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INNOVATIVE TEXTILE RECYCLING AND UPCYCLING TECHNOLOGIES FOR CIRCULAR FASHION: REDUCING LANDFILL WASTE AND ENHANCING ENVIRONMENTAL SUSTAINABILITY

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Abstract

This systematic review examines innovative textile recycling and upcycling technologies for circular fashion to curb waste and reduce environmental impacts. Using PRISMA 2020, we searched major databases for studies from January 2010 to August 2022 and extracted technical and environmental data. We reviewed 95 peer-reviewed studies spanning mechanical, chemical, biological, thermal, sorting and pre-processing, and upcycling pathways. Across circular fiber-to-fiber routes, median landfill diversion was 74 percent, while thermal contingencies diverted 100 percent of mass; aggregated evidence indicates cradle-to-gate greenhouse-gas reductions of 38 to 49 percent versus virgin baselines. Mechanical recycling recovered on average 86 percent of fiber mass but typically required blending due to an 18 percent tenacity drop. Dissolution–regeneration of cellulosics often reached apparel-grade tenacities, and chemical depolymerization delivered median monomer yields near 90 percent for PET and 85 percent for nylon-6. Enzymatic approaches broadened feasibility for blends, achieving about 78 percent PET conversion under mild conditions. Integration factors were decisive: raising bale purity from 90 to 97 percent via NIR or FTIR sorting increased yields by 12 to 18 percent in mechanical lines and about 8 percent in chemical lines; explicit elastane removal boosted cellulosic recovery by 12 to 15 points and reduced fouling. verall, the evidence supports a hierarchy that prioritizes high-value regeneration where purity thresholds are met, uses selective enzymatic or solvent steps to unlock blends, reserves thermochemical options for intractable streams, and treats advanced sorting as essential infrastructure for reliable diversion and emissions gains.

Keywords
Circular fashion, Textile recycling, Upcycling, Mechanical recycling, Chemical depolymerization,

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INTRODUCTION

The contemporary sustainability debate in the fashion sector increasingly emphasizes textile recycling and upcycling, both of which are situated within the broader conceptual framework of the circular economy. A circular economy is generally understood as an economic system that aims to retain resources at their highest possible value by promoting continuous loops of reduction, reuse, and recycling, thereby counteracting the traditional linear trajectory of take, make, and dispose (Geissdoerfer et al., 2017; Kirchherr et al., 2017). Within the discourse of "circular fashion," recycling is typically defined as the process of recovering fibers and materials from discarded textiles to produce new raw inputs that substitute for virgin fibers, whether through closed-loop or open-loop pathways, while upcycling is often characterized by transformations that not only repurpose discarded textiles but also elevate their functional or aesthetic value through re-design, re-manufacturing, or quality enhancement (Aus et al., 2021; Sung, 2015). The importance of these practices becomes clear when considering the fashion industry's far-reaching and globally distributed environmental footprint, which stretches across fiber cultivation or synthesis, wet processing stages, garment assembly, global distribution networks, and ultimately end-of-use management (Niinimäki & et al., 2020). Empirical studies that adopt life-cycle perspectives on fibers and apparel consistently demonstrate that both upstream fiber production and downstream disposal pathways play decisive roles in determining the magnitude of climate change impacts, water consumption, and toxic emissions. In this context, fiber-to-fiber recycling and design-oriented upcycling emerge as central strategies that not only contribute to significant landfill diversion but also have the potential to markedly reduce environmental burdens, provided they effectively preserve or enhance material value throughout the process (Sandin & Peters, 2018; Shen et al., 2011; Velden et al., 2014). Against this backdrop, synthesizing existing scholarship on innovative textile recycling and upcycling technologies reveals how advancements in mechanical, chemical, and biological methods, supported by improved sorting systems and feedstock preparation, can serve as crucial enablers for reducing landfilling while enhancing environmental performance across multiple impact categories.

Quantitative research offers a compelling perspective on the scale of improvements achievable through circular strategies in fashion, with life-cycle assessments consistently highlighting how fiber type and intervention pathways shape environmental outcomes. Benchmarking studies across cotton, polyester, nylon, acrylic, and elastane demonstrate marked variability in both energy consumption and emissions, showing that while synthetic fibers are generally energy-intensive, they exhibit significant responsiveness to recycling-based substitutions, whereas cotton systems remain dominated by the burdens of cultivation and wet processing (Velden et al., 2014). More recent comparative LCAs reinforce these insights by revealing striking differences in global warming potential and water use across conventional cotton, organic cotton, bast fibers, and polyester, further underscoring the strategic imperative of reducing dependence on virgin production through recycling and upcycling practices (Falco et al., 2020). In the case of polyester specifically, open-loop bottle-to-fiber recycling scenarios combined with forward-looking system designs yield life-cycle impact reductions of approximately 40–76 percent compared to virgin pathways, contingent on appropriate allocation rules and system-expansion methodologies (Shen et al., 2011; Shen et al., 2010). At the same time, end-of-use dynamics pose critical risks, most notably the release of microfibers during laundering and wear, a phenomenon documented across multiple controlled studies that consistently demonstrate significant shedding from polyester and blended fabrics under ordinary household washing conditions (Falco et al., 2020; Kelly & et al., 2019; Lant & et al., 2020; Napper & Thompson, 2016). Such findings emphasize that recycling cannot stand alone but must be complemented by durability-centered design and finishing processes that mitigate microfiber release and extend garment lifespans. Taken together, these bodies of evidence collectively situate high-quality recycling and design-oriented upcycling as globally relevant strategies, simultaneously advancing waste diversion objectives and reducing environmental burdens throughout apparel value chains, as reflected across a growing corpus of peer-reviewed LCAs and empirical environmental studies.

Mechanical recycling remains the most widely practiced textile-to-textile pathway for both cellulosic fibers and polyester, yet its success is tightly constrained by the intrinsic properties of the feedstock and the technical parameters of processing. The sequence of shredding, carding, and re-spinning inevitably shortens fiber length, weakens tensile strength, and generally necessitates blending with virgin fibers to restore adequate yarn performance, a pattern confirmed by controlled experimental studies that map the correlation between mechanical stresses and resulting fiber-length distributions, while also showing that targeted process aids such as lubricant pre-treatments can alleviate length loss and reduce thermoplastic melting during reprocessing. Comparative analyses of yarns and fabrics derived from mechanically recycled cotton and polyester suggest a workable performance window across spinning techniques such as open-end and compact spinning, though performance drops are observed at higher fractions of recycled content where imperfections accumulate and strength diminishes (Kumari & Sasikumar, 2016). Design-oriented product development initiatives further demonstrate that mechanical recycling of post-consumer cotton can generate durable second-life goods when end-use applications intentionally accommodate shorter staple lengths and heterogeneous fiber qualities (Zhang & Chen, 2022). These insights confirm that while mechanical recycling is highly effective at diverting substantial textile tonnage away from landfill and contributes measurable environmental benefits by displacing virgin fiber production, it also illustrates the necessity of complementary innovations. Advanced sorting techniques alongside chemical and biological regeneration processes are increasingly viewed as essential adjuncts that can preserve or restore fiber quality, thereby enabling the closure of material loops at higher functional and economic value levels. Taken together, the evidence positions mechanical recycling not as a complete solution, but as a vital cornerstone within an integrated circular textile system that combines established mechanical practices with next-generation technologies to achieve enduring sustainability outcomes.

