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ORIGINAL RESEARCH

Recycling Strategies of Post-Consumer Textile Waste - A comprehensive review

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Abstract

Post-consumer textile waste (PCTW) is an increasing environmental issue, yet less than 1% of the global fiber-to-fiber recycling rate is reported. This review represents an overview of existing recycling strategies (mechanical, chemical and biological) and addresses their technology readiness level (TRL), environmental impact and economic feasibility. Mechanical recycling is well established but limited by fiber degradation and downcycling. Chemical pathways, like depolymerization and dissolution-regeneration, achieve high-purity monomer and fiber recovery though solvent recovery and energy intensity represent formidable challenges. Biological recycling of cotton polyester blends through enzymatic processes faces scalability and cost challenges mainly due to the high price of enzymes and their limited reusability. The process is relatively slow and often requires strict control of temperature, pH, and mixing conditions when scaled to industrial levels. Additionally, pre-treatment and product separation steps increase operational complexity and overall processing costs. Blended fabrics, elastane content, and finishing agents affect all these methods and emphasize the requirement for enhanced pretreatment and blend-tolerant chemistries. Standardized LCA and TEA are crucial for performance benchmarking and policy-level guidance. This review concludes a direct focus on upcoming priorities in solvent recovery, biocatalysis and design for recyclability to enable the transformation towards a circular textile economy.

Keywords: Post consumer textile waste, Textile Recycling, Sustainability, LCA

1 | INTRODUCTION

Textile consumption and production have increased in recent decades due to growing disposable incomes and consumer demand for affordable fashionable clothing widely known as fast fashion, which has made it possible to design and produce textiles quickly with a short shelf life. As a result, post-consumer textile waste (PCTW) is now widely considered one of the most significant environmental problems, and the majority of unwanted clothing is ultimately sent to landfill or incineration streams, leading to greenhouse gas emissions, degradation of resources, and release of extra chemicals [11, 12]. Recycling is one such way of moving towards a circular economy for textiles, but recycling rates are still low, especially for fiber-to-fiber closed-loop reuse [13]. The fact that textile waste is diverse, such as cotton, polyester, polyamide, elastane, and their complex mixtures with dyes, coatings, and finishing, makes recycling textiles a major challenge [14]. Mechanical recycling is commonly used, but short fibers with low recycling value are produced frequently [15]. Chemical recycling, for example, depolymerization or dissolution processes, provides the possibility of generating high-quality monomers and recycled fibers; however, these methods are energy-intensive and influenced by contaminations [16]. Biological recycling with enzymes (e.g., PETase, cellulases) has lately arisen as a low-energy solution with potential for selective fiber recovery [17, 18]. Technical bottlenecks still persist with efficient sorting of mixed textiles, removal of elastane or finishes, scalability, and the absence of a harmonized environmental and economic assessment. Life cycle assessments (LCA) and techno-economic analyses (TEA) have shown some potential benefits of closed-loop recycling, but the lack of consistency among the methodologies and information on feedstock makes it difficult to compare between them and to make decisions [19]. The aim of this review is to contribute to such a comprehensive understanding of PCTW recycling scenarios with the focus on technical readiness, environmental performance, and product quality. In contrast to previous review work concentrating on an individual pathway or polymer type, the present study systematically investigates mechanical, chemical, as well as biological recycling, including pretreatment issues, blend compatibility, and industrialization uptake. By consolidating current knowledge and identifying research needs, the present work seeks to direct researchers, policymakers, and industry decision-makers toward scalable, sustainable, and high-value recycling routes for post-consumer textile waste.

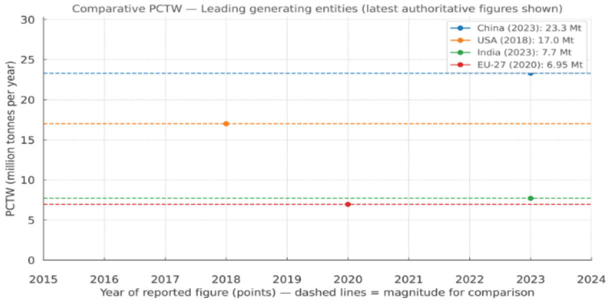

Figure 1: Global Scenario Post-Consumer Textile Waste (2015–2024)[2, 4, 5]

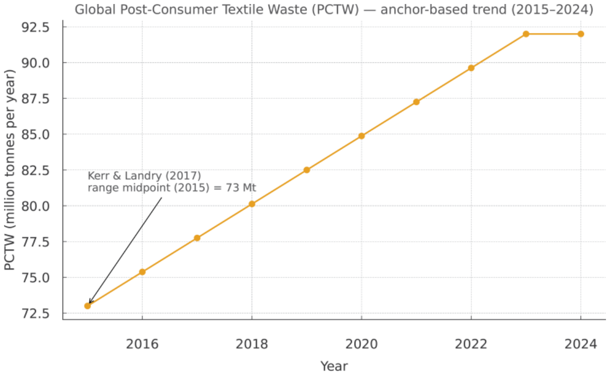

Figure 2: Comparative PCTW of Leading Generating Entities[4, 5]

2 | THE POST-CONSUMER TEXTILE WASTE LANDSCAPE

2.1 | Generation & Composition

Post-consumer textile waste (PCTW) mirrors the global fiber mix, with synthetic fiber, mainly polyester surpassing cotton production in volume worldwide and resulting in PCTW flows filled with polyester and polyester/cotton blends. This migration resulted in an increasing utilization of polyester and polyester/cotton blends within the overall PCTW streams [20]. The fields of the waste streams, blended fabric with polyester/cotton, cotton/viscose, and knits with 2–8% of elastane are conventional. These mixtures scatter fiber length, complicate the mechanical recycling process, and prevent chemical depolymerization unless specific elastane removal or degradation conditions are met [20]. Zippers, buttons, labels, interlinings, and coatings are some examples of non-textile parts that can contribute metal and polymer contaminants. They can damage machinery, and raise pre-processing requirements [21]. Recycling is made more difficult by dyes, prints, and finishes like resins, softeners, antimicrobials, and durable water repellents (DWR). When these fibers are recycled into new fiber, it is necessary to remove or control the color to ensure both the color and purity of the final product. Consequently, removing dyes and finishing is an essential part of pretreatment for both cellulosic and synthetic recycling streams[22]. Automated fiber identification using NIR, Raman, and hyperspectral systems (e.g., Fibersort, SIPTex) are improving sorting, yet accuracy still suffers under dark colors, moisture, coatings, and complex blends, limiting blend ratio quantification at industrial throughput [1]

2.2 | Collection Systems & Logistics

There are, therefore, two primary collection models: municipal networks (bring-banks; curbside and civic drop-off) and brand/retailer take-back. For European countries, the reuse of textiles is enshrined since it is legislated in the revised Waste Framework Directive (January 2025), and member states are forced to optimize logistics [23]. Brand take-back (in-store, mail-back) also expands but still represents a low volume percentage and often integrates into municipal collections; while those schemes do deliver cleaner input they rely on strong reverse-logistics set-ups as well as transparent end-markets to guarantee recycling rather than an export or burning [24]. The contamination is ongoing: Moisture, mold, food, dirt, and nanofiber debris add to the loss of quality and drive-up cost. Textiles collected from mixed waste streams are also more contaminated than vetted systems, which leads to reduced reuse rates and recycling [25]. The informal sector, especially in LMICs, is a key component of collection, sorting, reuse, and trade in timber. Lessons from such markets, like Kantamanto in Ghana, where the financial value and challenges of unsellable textile overflow have been illustrated, indicate that integrating the informal with the formal can improve capture and traceability for social benefit [25].

