies for converting MFs into less harmful and potentially value-added products [113,114]. Furthermore, research is needed to develop effective methods for capturing MFs and fibrils during the textile recycling process. Collectively, these initiatives illustrate how the textile industry can leverage recycling to advance a circular economy while contributing to the overall wellbeing of both people and the planet.

6. Conclusions

This review highlights the critical challenges and opportunities associated with the management of blended PET-based textile waste, with a focus on recycling strategies and the mitigation of microfiber release. The most studied PET-based textiles are those containing cotton and polyamide.

The separation of cellulose and PET from polycotton blends remains highly challenging due to the intrinsic structural and chemical complexity of these materials, particularly the difficulty in identifying a single solvent or processing method capable of selectively dissolving one component without affecting the other.

Overall, mechanical, chemical, and biological valorization routes contribute to circular economy objectives by recovering polyester and regenerative cellulose, energy or producing functional materials from textile waste streams.

Incremental improvements, such as partial substitution with recycled fibers, renewable energy adoption, and thermochemical valorization, can significantly enhance resource efficiency and contribute to the Sustainable Development Goals that address a responsible textile industry.

Future work should, therefore, focus on pilot-scale demonstrations, techno-economic assessments, and life cycle analyses to facilitate industrial-scale implementation of this environmentally beneficial process.

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