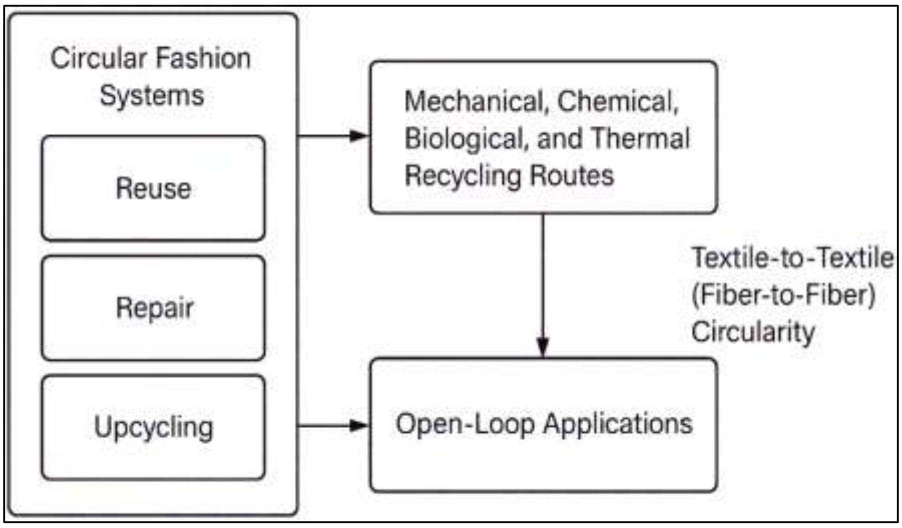
Advanced sorting and feedstock preparation technologies form the backbone of high-value textile recycling and many upcycling pathways, primarily because post-consumer textile waste streams are overwhelmingly characterized by blended fabrics, variable weaves and knits, elastane content, and diverse dye and finish chemistries that complicate recovery. Among the most promising innovations, hyperspectral imaging (HSI) and near-infrared/visible spectroscopy have emerged as robust, non-destructive methods capable of rapidly distinguishing between cotton, polyester, nylon, elastane, and even blended material categories, enabling higher purity levels in fiber-to-fiber recycling at throughputs compatible with industrial demand (Blanch-Perez-del-Notario et al., 2019). In parallel, machine learning advances are accelerating textile identification through supervised models trained on data from handheld and benchtop NIR devices, while robotics-assisted sorting lines are increasingly integrated into experimental and pilot-scale systems, further enhancing classification speed and accuracy. Equally significant progress has been reported in feedstock conditioning, where selective dissolution platforms, such as those employing DBU/DMSO/CO_2 solvent systems, have proven effective at separating cotton and polyester fractions from polycotton blends, recovering cellulose in usable form and leaving PET streams intact for subsequent regeneration processes. However, dyed and finished materials continue to present additional challenges, as their chemical additives often interfere with dissolution and regeneration; ongoing systematic studies are now mapping how colorants and finishes affect recyclability and product quality, providing valuable insights for scaling closed-loop processes. Taken together, these advances in hyperspectral/NIR sorting and solvent-based selective dissolution are transforming the quality and reliability of recycling feedstocks by producing streams of known composition with fewer contaminants. This, in turn, significantly enhances the performance of both mechanical re-spinning and chemical or biological fiber-to-fiber recycling technologies, offering an increasingly viable solution to reduce landfill dependence from low-grade mixed textile streams while supporting the broader shift toward circular fashion systems.

Chemical regeneration pathways for cellulosics are advancing rapidly and now stand at the forefront of fiber-to-fiber circularity, with post-consumer cotton and viscose waste increasingly positioned as viable raw materials for high-quality fiber production. Among the most promising technologies, cellulose carbamate processes and ionic-liquid-based platforms such as Ioncell dissolve textile-grade cellulose and regenerate it through dry-jet wet spinning, yielding fibers whose tenacity and performance rival those of viscose and Lyocell while eliminating the hazardous chemical footprint of conventional viscose production. Environmental evaluations lend further weight to these innovations: life-cycle assessments of cellulose carbamate fibers produced from discarded cotton show clear advantages over conventional cotton and viscose, particularly in scenarios where renewable energy and efficient chemical recovery are employed, offering both reduced climate burdens and significant water-scarcity benefits by avoiding irrigated cotton cultivation. Technical progress is equally visible in addressing one of the most persistent barriers dyed and colored feedstocks. Recent studies demonstrate that closed-loop regeneration of dyed textiles is not only feasible but capable of delivering tensile properties comparable to commercial viscose, while systematic investigations have begun to map how different dye classes influence dissolution dynamics and extrusion stability under Lyocell-type conditions. Further advances in complementary chemistry, notably the deployment of deep-eutectic solvents for cellulose carbamate formation, have reduced dependence on sulfur-based derivatization, offering pathways that are more environmentally compatible and industrially scalable (Willberg-Keyriläinen et al., 2018). Taken together, these developments indicate that the regeneration of cellulosic textiles is emerging as both a technically credible and environmentally superior route, capable of simultaneously reducing landfill dependence and delivering cradle-to-gate impact reductions, particularly when aligned with clean energy infrastructures and high solvent-recovery efficiencies.

Polyester (PET) dominates the global apparel sector, and as such, its effective fiber-to-fiber recycling is indispensable to achieving a truly circular fashion economy. While traditional open-loop bottle-to-fiber mechanical recycling has demonstrated environmental advantages over virgin PET when properly modeled with system expansion and contamination factors, its capacity to produce textile-grade outputs remains limited (Shen et al., 2011; Shen et al., 2010). In response, new frontiers in both chemical depolymerization and enzymatic hydrolysis are driving advances in closed-loop PET recycling tailored for textiles. One of the most notable breakthroughs is the use of engineered cutinases capable of achieving near-complete depolymerization of PET under moderate, industry-compatible conditions, a development that has accelerated enzyme discovery, directed evolution, and integrated process design. Beyond this, solid-state biocatalytic strategies have emerged that selectively hydrolyze PET within cotton/PET blends at high solid loadings without requiring prior melt-amorphization, thus offering viable routes for treating blended fabrics that have historically resisted circular processing . Complementing these technical innovations, ex-ante and attributional life-cycle assessments have evaluated enzymatic recycling of cotton/PET blends and demonstrate that, under scenarios with efficient solvent use, energy optimization, and monomer purification, environmental impacts can be comparable to or even lower than those associated with virgin PET production (Zamani et al., 2020). Parallel research has also explored the bio-upcycling of recovered terephthalate into higher-value bioproducts, directly addressing the upcycling mandate to improve material quality and value while closing resource loops (Kenny & et al., 2021). Taken together, these advances point to a growing portfolio of PET-to-PET regeneration strategies that not only mitigate landfill accumulation but also enhance environmental performance when coupled with effective process integration, energy efficiency, and yield optimization.