2.3 | Value Chain Mapping

The PCTW value chain consists of several key stages: Consumer discard → Collection → Primary sorting (reuse vs recycling) → Secondary sorting by fiber, content, and color → Pre-processing (de-trimming, decolorization, size reduction) → Recycling route (mechanical, chemical, thermal) → Intermediates (staple fiber, pellets, regenerated pulp, monomers) → Re-manufacturing (spinning, fabric formation) → Finished product. [1] Quality checkpoints play a vital role: intake triage removes soiled items, identification technologies sort materials, content verification adjusts blend thresholds, and preprocessing ensures the elimination of trims and decolorization. The process-entry gates inspect fiber length, intrinsic viscosity, or contamination levels before moving forward, all of which impact yield and product quality. [1, 26] Scaling recycling necessitates addressing three systemic gaps: (i) improving feedstock quality through enhanced collection or optical sorting; (ii) implementing design-for-recycling strategies that feature removable elastane and simplified trims; and (iii) providing policy support such as EPR fee adjustments, bans on the destruction of unsold goods, and consistent labeling to aid in traceability and material data [3, 27]

3 | SORTING & PRE-PROCESSING

The processes of sorting and preprocessing are fundamental to any method aimed at achieving high-quality recycling of post-consumer textile waste. Sorting is crucial as it affects the purity of materials downstream, which in turn determines the viability of mechanical, chemical, or blended-valorization routes. This section brings together the current state of practice and recent technological developments in manual and automated sorting, disassembly and decontamination, quality metrics that are significant for recycling pathways, and a pragmatic decision matrix for choosing preprocessing steps across various fiber types and blends.

3.1 | Manual sorting & grading

Manual sorting and grading continue to be prevalent in commercial operations due to the ability of human operators to swiftly make contextual assessments regarding garment categories, visible contamination, construction, and the necessity for accessory removal. Common manual grading categories employed at scale encompass: 1. Monomaterial (e.g., 100% cotton, 100% polyester), 2. Dominant-blend classes (e.g., ≥ 70% PET/≤ 30% cotton), 3. Color families, 4. Garment types (knit, woven, denim, outerwear); classifications that strike a balance between processing ease and market demands for high-value recycled feedstocks [28]. While manual grading is proficient at gross segregation, it is labor-intensive and exhibits variability in accuracy; operator fatigue and the significant proportion of blended garments in post-consumer streams diminish achievable purity unless supplemented by standardized protocols and quality checks. Pre-treatments implemented during manual sorting processes (e.g., hardware removal, gross soiling pre-wash, targeted wetting/oiling) have been shown to significantly affect the mechanical opening phase and the final distribution of fiber length. For instance, lubricant pre-treatment reduces inter-fiber cohesion and lessens fiber shortening during mechanical tearing, thereby enhancing the spinnability of the recovered fiber fraction. These operational strategies augment the proportion of spinnable fiber and enhance the economic viability of closed-loop applications for mechanically recycled yarns [28]

3.2 | Automated identification: spectroscopy, vision & digital tags

Automated identification platforms are evolving swiftly and have become crucial for scaling high-purity streams. Near-Infrared (NIR) spectroscopy, which encompasses line-scan NIR and NIR hyperspectral imaging, has developed to a stage where industrial prototypes can accurately predict the polyester/cotton content and identify pure monomaterials with encouraging throughput. Nevertheless, performance diminishes when dealing with intimate blends, textured knits, heavily finished or soiled textiles, and dark or dyed substrates where absorption features are obscured. Recent studies indicate that NIR-based sortability transfers effectively to polyester-containing lines when calibration sets accurately represent real waste variability. But blend quantification is still the bottleneck in closed-loop PET recycling, unless it is complemented by further sensors or pre-treatment [1, 2, 28]. When used in combination with machine learning (ML), Raman has demonstrated a higher level of compositional resolution in complex blends, due to its clearer molecular fingerprints than broadband NIR. When paired with ANN/CNN models, Raman classifiers have achieved over 95% grouping accuracy in laboratory environments, including precise blend class assignments at nearly realistic throughputs [29]. The practical challenges associated with vibrational spectroscopy include fluorescence interference, particularly in heavily dyed or dark garments, the necessity for effective background correction, and the integration of rapid sample presentation on industrial conveyors. Multimodal sensor set-ups (e.g., NIR with Raman or computer vision for label and trim recognition combined with AI fusion models) appear to be the most attractive option for the classification of heterogeneous post-consumer streams at industrial rates [2, 29]. If available, the lack of ambiguity can be overcome with digital product passports (DPP), RFID and on-garment QR tags, but the uptake in legacy waste and fast fashion flows is low. Such systems, which combine manual pregrading with sensor sorting along with selective human QC (quality control), represent the best compromise between throughput and purity for challenging chemical recycling applications [2, 29]. Overall, Automated textile identification technologies such as Near-Infrared (NIR) spectroscopy can effectively sort polyester containing materials, but their accuracy decreases for complex blends, dyed, or heavily finished textiles. Raman spectroscopy combined with machine learning provides higher compositional accuracy, achieving over 95% classification in laboratory conditions, though challenges like fluorescence and industrial integration remain. Therefore, multimodal sensor systems (e.g., NIR, Raman, and AI based vision) with human quality control are considered the most effective solution for high purity textile sorting in recycling processes.