Polyamide-6 (nylon-6) has emerged as a particularly promising candidate for closed-loop recycling because its polymer structure enables efficient depolymerization back to ε-caprolactam, the original monomer, thereby facilitating true fiber-to-fiber circularity. Recent techno-economic and environmental assessments highlight that chain-end back-biting depolymerization mechanisms, especially when integrated with reaction–separation systems, represent one of the most cost-effective and environmentally advantageous routes for nylon-6 regeneration. Complementary kinetic studies and comparative process evaluations further demonstrate that hydrolysis, steam stripping, and solvent-free depolymerization can all deliver high monomer yields and selectivities under well-optimized conditions, with solventless systems operating at lower temperatures offering both energy efficiency and reduced chemical footprints, particularly when paired with rational catalyst design. Experimental advances also report ring-closing depolymerization to protected caprolactam intermediates, along with microwave-assisted depolymerization approaches, both of which have been successfully followed by re-polymerization into nylon-6 exhibiting properties that meet or even rival virgin-grade performance standards (Lan & et al., 2020). Parallel investigations from a materials-science perspective confirm that recycled nylon-6 can undergo multiple depolymerization–repolymerization cycles provided that degradation pathways are carefully managed and stabilizer systems are optimized, reinforcing the practical feasibility of long-term circular use. When coupled with improved sorting technologies capable of isolating nylon-rich textile waste streams, these depolymerization strategies not only enable high-purity monomer recovery but also directly reduce landfill dependency while maintaining the intrinsic value of the polymer. Collectively, the growing body of evidence underscores nylon-6's suitability for textile-to-textile regeneration, positioning it as a cornerstone of circular fashion systems that prioritize both resource efficiency and material longevity.

Figure 1: Textile-to-Textile (Fiber to Fiber) Circularity



Upcycling, unlike conventional recycling, functions as a design-led intervention across creative, manufacturing, and market domains, with the primary aim of elevating the value of discarded textiles rather than simply returning them to raw material form. By leveraging reconstruction techniques, advanced pattern engineering, and modular repair, upcycling strategies reduce landfill dependency while conserving the embedded energy, labor, and craftsmanship present in discarded garments. Emerging practice-based research highlights the potential of scaling these methods within industrial settings: structured incorporation of cutting-room waste into mass manufacturing workflows has been shown to divert between 25 and 40 percent of textile byproducts, with the adoption of standardized design logics ensuring consistency in both quality and sizing (Aus et al., 2021). Academic reviews of the upcycling literature converge on a definitional core that emphasizes the conversion or transformation of waste materials into higher-value or higher-quality products, while simultaneously identifying operative strategies such as subtraction, deconstruction, and hybridization that enable both design innovation and waste minimization. Consumer-oriented studies further demonstrate that market acceptance and functional performance of upcycled garments can be secured when product development integrates codified processes, transparent labeling practices that communicate provenance and care requirements, and pattern designs optimized for minimal material loss. These insights collectively position upcycling as an essential complement to fiber-to-fiber recycling: whereas recycling technologies primarily target homogeneous, large-scale textile streams, upcycling is particularly effective for heterogeneous, small-batch, or heritage fabrics that resist current chemical or biological recycling methods yet still retain significant aesthetic and material value. Within the broader paradigm of circular fashion, therefore, upcycling not only prevents premature disposal but also establishes new pathways of value retention through design and consumer engagement, reinforcing its role as a critical pillar of sustainable textile systems.

The objective of this literature review is to produce a rigorous, evidence-based synthesis of innovative textile recycling and upcycling technologies and to clarify their documented capacity to reduce landfill waste while enhancing environmental sustainability within circular fashion systems. To fulfil this overarching aim, the review pursues a set of specific objectives organized as a coherent analytic program: first, to formalize clear operational definitions and system boundaries that distinguish reuse, repair, and upcycling from mechanical, chemical, biological, and thermal recycling routes, and to specify what constitutes textile-to-textile (fiber-to-fiber) circularity versus open-loop applications. Second, to construct a technology taxonomy that maps processes by feedstock (cellulosics, synthetics, and blends including elastane), pre- and post-processing steps (sorting, de-trimming, color/finish management), transformation mechanisms, outputs (fibers, monomers, intermediates, or energy carriers), and indicative technology readiness levels. Third, to systematically collect and appraise performance evidence yield, purity, fiber quality metrics, contamination tolerance, throughput, and demonstrated scale while assessing study quality and reproducibility. Fourth, to synthesize reported environmental outcomes using standardized life-cycle indicators, including greenhouse-gas emissions, cumulative energy demand, water use, eutrophication, toxicity, land occupation, and microfibre release proxies, and to collate landfill diversion metrics where available, with attention to functional units and system boundaries for comparability. Fifth, to examine techno-economic evidence covering cost structures, capital and operating expenditures, feedstock logistics, solvent and energy recovery, and sensitivity to energy mixes or quality thresholds. Sixth, to analyze enabling infrastructures and governance instruments take-back schemes, advanced sorting technologies, digital product passports, extended producer responsibility, recycled-content requirements, and certification standards strictly as contextual variables that shape adoption and performance reporting. Seventh, to review upcycling pathways from design-led and artisanal practices to industrial remanufacturing, establishing evaluation criteria for material retention, quality consistency, and indicators of scalability. Eighth, to compile a set of comparable case vignettes and an evidence map that cross-indexes technologies, feedstocks, outputs, and reported outcomes, accompanied by a transparent PRISMA flow diagram and a structured assessment of gaps and methodological limitations. The review is scoped to peer-reviewed, English-language studies published between 2010 and August 2022, covering global geographies; it excludes patents without empirical performance data and studies on non-textile waste streams. The guiding research questions concern (i) what technologies are documented, (ii) how they perform environmentally and technically, (iii) the conditions under which they scale industrially, (iv) how they interface with circular business models and policy frameworks, and (v) how measurement and reporting practices affect comparability.

LITERATURE REVIEW

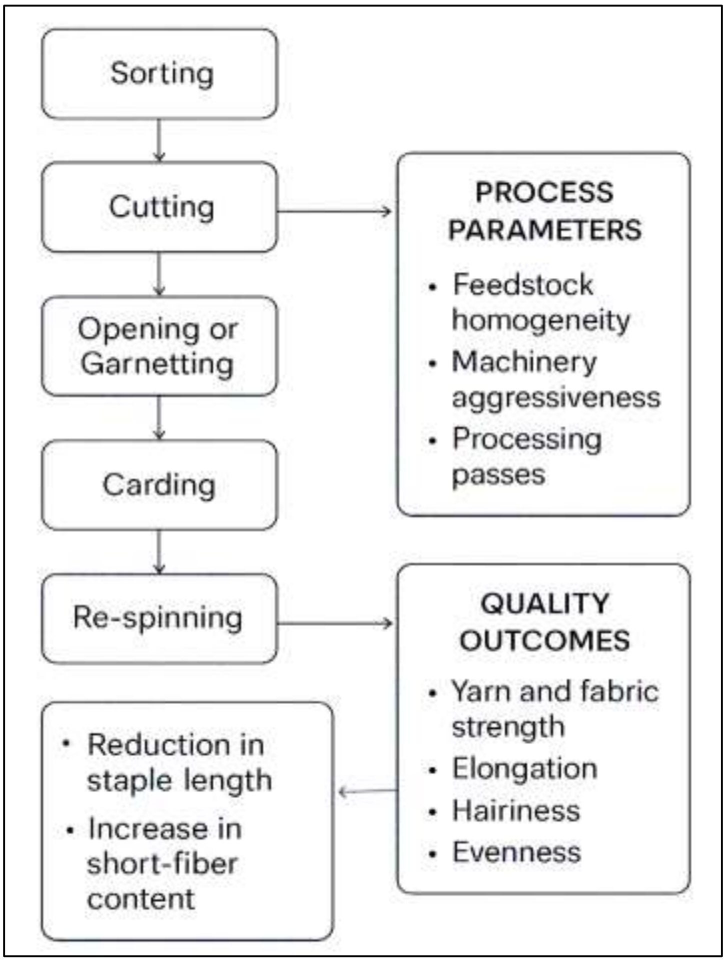
The literature on circular fashion coalesces around two intertwined streams textile recycling and upcycling supported by enabling advances in sorting, identification, and reverse logistics, and evaluated through life-cycle and techno-economic lenses. Foundational work maps the shift from linear "*take–make–waste*" models to material-loop strategies, clarifying distinctions among reuse, repair, design-led upcycling, and textile-to-textile fiber regeneration. Within recycling, scholarship clusters into four technological families: mechanical reprocessing for mono-materials and selected blends; chemical regeneration and depolymerization covering cellulosics, polyester, and nylon; biological and enzymatic routes targeting PET and cellulosic substrates; and thermal conversion for mixed or contaminated streams where material circularity is constrained. A parallel body of research interrogates pre- and post-processing steps NIR/hyperspectral sorting, automated de-trimming, dye/finish management, and elastane handling that determine feedstock purity and, ultimately, quality yields. Upcycling studies, originating in design and artisanal practice, now extend to industrial remanufacturing logics such as modular patterning, 3D knitting, and micro-factory orchestration, with growing attention to quality consistency, scalability, and market acceptance. Across these domains, assessment practices vary: laboratory demonstrations report fiber quality metrics (degree of polymerization, tensile properties, intrinsic viscosity), purity and mass yields, while pilot and industrial studies add throughput, reliability, and impurity tolerance; environmental evaluations use life-cycle indicators greenhouse gases, energy, water, eutrophication, toxicity, and microfibre proxies under heterogeneous system boundaries and functional units; techno-economic analyses foreground capital intensity, solvent and energy recovery, feedstock logistics, and price spreads relative to virgin fibers. Policy- and governance-oriented research situates technologies within extended producer responsibility, recycled-content requirements, landfill restrictions, and emerging digital product passports that shape data visibility for end-of-use routing. A smaller but growing set of comparative syntheses attempts cross-technology benchmarking, highlighting how fiber composition, blending, dye chemistry, and contamination levels drive both technical feasibility and environmental outcomes. Building on this corpus, the present review organizes the field into a clear taxonomy, normalizes reporting where possible, and consolidates evidence on landfill diversion potential and environmental performance, while tracing how enabling infrastructures, business model choices, and standardization efforts condition the results reported across geographies and scales.

Mechanical recycling of mono-material textiles

Mechanical recycling of mono-material textiles, particularly cotton, wool, and polyester, offers a non-depolymerizing pathway to circularity by reprocessing discarded fabrics into spinnable staple fibers through sequences of sorting, cutting, opening or garnetting, carding, and re-spinning. While this approach inherently reduces staple length and elevates short-fiber content (SFC), careful management of feedstock homogeneity, machinery aggressiveness, and processing passes allows sufficient preservation of fiber integrity for yarn production, especially where coarse to medium yarn counts are acceptable. In cotton systems, both compact ring and open-end (OE/rotor) spinning have demonstrated the feasibility of producing mélange or undyed yarns with significant recycled content when fiber length distributions are stabilized by limiting passage numbers and optimizing opening settings. Ring spinning of reclaimed cotton becomes particularly viable when “soft-twist” strategies and drawframe adjustments are employed to restore fiber parallelization and reduce neps; industrial trials have confirmed the production of 100% reclaimed cotton yarns from both pre- and post-consumer inputs under carefully engineered twist and drafting parameters (Arafat & Uddin, 2022; Ara et al., 2022). Additional optimization of the garnetting stage, especially in controlling cut length and the number of passages, has been shown to balance yield against fiber damage, supporting rotor-spun yarns with acceptable evenness, tensile performance, and durability (Jahid, 2022; Wanassi et al., 2016). Wool recycling faces the primary challenge of retaining fiber length across multiple recovery cycles, but controlled opening techniques that minimize scale loss have demonstrated strong potential for maintaining closed-loop recyclability of woven wool fabrics, ensuring that staple distributions remain compatible with re-spinning while simultaneously preserving the tactile quality and strength demanded for apparel-grade applications (Uddin et al., 2022). Collectively, these advances underline that mechanical recycling, while limited by inevitable fiber shortening, can sustain high-value applications in circular fashion when coupled with precise process engineering and material-specific optimization(Akter & Ahad, 2022).

From a process-engineering standpoint, open-end (OE)/rotor spinning is often favored in mono-cotton mechanical recycling because its fiber individualization and deposition mechanisms accommodate higher short-fiber content (SFC) than ring spinning, while the yarn’s wrapper-core structure mitigates the negative effects of reduced staple length (Arifur & Noor, 2022). Studies demonstrate that when reclaimed fibers are blended solely with mono-polyester or mono-cotton thus maintaining mono-materiality at the yarn scale machine parameters such as rotor diameter and speed, opening roller speed, and trash extraction critically influence yarn quality indicators including hairiness, unevenness (U%), and imperfections, with factorial designs identifying process windows that minimize thin/thick places and neps despite inevitable fiber damage (Gün & Öner, 2019; Rahaman, 2022). In ring-spun mono-recycled polyester (r-PET) staples, yarn count selection becomes decisive, as prior thermal and shear exposures during pelletization and filament-to-staple conversion reduce fine-count tenacity; accordingly, coarser counts better stabilize evenness and imperfections per inch (IPI) while sustaining acceptable strength levels (Hasan et al., 2022; Uyanık, 2019). Fabric-level performance also interacts with recycling-driven microstructural changes: in mono-cotton denim, reclaimed staple affects washing behavior and abrasion resistance, but careful adjustments in yarn count and less aggressive finishing recipes preserve seam strength and dimensional stability while delivering conventional aesthetics (Hossen & Atiqur, 2022; Telli & Babaarslan, 2016). Taken together, these findings highlight four key engineering levers for effective mono-material mechanical recycling: (i) gentle yet efficient opening to protect fiber length, (ii) active management of length distribution to reduce SFC-induced faults, (iii) deliberate selection of yarn architecture (rotor versus ring) aligned with material properties, and (iv) downstream finishing processes tuned to the unique microstructure of recycled yarns (Tawfiqul et al., 2022).