3.3 | Disassembly & decontamination

Disassembly, which involves hardware removal, seam-cutting, and selective unpicking, along with decontamination processes such as washing, decolorization, and chemical stripping, are crucial preprocessing steps that have a significant impact on the recycling pathways that remain viable. The processes of trims and hardware removal are largely manual for complex garments; however, there is a growing trend towards automation in seam-ripping and robotic pick-and-place for high-volume categories like jeans and sportswear. In the context of chemically sensitive downstream processes, such as enzymatic hydrolysis or solvolysis, it is essential to remove non-fibrous components, including zippers, elastics, and coatings, to avoid catalyst poisoning and to maintain polymer recovery yields [2, 9]. Decolorization and dye removal are frequently required to enhance the value of colored cotton and cellulose streams, converting them into regenerated cellulose or pulp-grade feedstocks. Advanced oxidation methods, including Fenton, photo-Fenton, and persulfate processes, as well as reductive decolorization protocols, have been shown to achieve high efficiencies in color stripping from reactive-dyed cotton. However, these methods can partially oxidize or depolymerize the cellulosic matrix, which may lead to a reduction in mechanical strength and thus affect mechanical recycling yields. Recent studies on controlled Fenton-type discoloration have indicated that significant color removal can be achieved, but this often results in lowered tensile properties and some fiber shortening, which must be balanced against the increased value of whitened feedstock for closed-loop reuse [30]. As a result, process selection necessitates a comprehensive understanding of the acceptable strength loss for the intended downstream product.

Fiber Type / Blend	Recommended Sorting Method	Key Pre-Processing Steps	Purity Target	References
100% Cotton	NIR spectroscopy; manual visual inspection of any contaminants or foreign matter	Buttons/zippers removal, shredding, metal detection	≥ 95% cellulose for dissolution/ hydrolysis	[31, 32]
100% PET	NIR spectroscopy; density separation	Label removal, washing, flake preparation	≥ 98% PET for glycolysis/ methanolysis	[33, 34]
PET / Cotton blend	NIR spectroscopy with blend ratio estimation	Mechanical separation, removal of non-textile parts	≥ 90% pure polymer for chemical route	[35, 36]
PET / Elastane blend	NIR spectroscopy; elastane detection via FTIR	Pre-treatment of elastane removal (solvent or thermal), washing	≥ 95% PET for chemical depolymerization	[37, 38]
Wool blend	NIR spectroscopy; burn test confirmation	Dehairing, scouring, synthetic contaminants removal	≥ 90% protein fiber for enzymatic hydrolysis or selective dissolution	[39-41]

Table 1. Sorting/Pre-processing Decision Matrix

4 | MECHANICAL RECYCLING

4.1 | Shredding, opening, re-spinning

Because of its adaptability and minimal capital needs, spontaneous recycling of post-consumer textiles (PCT) is often used to keep clothes out of landfills. However, a significant technical limitation arises from the damage to fibers caused by the reduction in size. Cutting, ripping, and opening lower staple length boosts surface fibrillation and raises the ratio of short fibers and microfibers, thereby compromising spinning efficiency and yarn strength[28]. The main trade-off in mechanical routes, gentler opening preserves length but retains more contamination and neps, therefore influencing downstream processing is managed by shredding and opening steps. Conversely, higher throughput and coarser comminution improve mean fiber length and decrease tensile characteristics while also increasing mass recovery. Pre-treatments, including lubrication and regulated humidity, help to minimize length loss during carding and opening by lowering inter-fiber friction and breakage. These improvements to the process can raise downstream yield without significantly lowering throughput[28]

In figure 3, The figure shows the degradation of fiber quality during mechanical textile recycling. As the number of recycling passes increases, mechanical actions such as shredding and opening damage the fibers, causing a reduction in their properties. The solid line indicates the decrease in mean fiber length, while the dashed line represents overall damage from shredding/opening processes. After several recycling cycles, fiber properties drop significantly, limiting their reuse without blending with virgin fibers. Mechanical fiber streams are mixed with some virgin fibers once opened, sorted by kind, and either re-spun or turned into non-woven webs. Rotor spinning is preferred for high recycled content yarns since it can handle shorter staples and greater nep counts than ring spinning. Ring spinning produces stronger, smoother yarns but needs tighter process control and longer fiber lengths. Studies show trade-offs between the rotor's yield and structural performance; hence, the rotor is preferred in order to maximize recycled content[42, 43] Mechanical recycling systems have to accommodate different qualities of fibers and choose the right spinning technology and mixing ratios to match what the product needs. While knitwear and fine woven goods typically call for combining with virgin fiber or restoring fiber length, denim and non-woven insulation can accept lower tensile qualities and therefore permit larger recycled fractions [42, 43]

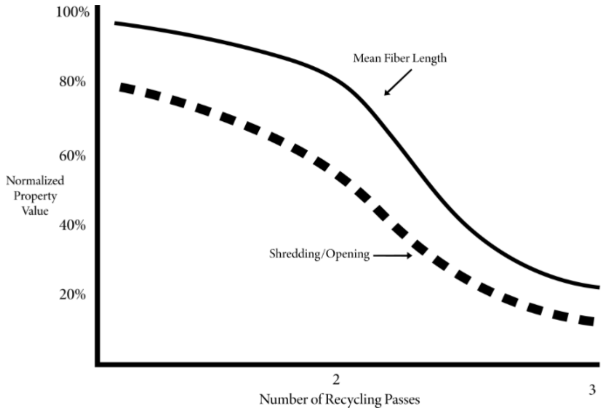

Fig 3: Mechanical Recycling Quality Degradation Curve [10]

4.2 | Shredding, opening, re-spinning

Mechanical recycling outputs are very fiber dependent. For uses like stuffing and low-quality yarns where structural integrity is not required, natural cellulosic fibers like cotton and wool can survive harsh processing. But with every recycling cycle, their length and strength diminish. Consequently, recycled cotton is usually downcycled into nonwoven or mixed yarn items instead of being recycled into closed-loop textile-to-textile processes [43, 44] By shredding and thermomechanical recycling, including melt extrusion and re-spinning, synthetic fibers like polyester and nylon can be mechanically recovered. This approach better retains polymer properties compared to cellulose-based materials. However, elastane fibers, dyes, and pollutants can compromise melt quality and color consistency. Thermomechanical methods sometimes call for eliminating non-polyester components or sorting feedstocks when excellent filament is required. Thus, unlike blended cotton/polyester fabrics, which have to be separated before recycling can efficiently continue, polyester works better for thermomechanical closed-loop recycling, especially when converting bottles into fiber[1] Open loop end-uses (such as nonwovens, felts and padding, fiberfill, insulation and composite fillers) are at present the largest market for mechanically recycled fiber with the majority of such open loop applications accepting lower grades of fiber quality than closed-loop textile to textile recycling. Textile engineering strategies increasingly couple mechanical lines with product design for recyclability (e.g., simplified fiber mixes or elastane removal) in order to maximize the proportion of material which can be upgraded to yarn as opposed downcycled.[24, 44]

4.3 | Quality enhancement

In order to increase the uses of textile-to-textile, a number of technical solutions are being developed to improve the quality and spinnability of mechanically recycled fiber:

1. **Fiber surface modification/finishing:** Chemical or enzymatic treatment can reduce fibrillization, remove surficial contaminants, and improve the spinnability of fibers through oxidation in the spinning process. Recent enzymatic procedures, including cellulases and dedicated glycoside hydrolases, are likely to be of value in altering surface polysaccharides selectively for easier handling and to permit pretreatment at lower temperatures and with decreased chemical input.[45]
2. **De-colorization and disinfection:** Pre-spinning de-colorization by oxidative treatments or advanced oxidation technologies, including Fenton-type processes, can successfully remove reactive dyes of deep shades that otherwise would have to be downcycled. Proof-of-concept studies suggest that effective color removal is possible at the bench scale, although consideration of scale-up includes management of fiber damage and secondary solid waste streams.[30]
3. **Incorporate compatibilizers and fiber finishes into mixtures**: For mechanical blends (i.e.,

cotton/polyester composites or fiber reinforced plastics), surface coupling agents (silanes, maleated polymers) and nano-scale finishes will enhance interfacial adhesion allowing for increased recycled content when fibers are used as fillers in composites or re-spun into blended yarns. Such compatibilization approaches become particularly key when recycled fiber is incorporated within polymer matrices or hybrid yarn systems.[46]

4. **Blending with virgin or long-staple fibers:** in practice, typical industrial practice for restoring yarn strength is to blend mechanically recycled staple with a certain percentage of virgin long-staple fibers; the exact proportion may be determined by design intents (i.e., target tenacity, elongation, cost, and circularity)[42, 43] LCAs and TEAs are required to investigate the optimal business model, as they increase TYY (feed consensus: proportion of feedstock that was ideal for textile-grade yarn) and the market value of recycled output. However, these processes are often relatively complex and increase the number of operations as well as the costs of fabricating a device[24]

4.4 | Environmental & economic performance

Comparative life cycle analysis indicates how mechanical recycling can significantly reduce the consumption of primary resources and embodied carbon as compared to virgin fiber. However, results may vary, depending on system boundary conditions, logistics (collection/sorting), and how much of the material can be upgraded to textile-grade products rather than downcycled/used for fuel. The environmental benefit of releasing material streams is diminished by the presence of low-grade, highly contaminated streams or by long transport distances. Whereas large mechanical facilities facilitate high collection rates and effective pre-sorting, leading to better performance in terms of GWP and energy efficiency. [24]

4.5 | Quality enhancement

Though textile-to-textile closed-loop mechanical recycling (i.e., high-quality yarn replacement for same-grade garments) is still limited due to feedstock heterogeneity, elastane contamination, and dye complexity, mechanical recycling is technologically advanced for open-loop and blended yarn applications (commercial rotor-spinning plants and non-woven lines exist on an industrial scale). The significance of integrated systems, scalable sorting, pre-treatment, and matching end-markets in boosting overall circularity is highlighted by policy reviews and government technology assessments. [46] A number of vertical startups and incumbent fiber producers are progressing pilot to early commercial lines (dissolving-pulp chemical recycling for cellulose, thermomechanical polyester recycling), but mechanical recycling will still be essential due to its lower energy footprint for many outlets and the ability to valorize mixed, contaminated streams into nonwovens and blended yarns. Further R&D in the area of gentler opening, enzymatic pre-treatment, smart blending strategies and downstream compatibilization will step by step increase the quantity of post-consumer feedstock that can be upgraded into textile-grade products. [28, 45, 46]

Feedstock	Process	Typical Output	Key Properties	Limitations / Downcycling Risk	References
Cotton	Mechanical shredding, carding, re spinning	Short staple cotton fibers, nonwovens	Reduced staple length (often <15 mm), lower tensile strength	Fiber shortening limits spinnability; often blended with virgin fibers; quality loss after each cycle	[47, 48]
Wool	Garnetting, carding, re spinning	Recycled wool yarns, insulation, felt	Fiber crimp retained, but reduced length and strength	Felting risk; contamination from synthetic blends; limited to coarse applications	[40, 49]
Polyester (PET)	Cutting, shredding, melt spinning (if thermomechanical)	Recycled PET fibers, nonwovens, filling	Maintains thermoplasticity; variable fiber fineness	Thermal degradation; color contamination; mechanical properties decline	[49]
Blends	Shredding, mechanical separation (if feasible)	Mixed fiber nonwovens, insulation	Retains mixed fiber properties; low uniformity	Separation challenges; poor compatibility in re spinning; high downcycling risk	[50, 51]

Table 2: Mechanical Route Summary

5 | CHEMICAL RECYCLING

Post-consumer textile waste polymers are transformed via chemical recycling into monomers or soluble components suitable for purification, repolymerization, or regeneration into usable fibers and chemicals. Chemical techniques have recently become more important for treating mixed, colored, or tainted textiles unfit for mechanical recycling. These approaches include depolymerization processes such as glycolysis, methanolysis, hydrolysis, and enzyme hydrolysis;

solvent-based selective dissolving techniques such as solvent fractionation; and conversion of polyamides into caprolactam or related monomers. The following subsections look at the main processes, technical limits (like how well it can handle feedstock, catalysts, and solvent recovery), and how well it does in comparison to others, like yield, product quality, and mass/energy balances.

5.1 | Polyester (PET) depolymerization—glycolysis, methanolysis, hydrolysis & enzymatic routes

Polyethylene terephthalate (PET) is the dominant synthetic polymer in textiles and a major candidate for chemical recycling, as its monomers (terephthalic acid/DMT and ethylene glycol) can be recovered and repolymerized into virgin-grade PET when high purity is achieved. Chemical PET recycling methods are generally classified as glycolysis, methanolysis (alcoholysis), hydrolysis (acidic, basic or enzymatic) and aminolysis. Glycolysis and methanolysis are the furthest developed at industrial pilot or demonstration scale.[52]

Glycolysis (transesterification with ethylene glycol or other diol) degrade PET into bis(hydroxyethyl) terephthalate (BHET) and oligomers at moderate temperatures (180–240 °C) under the catalysis by a certain catalyst (metal acetates like zinc or manganese salts, ionic liquids and heterogeneous catalysts). Catalysts dramatically affect reaction rates and selectivity to BHET. However, zinc and manganese acetates are still prevalent as homogeneous catalysts, while for heterogeneous options as well as ionic liquids have recently been studied which allow faster depolymerization or simpler recovery of the catalyst without high amounts of contamination with BHET. The BHET is further purified by crystallization and repolymerized, where the purity of the product depends on contaminations from feedstock (PVC, polyamides, dyes, flame retardants) and sophistication of downstream technology options (recrystallisation/distillation).[53, 54]

Methanolysis transforms PET into dimethyl terephthalate (DMT) and ethylene glycol or straight into methyl esters under severe methanol circumstances. Because of the process's resistance to pigments and additives, industrial methanolysis facilities claim to effectively treat mixed PET materials, including colored or dirty ones as long as purification and distillation follow. Methanolysis facilities need a lot of money and energy to heat and distill. But they can generate monomers almost as effective as fresh feedstocks if they are purified correctly. [53]