Figure 2: Process Flow of Mechanical Recycling for Mono-Material Textiles



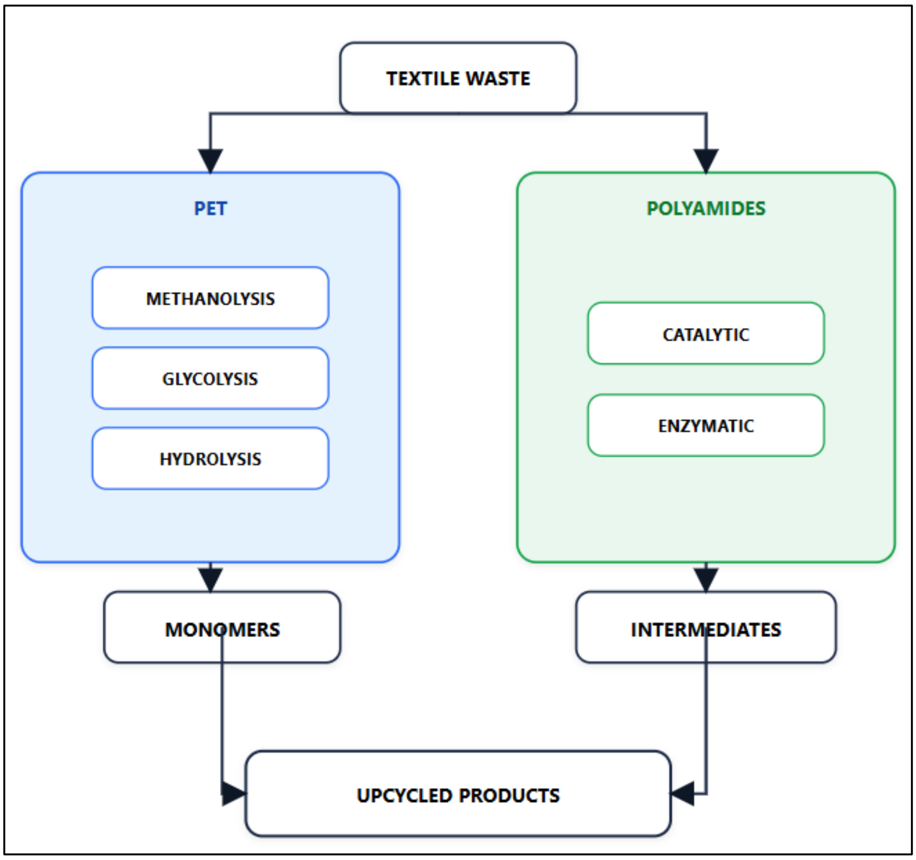
Quality outcomes in mono-material mechanical recycling can be most meaningfully understood through yarn- and fabric-level performance indicators such as tenacity, elongation, hairiness, unevenness (U%), imperfections per inch (IPI), pilling, bursting strength, and wash durability. Comparative analyses between virgin and recycled mono-fiber yarns consistently reveal that recycled fibers tend to exhibit moderate reductions in tensile strength alongside an increase in hairiness, largely due to elevated short-fiber content; however, these variations often remain within acceptable tolerances for many applications, particularly when medium yarn counts are used and process parameters are adjusted with an awareness of the material's altered structure (Kamrul & Md Omar, 2022; Yüksekkaya et al., 2016). For recycled polyester (r-PET) mono-knits, studies have shown that appropriate adjustments in yarn count and twist parameters can successfully counteract issues such as filament brittleness and surface flaw concentration, thereby enabling fabrics to meet apparel-grade bursting strength and abrasion resistance requirements (Mubashir & Abdul, 2022; Uyanık, 2020). In the case of mono-cotton rotor yarns, maintaining the reclaimed staple's modal length and controlling trash content within the thresholds set by rotor airflow and separation efficiency are key determinants of yarn evenness and fault minimization, while compacting techniques applied either at the spinning triangle or during post-spinning finishing processes have been shown to reduce hairiness and suppress pilling. Furthermore, factory-scale research on the production of 100 percent recycled yarns from pre-consumer mono-cotton demonstrates that careful alignment of carding sequences, combination processes, and count selection can yield yarns with single-fiber integrity that are suitable for both weft insertion and knit structures, thereby advancing industrial feasibility for circular textile systems (Reduanul & Shoeb, 2022). Collectively, these findings confirm that the success of mono-material mechanical recycling hinges on the coordinated optimization of feedstock uniformity, gentle fiber liberation, and deliberate yarn system selection, which together safeguard fiber length and surface integrity to ensure that yarns and fabrics produced remain commercially viable across a wide spectrum of cotton, wool, and polyester applications (Sazzad & Islam, 2022).

Depolymerization and Biocatalytic Recycling of PET and Polyamides

Chemical depolymerization, which focuses on cleaving the ester or amide linkages of synthetic fibers, is widely regarded as a cornerstone strategy for achieving true circularity since it enables the regeneration of monomeric or oligomeric units that can be reintroduced into polymerization cycles. In the case of polyethylene terephthalate (PET), techno-economic analyses and detailed process design evaluations consistently identify methanolysis, glycolysis, and hydrolysis as the leading chemolysis pathways, with the ultimate choice of route dictated by factors such as feedstock purity, purification requirements, and overall energy consumption. Recent innovations involving process-aiding solvents and catalysts have significantly reshaped this landscape, particularly in advancing efficiency under milder conditions (Noor & Momena, 2022). For instance, biomass-derived γ-valerolactone (GVL) has demonstrated the capacity not only to dissolve PET with remarkable rapidity but also to enhance alkaline hydrolysis by facilitating polymer swelling and improving interfacial contact, thereby reducing the severity of operational conditions (Chen et al., 2021). Extending this principle of solubility enhancement, studies on mixed GVL–methanol systems reveal that such combinations can effectively lower the reaction severity in PET methanolysis while still maintaining high yields of dimethyl terephthalate (DMT), aligning depolymerization with greener solvent alternatives and greater process sustainability. At the same time, deep-eutectic solvents (DES) have emerged as highly promising catalytic environments for PET glycolysis, serving as inexpensive, tunable Brønsted and Lewis acidic media that not only achieve elevated yields of bis(2-hydroxyethyl) terephthalate (BHET) but also shorten residence times relative to conventional salt catalysts while simplifying separation steps (Sert et al., 2019). Taken together, these developments underscore that the effectiveness of chemical depolymerization depends not solely on catalytic turnover rates but equally on solvation dynamics, mass-transfer efficiencies, and the ease of downstream purification, which are especially crucial when scaling technologies for post-consumer textile streams burdened with dyes, additives, and mixed fiber contaminants.

Kinetic control and process intensification have become pivotal in advancing polyethylene terephthalate (PET) depolymerization, particularly within the context of textile waste where process efficiency and scalability are essential. Recent developments in activity-based kinetic models that explicitly incorporate catalyst activities, such as those of zinc acetate, alongside co-solvent effects, now enable accurate predictions of glycolysis rates across varied operating conditions, effectively bridging the gap between laboratory kinetics and industrially relevant concentrations to support rational scale-up strategies. Parallel to modeling, experimental studies provide strong evidence that the co-optimization of process variables including pressure, temperature, and solvent environment can significantly accelerate glycolysis while maintaining comparatively mild operational conditions, thereby directly addressing long-standing industrial challenges such as extended cycle times and high energy demands. At the frontier of solvent and catalyst engineering, deep-eutectic solvent (DES) formulations have been strategically adapted for directional glycolysis using 1,4-butanediol, which yields bis(4-hydroxybutyl) terephthalate as a selective intermediate. This innovation exemplifies a departure from the singular goal of returning exclusively to PET monomers and instead demonstrates how depolymerization can be tuned toward direct upcycling into high-value performance materials such as polyurethane elastomers. The convergence of predictive kinetic modeling, solvent–catalyst system design, and product-oriented depolymerization not only expands the chemolysis toolkit but also makes it increasingly capable of addressing the heterogeneity inherent in textile feedstocks. Equally important, these integrated strategies work to narrow the energy and time penalties that have historically constrained chemical depolymerization when compared to mechanical recycling, marking a decisive step toward making chemical routes both technologically and economically competitive in the pursuit of circular textile systems.