During **Hydrolysis**, PET can be broken down into terephthalic acid (TPA) and ethylene glycol under acidic, alkaline, or neutral conditions. Since it can tolerate a variety of additives, neutral hydrolysis at high temperatures and pressures is ideal for feedstocks with pollutants. This approach uses a lot of water and energy, though, and it makes diluted solutions that have to be separated well. [52]

Enzymatic depolymerization has made commanding progress, engineered PET hydrolases (cutinase, PETase variants) are capable of processing amorphous PET and certain colored / industrial textiles with reduced energy requirements to produce TPA and MHET/EG fractions; commercialization activities (e.g., Carbios, and other industrial biotechnology entities), demonstrate plant scales, that such enzyme-based processes can process mixed/colored textiles with controlled pre-treatment. Enzymatic pathways are still being optimized in terms of activity toward highly crystalline PET as well as long-term operation, but offer great prospects for lower-temperature and reduced emission monomer retrieval when enzyme engineering and process intensification further develop.[55]

Dye and finish tolerance, All PET chemical recycling routes are affected by non-PET impurities. PVC, adhesives, metal hardware and halogenated flame retardants induce the formation of corrosive or toxic molecules during depolymerization whereas pigments and incorporated dyes are distributed among various oligomer fractions which may require subsequent purification (active carbon, solvents, distillation). Pre-sorting, detergent washing and selective decolorization enhance monomer purity slightly but at the expense of increasing costs and effluent management needs.[52, 53]

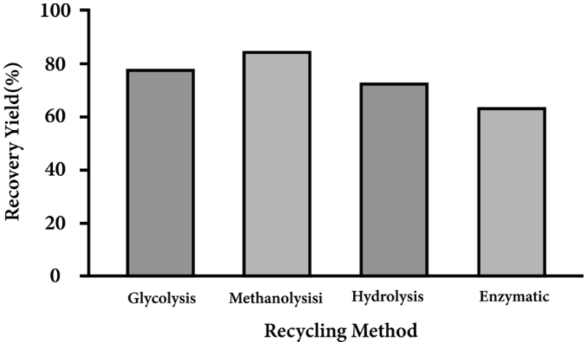

Fig.4: Recovery Yield (%) of various Depolymerization process[1-3]

5.2 | Cellulosic dissolution, regeneration & hydrolysis to platform molecules

Two basic chemical processes can be used to recycle cellulosic materials (cotton, rayon, and viscose): (a) dissolving and regeneration to create dissolving pulp for viscose or (b) depolymerization or hydrolysis to convert them into sugars for fermentation or chemical enhancement from lyocell (MMCF) or direct filament spinning. Both techniques call for close regulation of variables, including solvent or chemical recovery, contaminants, and degree of polymerization (DP).[56]

a. **Dissolution–regeneration (NMMO, ionic liquids, solvent systems):** The lyocell process (N-methylmorpholine N-oxide, NMMO) dissolves cellulose and can be implemented on waste cotton to produce man-made cellulosic fibers with high DP and good mechanical properties. Industrial lyocell mills routinely report solvent recovery >99% when well-designed recovery trains are used, minimizing solvent losses and associated environmental impacts. Ionic liquids and deep eutectic solvents (DES) are attractive because they dissolve cellulose under milder conditions and allow direct shaping or spinning, but ILs require careful selection (toxicity, cost, viscosity) and efficient recovery loops to be sustainable at scale. Recent material-science reviews highlight ionic liquids' strong solvating power and process innovations (reactive extrusion, continuous dissolution) that may lower energy intensity and improve throughput for textile feedstocks.[57, 58]
b. **Regeneration vs hydrolysis:** Dissolution–regeneration aims to preserve DP to produce high-quality dissolve pulp for viscose/lyocell, whereas hydrolysis (acidic or enzymatic) targets complete depolymerization to glucose/monosaccharides for biochemical routes (bioethanol, platform chemicals). Hydrolysis tolerance to dyes and finishes is variable: strong oxidants or concentrated acids can degrade colorants and remove finishes but generate effluent streams needing neutralization and treatment. The choice between regeneration and hydrolysis depends on end-product value (textile fibre >> biofuel) and energy balances. [56, 58]

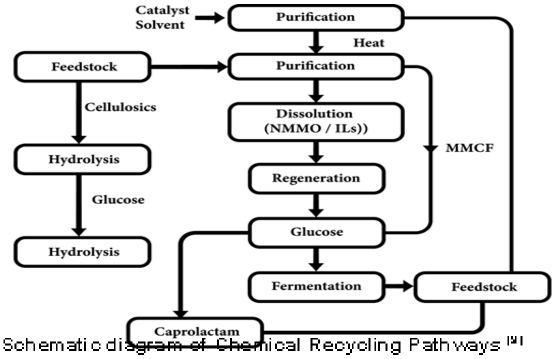

Fig 5: Schematic diagram of Chemical Recycling Pathways [9]

5.3 | Elastane & multi-material garments

Elastane (Spandex) is widely used in small fractions (1–10%) to impart stretch but is a major operational headache for chemical recycling. Elastane is chemically resistant to many depolymerization routes and can gum filters, reduce solvent recyclability, and form crosslinked residues that contaminate reactors. Strategies include selective dissolution that dissolves cellulose or PET while elastane remains insoluble and is removed as a solid residue, targeted solvent systems that dissolve elastane for separate recovery, or pre-removal (mechanical or chemical) prior to high-value chemical recycling. Several solvent systems and process flows (reported in lab and pilot studies) remove or dissolve elastane selectively, but scale-up remains limited and often adds cost. Thus, elastane content often reduces feedstock acceptability for many chemical lines unless specific pre-treatment or hybrid routes are available. [2, 59, 60]

5.4 | Process safety & sustainability — solvents, emissions, mass/energy balances

Energy consumption, solvent toxicity, emissions and waste management have to be taken into account while evaluating the chemical recycling routes and the effectiveness of solvent recovery. NMMO and properly selected ionic liquids can be recovered to >99% in optimized lyocell lines, dramatically reducing solvent losses. But recovering solvents requires costly techniques like multistage evaporation, ion exchange, and purification. Methanol hydrolysis of PET requires such fire safety precautions while recovering and distilling at high temperatures. The glycolysis method is only applicable for producing oligomers, and the processing also involves solids handling and crystallization. Enzymes might reduce energy inputs for high temperatures, but biological contaminants, nutrient management as well as enzyme production, still need to be managed. Pertinent environmental issues in chemical treatments will be the quantity of solvents recovered, energy consumption per ton treated and how much pre-sorting is needed to reject toxic pollutants. The study found that, compared to virgin polymer production, the potential for worldwide warming reduction relies on steady high solvent recovery performance and efficient local heat use; low solvent contamination or recyclability can potentially be compromised by raw material pollution or recovery [57, 58, 61]

Polymer	Process	Solvent / Catalyst	Conditions (T, P)	Typical Yield (% mass)	Product Purity (%)	Solvent Recovery (%)	References
PET	Glycolysis	Ethylene glycol + metal acetate catalyst (e.g., zinc acetate)	180–240 °C, atmospheric	80–90	≥ 98 (BHET)	90–95	[62, 63]
PET	Methanolysis	Methanol + metal catalyst (e.g., cobalt, manganese)	180–280 °C, 2–4 MPa	85–95	≥ 99 (DMT, EG)	85–90	[14]
PET	Enzymatic	PET hydrolase (e.g., cutinase, PETase) in aqueous buffer	30–70 °C, ambient	60–80	≥ 95 (TPA, EG)	N/A	[64]
Cellulose	NMMO dissolution	N-Methylmorpholine N-oxide (aqueous)	90–120 °C, atmospheric	90–95	≥ 98 (regenerated cellulose)	98–99	[65]
Cellulose	Ionic liquids	ILs (e.g., [EMIM][OAc])	80–120 °C, atmospheric	85–95	≥ 98 (regenerated cellulose)	90–95	[66]
PA6	Hydrolysis	Water or dilute acid/alkali	200–250 °C, 1–2 MPa	85–95	≥ 98 (caprolactam)	N/A	[10]

6 | BIOLOGICAL PATHWAYS

Biological conversion pathways for post-consumer textile waste (PCTW) include enzymatic hydrolysis of cellulosic fibers to fermentable sugars, enzymatic depolymerization of polyesters (particularly PET) to monomers, and new microbially mediated or enzyme-assisted upcycling techniques that integrate hydrolysis products into biochemical or polymer value chains. The potential for producing high-purity monomers or platform biochemicals at comparatively low temperatures makes these pathways alluring. However, factors such as reaction kinetics, enzyme cost, blend complexity (e.g., elastane, PET–cotton blends), substrate crystallinity, dyes, and finishes severely constrain these pathways[67, 68]

6.1 | Cellulose bioconversion

In the enzymatic hydrolysis of cellulosic textile fractions (cotton, viscose), cellulase cocktails (endoglucanases, exoglycanases, and β-glucosidases) are used to convert cellulose to glucose, which can subsequently be fermented to ethanol or lactic acid or used as a substrate for biochemical syntheses. Although successful demonstrations have been reported that high (>80–95%) glucose yields can be achieved on pretreated cotton textile substrates, efficient physical and chemical pretreatments (e.g., alkaline swelling, NaOH/urea freezing, steam explosion, mechanical fibrillation or ball-milling) are often necessary to reduce crystallinity, enhance surface area accessibility and eliminate surface finishes. [68, 69] The presence of textile-derived inhibitors is a significant barrier to operational implementation. Reactive dyes, vat/azo dyes, mordants, finishing agents (oils, silicones, durable press cross-linkers), etc. are some of the compounds which could adsorb the enzymes onto paper's fabric network or occlude access to polysaccharide chains or generate colored, inhibitory hydrolysates during fermentation. Numerous reports demonstrate that a severe oxidative or alkali pretreatment can lead to enzymatic accessibility and color removal, although further chemicals are used for treatment and/or plant loading, or energy input. Therefore, there is a desire to develop pretreatments with lower impact (mechanical micronization, ionic-liquid-assisted swelling, and enzyme delignification analogues), which may be more consistent with matching the amount of enzyme loaded per ton of biomass to disadvantageous ecological effects.[67-69] Enzymatic routes to glucose, rather than low-value fuels, are desirable for the synthesis of high-value products such as PLA precursors and specialty chemicals. High solid loadings, mass transfer limitations, enzyme inhibition by soluble dyes, and the formation of microfibers that make solid-liquid separation difficult all need to be addressed in reactor design. The results from the techno-economic analysis indicate that the key process variables affecting opex include solids loading, pretreatment severity, and enzyme dosage, such that a feasible process necessitates robust pretreatments and high enzyme performance.[67, 69]

6.2 | PET-active enzymes

Enzymatic polyester recycling has been significantly enhanced with the discovery of PET-active hydrolases, including PETases, cutinases, and MHETases/BHETases. Note that, severe conditions are inappropriate when using engineered variants (for example, members of the LCC-ICCG lineage), as depolymerization also works very well under mild conditions, which is likely a result of synergistic action and does not release toxic EG or MHET. Pilot-scale processes of the engineered variants can now be operated efficiently and cost-competitively at a large scale, achieving good thermostability, catalytic turnover, and operational stability[8, 70] Enzyme variations that are active at high temperatures and exhibit enhanced substrate interactions, such as in the case of micronized PET, seem necessary for obtaining industrially relevant yields in enzymatic PET depolymerization. Unlike amorphous PET, which usually requires pretreatments to achieve satisfactory depolymerization rates, engineered hydrolases are less effective on crystalline PET (typical for textile fibers and bottles). This process can generate polymer-grade monomers, which have been demonstrated to exist in pilot plants, although the costs of enzymes, reaction times, and substrate pre-treatment are determining the economic viability[8, 70, 71]

6.3 | Prospects & limits

Although biological pathways have clear benefits, like a lower need for thermal energy and the possibility of producing high-purity monomers, they also have drawbacks.

1. **Enzyme turnover and cost**: Industrial formulations of enzymes and methods for further reducing the cost of enzymes/ton (including immobilization, continuous reactors, enzyme recycling) are required. Enzymatic depolymerization also requires longer residence period than most thermochemical techniques unless the substrate is pretreated, so it remains a target for research to identify more commercially relevant residence period without significant pretreatment.
2. **Crystallinity constraints**: Polymer crystallinity is inversely related to cellulose accessibility, and PET hydrolysis; mechanical, chemical or heat pretreatments which reduce crystallinity strongly increase the processes rates but raise lifespan burdens.
3. **Product purification**: Chemically pure monomers (TPA, EG and glucose) can be obtained via enzymatic pathways, but the soluble dye fragments or oligomeric by-products require polishing steps such as adsorption, ion-exchange and crystallization in the case of highly contaminated feedstock.