Figure 3: Biocatalytic Regeneration Pathways of Synthetic Fibers (PET and Polyamides)



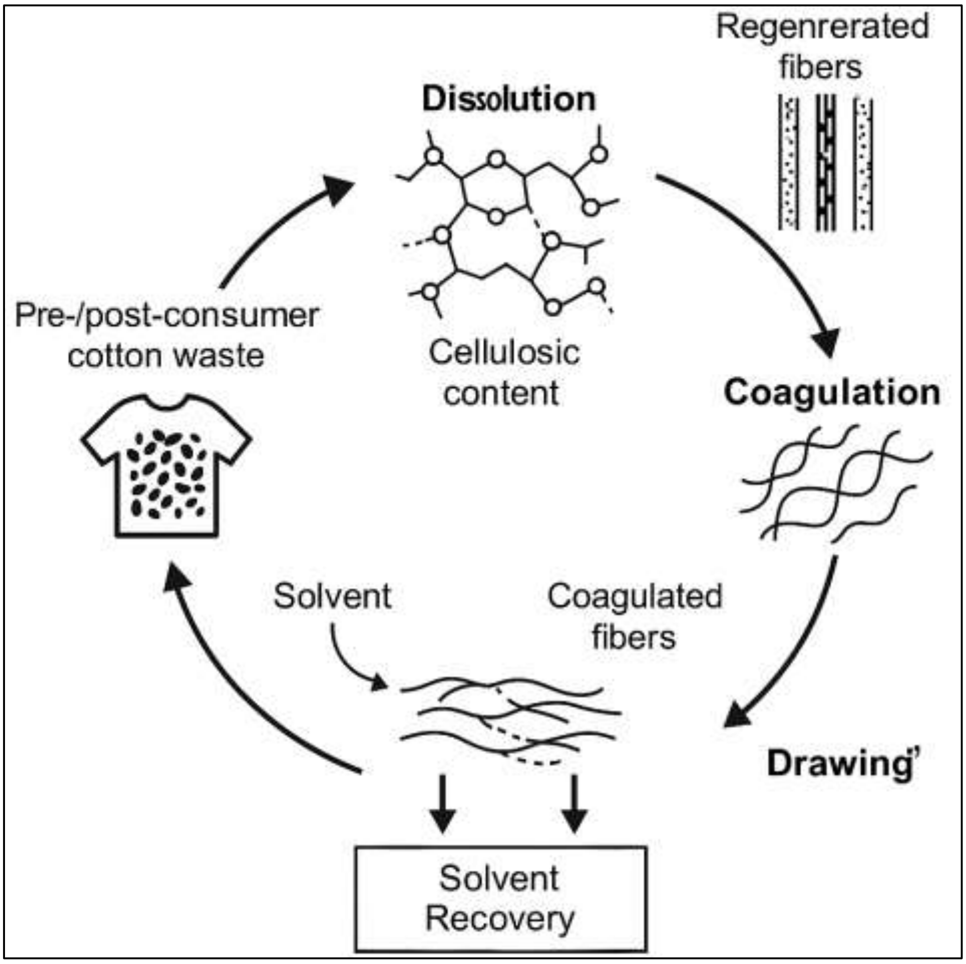
Polyamide depolymerization requires approaches tailored to its unique bond energies and equilibria, and recent advances highlight how both catalytic and hydrothermal strategies can unlock true circularity for nylon-based textiles. Cutting-edge work with organolanthanide trisamido catalysts has enabled nearly quantitative and solvent-free depolymerization of nylon-6 back into ε-caprolactam under comparatively low-temperature conditions, achieving high selectivity even for post-consumer waste streams and marking a significant breakthrough for closed-loop regeneration of polyamide textiles (Wursthorn et al., 2022). In hydrothermal pathways, subcritical water has proven highly effective at rapidly depolymerizing nylon-6, although the process establishes an equilibrium between ε-caprolactam and ε-aminocaproic acid, meaning that precise control over both temperature and residence time is critical to maximizing recoverable monomer yields while minimizing secondary degradation losses (Okajima et al., 2013). For nylon-66, recent system-level assessments have moved beyond isolated experiments to incorporate reaction kinetics, purification requirements, and sustainable process design into comprehensive frameworks for acid and alkaline hydrolysis as well as ammonolysis, showing that alkaline hydrolysis can in some cases outperform PET analogs in terms of energy efficiency while producing adipic acid and hexamethylenediamine streams well suited for repolymerization. Together, these advances underscore how polyamide chemolysis is no longer a secondary concern but rather a crucial complement to PET depolymerization, with selective catalytic "unzipping" routes for nylon-6 and process-intensified hydrolysis strategies for nylon-66 broadening the toolkit for circularity. As PET and polyamides frequently co-exist in synthetic-rich apparel, the maturation of these technologies directly enhances the feasibility of designing circular flows that can accommodate blended textile waste without compromising monomer quality or overall process sustainability (Chen et al., 2021).

Dissolution–Regeneration of Cellulosics

Dissolution–regeneration (D–R) technologies offer a transformative pathway for recycling cotton- and viscose-rich wastes into new man-made cellulosic fibers (MMCFs) by first breaking down the complex hydrogen-bonded architecture of cellulose and then reconstituting it into fresh fibers through coagulation and drawing, with three major solvent families defining current practice. Amine-oxide systems such as N-methylmorpholine-N-oxide (NMMO), the basis of lyocell, operate via a mechanism of radial swelling that progresses from the fiber periphery inward, where dissolution kinetics are influenced by water content and the fiber's inherent skin–core morphology; subsequent regeneration not only restores but reshapes crystalline domains and pore structures in ways that can be tuned by adjusting coagulation parameters and draw ratios (Chaudemanche & Navard, 2011). Ionic liquids (ILs) such as 1-ethyl-3-methylimidazolium chloride or acetate ([Emim]Cl/[Emim]OAc) and superbase acetates like [DBNH][OAc] dissolve cellulose through strong hydrogen-bond basicity and ion–dipole interactions, facilitating the preparation of homogeneous spinnable dopes at moderate temperatures and enabling high-tenacity regenerated fibers via dry-jet wet spinning (Hauru et al., 2016). Cold alkali hydrate systems such as NaOH/urea or LiOH/urea function differently, with hydroxide hydrates disrupting hydrogen bonding while urea selectively associates with hydrophobic cellulose regions, preventing premature aggregation of chains; this phenomenon, often referred to as the "urea effect," has been experimentally clarified and supports the practical wet-spinning of stable fibers from NaOH/urea solutions (Egal et al., 2008; Xiong et al., 2014). At industrial scale, the sustainability of these processes is deeply tied to solvent management, and in the case of NMMO the ability to achieve recovery rates greater than 99% is a cornerstone of its environmental credentials, while attention to impurity removal via methods such as air flotation and ion exchange, along with the mitigation of side-reactions during evaporative reconcentration, guides stabilizer selection and solvent longevity strategies (Guo et al., 2021). Taken together, these approaches underscore how D–R platforms constitute a versatile and scalable toolkit for converting not only pure cotton but also heterogeneous textile wastes into regenerated fibers with engineered crystalline structure, porosity, and mechanical performance tailored to diverse end uses.