In conclusion, enzymatic and biocatalytic pathways are moving from the lab promise towards targeted industrial uses: targeted pretreatment, smart feedstock sorting (to avoid elastane rich or heavily treated garments), as well enzyme engineering that increases activity on crystalline substrates and reduces processing times means value chains over textile-to-chemicals or textile-to-bioproducts become feasible. Textile engineers must make it a priority to match enzyme-friendly feedstocks with upstream sorting and product design (lower finishing loads, separable elastane, reduced dye chemistry) to facilitate scalable biological recycling. [8, 68, 70]

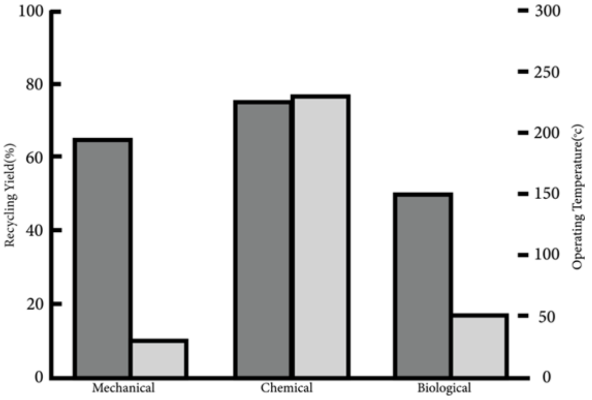

Fig.06: Comparison chart Of Mechanical, Chemical and Biological Recycling Pathways[6-8]

7 | Recycling of Blends

Blended textiles, particularly cotton/polyester (Co/PET) and blends with polyamide, wool, and trace amounts of elastane, are among the most common and difficult post-consumer streams for fiber-to-fiber recycling since they combine chemically and mechanically different polymers in the same textile structure. High-quality circular solutions must therefore include (a) effective fractionation or selective depolymerization processes to produce monomaterial streams, and (b) downstream purification, respinning, or repolymerization processes that meet target purity and property requirements for fiber-to-fiber reuse. Recent surveying and experimental work show an expanding portfolio of sequential and selective techniques (mechanical + chemical + solvent + enzymatic) as an alternative to a one-size-fits-all approach[17]

7.1 | Cotton/Polyester (Co/PET)

Logical sequencing strategies have been developed for Co/PET, including polyester-first (depolymerizing or dissolving PET and recovering cotton as a solid residue) and cellulose-first (dissolving or hydrolyzing cellulose to recover PET as an intact thermoplastic). Both routes involve trade-offs.

Polyester-first processes (alkaline hydrolysis, glycolysis, or selective solvent dissolution for PET) can yield monomers (like BHET and PTA/EG streams) suitable for high-quality PET repolymerization. However, they often require high temperatures, catalysts, and intense bleaching/decolorization to remove dyes and finishes, which can degrade cotton quality or require further textile pretreatment steps[72]

Cellulose-first methods selectively dissolve cotton, leaving PET as a recoverable solid, using high-ethanol alkaline aqueous (HHeAA) processes, switchable solvent systems, or ionic liquids. Following dissolution, the cellulose can either be recycled into MMCF (such as viscose/lyocell-type pulps) or transformed into glucose for biochemical valorization. Although the recovered cotton stream may retain more mechanical integrity using these techniques, there are drawbacks, such as colorant/finish removal issues, solvent cost, and solvent-recovery energy penalties[73]

7.2 | Cotton/Polyamide, Wool Blends, Elastane-Containing Garments

For wool and cotton/polyamide mixtures, the routes diverge:

1. **Wool blends:** Proteolytic or keratinolytic enzyme cocktails can hydrolyze proteinaceous fibers selectively to amino acids or peptides, protecting synthetic polymers for recovery. Enzymatic formulations designed for industrial settings improve amino acid recovery and reduce reaction durations, despite the fact that crystalline domains and particular finishes slow down the kinetics and that temperature control and enzyme cost are major problems[37, 40]
2. **Cotton/Polyamide:** Selective cellulose dissolution (ionic liquids or alkaline methods) or selective depolymerization of PA (if targeting nylon monomers) are possible depending on the end-product targets (i.e., cellulosic fibers vs. polyamide monomers). Sequence selection should be based on the higher-value product (e.g., caprolactam for PA6 reuse vs. regenerated cellulose for MMCF). [17, 61]
3. **Clothing containing elastane:** Elastane, also known as spandex or polyurethane, is a lightweight but potent contaminant; even below 5% of elastane present in a yarn, can make it more difficult for the other polymer fractions to undergo high-quality melt-related processing and chemical recycling. Two promising alternatives have been presented: a) selective dissolution/precipitation of elastane with solvent mixtures or benign solvents (then filtration) and b) selective depolymerization/aminolysis to depolymerize the elastane without affecting PET or cellulose. While either pathway can facilitate the recovery of "clean" PET or cellulose streams, elimination of solvent recovery loops or aminolysis byproducts must also be considered[74, 75]

7.3 | Quality & Yield Outcomes

The target purity for fiber-to-fiber recycling is high. The targets themselves need to lie within the MCCF spinning process window for PET → monomer (or IV/polydispersity) with the tolerance of virgin feed (PET IV and low colorant/contaminant levels) to be successful in polymerization. While cellulose regeneration and DP retention are severely influenced by decolorization and acid/base effects, empirical research shows that recovered PET yields from ideal lab/pilot tests could range between 70–95% (subject to contamination levels and pre-sorting).[61, 76] In the near future, various regional settings will realize hybrid value chains that incorporate thermochemical fallback, fiber-to-fiber chemical routes, and mechanical recovery. Some operational implications are a) preprocessing (sorting, removal of elastane, and de-finishing) has a dominant impact on yield as well as cost; b) solvent-based and enzymatic fractionation is expensive in terms of CAPEX and the solvent/enzyme OPEX, but can produce streams pure enough for high-value reuse[17, 61]

8 | BARRIERS & CROSS-CUTTING CHALLENGES

8.1 | Technical Barriers

Post-consumer textile recycling encounters many material-level obstacles. A major challenge is the presence of elastane, a component frequently used in stretchy garments such as sportswear, and denim blends. With extreme stretchability and thermal or chemical stability, this creates a compatibility issue with the majority of recycling processes, as it is incompatible with recycled fiber streams, often interfering in recycled fiber's chain [77] Beyond elastane, clothes might include trims, coatings, and chemical finishes that impair reuse options. For instance, flame retardant, water repellent or antimicrobial treatments can withstand collection and sorting processes, degrading the fiber purity and compromising chemical recycling methods.[77] A second significant problem is the color range. As post-consumer textiles are delivered to recycling facilities in such a variety of colors, patterns, and dye classes for reuse potential, which severely confines their potential usage in new products without reprocessing. Discoloration may cause the degradation of fiber stiffness, energy intensity, and fiber strength [51], although it is technically feasible. The quality of the fiber is not consistently satisfactory after mechanical recycling. With each use, the molecular weight and tensile strength of polymers like polyester or nylon reduce to a point that recycled fibers are not appropriate for performance applications [51] In the case of polyester as well as polyamide, the chemical treatment, such as solvent toxicity and polymer degradation, suffers from several problems in chemical disposal. Some depolymerization solvent systems are toxic to workers, and others cause fiber cracking, which will decrease the performance at downstream applications [78] Together, these factors set the mass-based technical barriers that limit the successful development of recycling solutions.

8.2 | Quality Barriers

Quality remains one of the primary concerns in textile recycling. Mechanically recycled fibers are unlikely to match the performance of their virgin counterparts, as tensile strength, dye uptake, and durability of these fibers are found to be inferior [51] This disadvantage limits their use to waste products such as insulation, wipers, or stuffing, not high-quality textiles. Chemical recycling provides improved molecular recovery but is plagued by quality uncertainties. For example, such depolymerized monomers may be contaminated with impurities that impact the polymerization and quality of regenerated fibers. Further, no standard test methods yet exist to test the quality of recycled fiber and monomer. There are no common test procedures, which makes it challenging for brands and manufacturers to compare performance, which leads to mistrust and limited adoption [79]

9 | RESEARCH GAPS & FUTURE PROSPECTS

9.1 | Blend-Tolerant Chemistries

One of the key research gaps in textile waste recycling is the lack of scalable blend-tolerant chemistries. Although cotton/polyester blends are dominant in post-consumer waste streams worldwide, there are limited methods enabling an effective separation or recycling of both fractions without a loss of quality. Present methods, such as glycolysis or heat depolymerization, cannot address the content of numerous synthetics or elastane and generally require high purity. [80] Research should be oriented toward universal solvent systems or catalytic pathways that can address heterogeneous feedstocks with economic and environmental sustainability. [80]

9.2 | Elastane-Selective Removal

Elastane is one stubborn obstacle to textile recycling. It even inhibits both mechanical re-spinning and chemical depolymerization routes at relatively low concentrations (1–5%). The existing chemical delignification techniques deteriorate the quality of fibers and also have a negative impact on the environment since strong solvents or heat degradation are being used. [81] In the future, selective depolymerization or bio-catalytic treatments of polyurethane-based elastane can be pursued while maintaining other fibers intact.[82]

9.3 | Enzyme-Facilitated PET Recycling at Industrial TRLs

Novel synthetic PET hydrolases, such as the FAST-PETase[83] and LCC [84], resulted in a tremendous potential to depolymerize PET under mild conditions. Their low industrial TRLs were ascribed to the fact that there are issues of scalability, feedstock variability, and enzyme stability. [85] Future research should focus on process intensification, immobilizing methods and cost cutting measures to enable a transition of enzymatically PET recycling from the lab scale towards industrial demonstration [85]

9.4 | Greening of the Solvent Systems and Full Recovery

Most textile recycling methods use ionic liquids, deep eutectic solvents or organic solvent system for cellulose dissolution and polymer re-use. Although the laboratory results are encouraging, their toxicity and high cost, combined with poor recyclability prevent industrial use on a large scale. [85] An outstanding challenge in research is the development of green solvents (biodegradable, low toxicity) and ensuring closed-loop recovery rate over 99% which is crucial to minimize environmental impacts [83]

9.5 | Enhances Color and Finish Libraries for Quicker decolorization

Residual dyes, coatings and functional finishes complicate recycling because they contaminate the recovered fibers or necessitate aggressive bleaching agents. To date, these strategies do not have benchmarked libraries for dyes chemistries nor a standard predictive model of their removability. [84] The development of shared color or finishing databases and AI-driven predictions of de-colorization would be expected to expedite process development, reduce chemical use, and support recyclability assessments. [84]

9.6 | AI-Enabled Composition Prediction

Sorting is still one of the most expensive and inefficient textile recycling methods. However, the existing methods, such as NIR spectroscopy, are restricted by multilayer material, coating, and dark color. [86] The combination of AI algorithms with RFID, digital product passports, and hyperspectral photography provides promising ways for the prediction of composition to be more accurate. [87] To achieve this, future investigations should focus on real-time AI-empowered feedstock prediction for dynamic routing and adaptation.

9.7 | Harmonized LCA Datasets and Primary Data Sharing

Different assumptions regarding functional units, system boundaries, and effect categories limit the comparability of the various Life Cycle Assessments (LCAs) for textile recycling. [51] Standardized LCA datasets supported by open access primary industry data and generated using international collaboration must be available to the business community. [88] This harmonization is needed for sound policy, accepted by all industry players, and technology benchmarking.

9.8 | Design-for-Recyclability Principles

Textile products are generally designed for aesthetics, and performance, not to be recycled when their useful lives are over. Future development requires eco-design approaches that prioritize monomaterial textiles, non-toxic colors, consistent labeling, and detachable trimmings. [89] These concepts would significantly reduce downstream costs and improve recyclability [90]

9.9 | Low-Carbon Heat Integration

Energy consumption is still a significant driver of the ecological footprint of most recycling processes. Several thermochemical and solvent-based processes are energy intensive, often fueled by fossil energy sources. [90] Low-carbon heat integration methods such as hybrid electro-thermal systems, process heat recovery, steam from renewable sources, etc., are the target areas of research [91]

9.10 | Standardized Quality Metrics for Fiber-to-Fiber Recycling

Finally, one of the least developing modules is the harmonization of quality metrics for recycled fibers and monomers. Without agreement on benchmarks such as fiber tensile strength, polymer purity, and dyeability, markets are uncertain and risk averse. Global standards for the quality of recycled materials also need to be set by relevant bodies so that they can compete with their virgin counterparts [92]

10. Conclusions

The review reveals that recycling approaches to post-consumer textiles are in a period of rapid development, but a large gap still exists between what can be done in the laboratory and what needs to be achieved by industry. Chemical recycling can provide pathways for true fiber-to-fiber recovery in a manner of stepwise depolymerization, including monomer recycling, dissolution-reprecipitation, and enzyme processes; it particularly has potential applications for the polyester-cellulose blend [93, 94] Nevertheless, the technology readiness level of these technologies varies greatly and only a handful of pathways has achieved demonstration or pilot-scale deployment. [95] Blended textiles are still the most difficult to recycle, especially when elastane or sophisticated coatings are included. Selective solvent systems, enzymatic treatments, and blend-compatible chemistries represent a potential advance. However, these options must demonstrate industrial applicability in terms of energy usage, solvent regeneration and cost-competitiveness. [96] In a similar vein, the problem of color variability and finishing chemicals that hinder reprocessing need to be addressed by establishing standardized color/finish libraries, combined with more effective decolorization methods. [51] Digitalization and traceability are key enablers for the circular economy. Novel concepts, like digital product passports (DPP), RFID or QR coding, and AI-based sorting, can improve transparency in material flow and support an optimized feedstock allocation [94] However, such tools need standardized data and verification systems, along with global policy support to avoid greenwashing and gain consumer confidence. [94] Textile recycling needs to reach carbon and energy parity with virgin production from both an environmental and a techno-economic standpoint. However, lack of data and methodological consistency still pose challenges. [97] More available primary industrial data, open and uniform benchmarking frameworks will be key for future advancement [98] Ultimately, unlocking fiber-to-fiber recycling at mass scale will require a system approach including the development of blend-separating technologies and their integration in EPR concepts, as well as design-for-recyclability principles and standardized quality dimensions for recycled outputs. The entanglement condition of material science, digital traceability, and facilitating regulation would ultimately decide if textile recycling breaks away from a niche innovation towards a mainstream reality across the globe. [98]

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