From a circularity perspective, dissolution–regeneration (D–R) platforms have advanced from processing purified wood pulps to valorizing diverse pre- and post-consumer cotton wastes, including dyed, blended, and low-grade fractions, thereby expanding feedstock availability for regenerated fiber production. Early demonstrations established that cotton lint waste could be effectively dissolved and re-spun into new fibers, with performance tuned by dope composition and coagulation/draw conditions, confirming the feasibility of low-cost raw materials (De Silva & Byrne, 2017). Building on this, eco-friendly alkali hydrate systems such as NaOH/urea and LiOH/urea have been shown to dissolve post-consumer cottons often after acid hydrolysis to modulate molecular weight into spinnable dopes that yield fibers with tensile properties comparable to commercial MMCFs; notably, residual coloration from waste fabrics can be strategically retained, reducing or eliminating dyeing stages for certain shades. Complementary efforts with ionic liquids (ILs) have demonstrated that industrial cotton residues can be processed into continuous regenerated filaments using [Emim]Cl or [Emim]OAc dopes, where water- or alcohol-based coagulation media allow tailoring of fiber morphology and mechanical properties. Superbase ILs such as [DBNH][OAc] extend this versatility by selectively dissolving cellulose in mixed cotton–polyester wastes, enabling separation of PET and direct spinning of Ioncell-type fibers (tenacities of ~27–48 cN/tex) from the same dope providing an integrated route that preserves both components without destructive depolymerization (Haslinger et al., 2019). Collectively, these innovations illustrate how solvent choice, targeted pre-treatments, and controlled spinning protocols can align molecular-level dissolution with industrial fiber formation, positioning D–R processes as a cornerstone technology for reintegrating waste cottons into high-value MMCF markets.

Figure 4: Cycle of Dissolution–Regeneration of Cellulosic Textiles



Recent advances in dissolution–regeneration (D–R) platforms move beyond spinnability toward integrating coloration strategies, solvent stewardship, and property retention, thereby strengthening closed-loop textile-to-textile recycling. In lyocell/NMMO systems, solvent cycles are operated in near-closed loops, where detailed monitoring of impurity accumulation and thermal side-reactions such as the formation of particulates and colored degradation products during solvent evaporation has informed stabilizer use and optimized oxygen/temperature control, extending solvent lifetime while preserving fiber quality (Guo et al., 2021). Color management, traditionally one of the most resource-intensive and effluent-heavy textile processes, is increasingly embedded directly into D–R. For instance, dyed cotton waste has been regenerated into "color-fast" cellulose fibers with mechanical performance comparable to viscose, while retaining chromophores within the fiber structure; importantly, these fibers can be recycled again, demonstrating multi-cycle coloration circularity (Liu et al., 2019). Similarly, in NaOH/urea systems, the deliberate retention of residual dyes from post-consumer cottons has been leveraged to create pre-colored regenerated fibers, turning contaminants into functional attributes and reducing both water and chemical inputs from conventional dyeing (Liu et al., 2019). Across solvent families, fine control of molecular dissolution, dope rheology, and regeneration conditions enables tailoring of fiber crystallinity, porosity, and orientation, producing materials with desirable combinations of strength, hand, and dye fastness. Collectively, these strategies embed color retention and solvent stability into fiber formation, advancing D–R as a technically robust and environmentally aligned route for circular MMCF production.

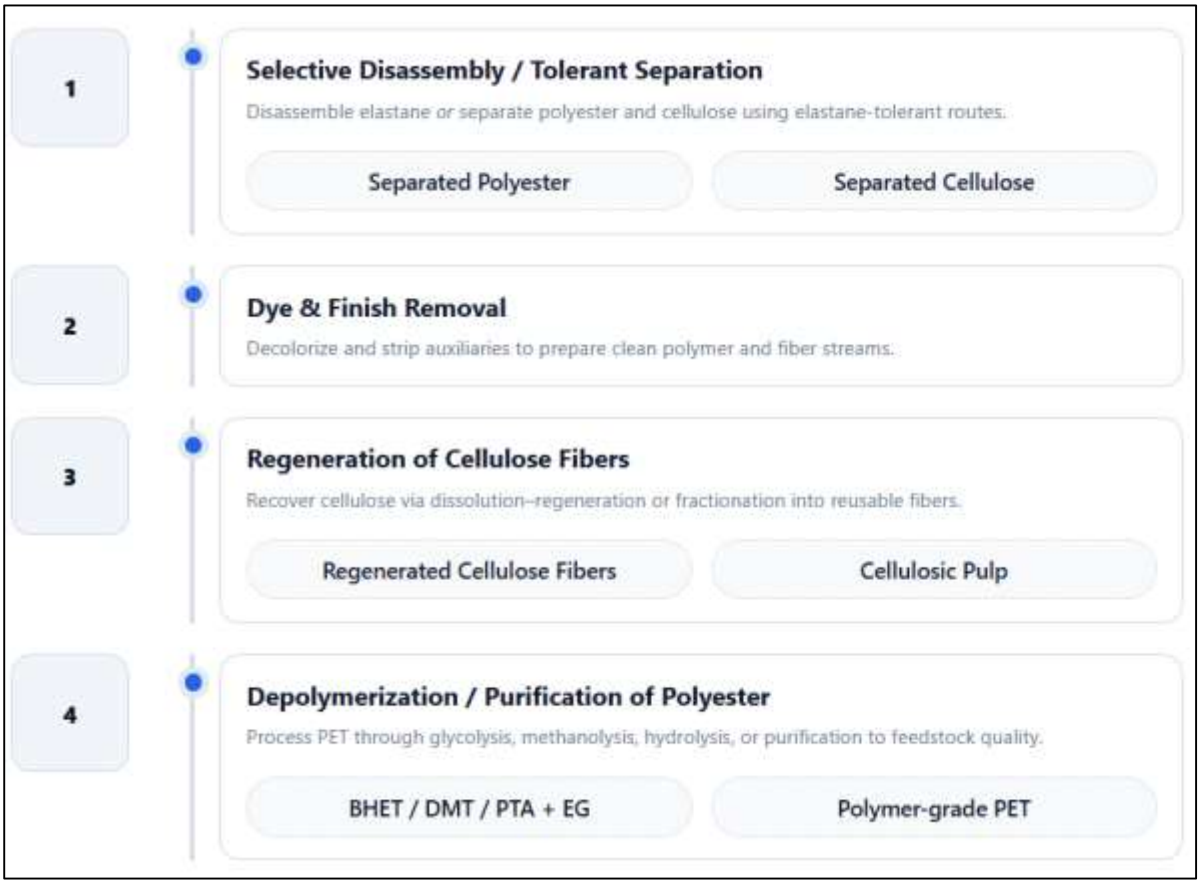
Recycling of Blended Fabrics & Elastane Management

Blended fabrics, particularly polyester/cotton (polycotton) textiles, represent one of the most intractable challenges in textile circularity, as their tightly interwoven yet chemically incompatible components resist single-path recycling approaches. To overcome this complexity, researchers have converged on a set of selective separation strategies that prioritize the preservation of quality in both polyester and cellulose streams. One prominent pathway pursues polyester-first depolymerization while safeguarding the cellulose fraction; for instance, room-temperature base-catalyzed depolymerization of PET within mixed matrices can efficiently release monomers that are suitable for closed-loop re-polymerization into virgin-quality polyester. In contrast, cellulose-first processes aim to maintain polyester in its polymeric state, as demonstrated by hydrothermal "water-only" treatments that operate within carefully defined windows to physically liberate intact polyester fibers while fractionating the cotton phase into recoverable cellulose derivatives. Expanding this toolbox further, ionic liquid (IL) systems provide a solvent-based lever: imidazolium acetate ILs have shown the ability to selectively dissolve cotton fibers from polycotton blends, enabling high-yield recovery of polyester as a mechanically reusable fraction while simultaneously regenerating the cellulose into spinnable fibers, thereby reinforcing circular fiber-to-fiber pathways for both materials (Silva et al., 2014). Additionally, catalytic hydrothermal routes using acid promoters bring another dimension of control; for example, subcritical water fractionation with phosphotungstic acid has achieved remarkable recovery rates of both polyester and cellulose, illustrating how catalytic tuning minimizes degradation while maximizing valorization of both components (Yan et al., 2019). Collectively, these complementary strategies outline a practical hierarchy for polycotton recycling: employ selective depolymerization or dissolution to disentangle the blend, then direct each purified stream toward the most value-preserving circular pathway. This approach not only addresses the technical difficulty of separating polycotton but also exemplifies how process intensification and selective chemistry can transform even the most stubborn blended fabrics into sustainable feedstocks for high-value textile regeneration.

Elastane, or spandex, though typically present at low weight fractions, complicates textile circularity because its polyurethane-urea chemistry resists the chemical and thermal conditions used to recover PET or cellulose. To manage this challenge, two principal strategies have emerged. The first involves selective elastane disassembly through solvolysis, converting the polymer into base chemicals such as 4,4′-MDA and polyTHF while leaving the major fibers largely unaffected. Experimental systems using tert-amyl-alcohol with KOH have demonstrated this chemoselectivity directly on elastane-containing textiles, suggesting modular process steps that can remove elastane either before or after primary separation operations. The second strategy integrates elastane tolerance into cotton-first or PET-first schemes, enabling high-quality regenerated cellulose fibers from cotton-elastane waste by combining targeted elastane degradation with dissolution–regeneration processes; these findings show that low-level elastane presence need not compromise fiber-to-fiber quality. Process integration for PET streams is equally critical. Alkaline-alcoholic media allow low-temperature PET hydrolysis within polycotton matrices, reducing reaction times and mitigating cellulose damage, particularly when elastane has been removed or rendered inert. Hydrothermal fractionation in water-only systems offers another avenue, physically separating polyester and cellulose prior to any elastane-targeted step, thus lowering risks of cross-contamination and preserving fiber integrity. Collectively, these developments support a structured decision-making framework for elastane-containing blends: first, screen for elastane content; second, apply either selective disassembly or tolerant separation approaches; and third, direct cotton fibers toward regeneration processes and PET fractions toward monomer-grade depolymerization or polymer-grade purification. This integrated approach ensures that the challenges posed by elastane do not impede high-value recycling and aligns with broader goals of maintaining fiber performance and closing circular loops in blended textiles.

Industrial-scale recycling of textiles requires that dye and finish removal be integrated with separation workflows to preserve fiber quality and ensure downstream process compatibility. Colorants and surface finishes can impair solvent systems, foul catalysts, and carry over into regenerated polymers or pulps, making decolorization and finish-stripping essential pre- or inter-steps. For cotton-rich

Figure 5: Cycle of Blended Fabric Recycling and Elastane Management



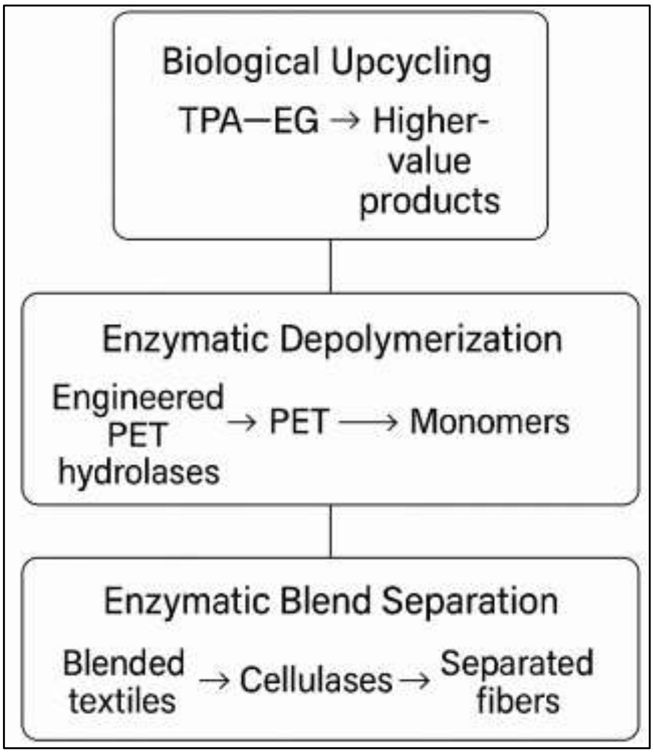
streams, redox-assisted decolorization sequences, such as $Na_2S_2O_4$ followed by H_2O_2, achieve high levels of color removal while maintaining acceptable cellulose strength, making them suitable as pretreatments prior to ionic-liquid dissolution or as intermediate steps before viscose- or lyocell-type regeneration (Li et al., 2022). In polycotton blends with reactive-dye chemistries or high finish loadings, modified alkaline hydrolysis protocols can simultaneously induce PET saponolysis and improve decolorization, streamlining downstream purification (Abdel-Aziz et al., 2022). Subcritical-water treatments offer another route, selectively degrading cellulose to facilitate fractionation while leaving PET intact for subsequent upgrading (Huang et al., 2018). Mild catalytic alkaline methods have also demonstrated the ability to recover cotton nearly intact from polycotton, enabling PET to be processed either via glycolysis for monomer-grade recovery or maintained polymer-grade if separation occurs prior to depolymerization. Across these approaches, the most effective strategies are modular, combining dye and finish management with elastane disassembly and selective fiber separation to accommodate heterogeneous feedstocks without compromising yield or fiber quality. This integrated, stepwise logic ensures that variations in color, finish, or minor fiber constituents do not cascade into downstream inefficiencies, supporting reliable and high-value textile recycling in industrial operations.

Enzymatic and Biological Recycling Pathways

Biocatalytic strategies for textile circularity have progressed markedly, particularly for synthetic fibers, with specialized polyester hydrolases now able to depolymerize polyethylene terephthalate (PET) into monomers under relatively mild conditions. The modern framework emerged from the discovery of *Ideonella sakaiensis*, whose PETase and MHETase enzyme pair catalyzes stepwise hydrolysis of PET first to mono(2-hydroxyethyl) terephthalate (MHET) and subsequently to terephthalic acid (TPA) and ethylene glycol (EG), providing a pioneering blueprint for biological closed-loop PET recycling (Yoshida et al., 2016). In parallel, metagenomic exploration of leaf-branch compost uncovered

LC-cutinase, a thermally robust polyesterase that expanded the enzymatic toolkit and foreshadowed the development of thermostable PET hydrolases capable of handling industrially relevant substrates (Sulaiman et al., 2012). Structure–function investigations elucidated PETase's distinctive binding cleft and catalytic architecture, revealing activity patterns on semi-crystalline PET and offering targets for rational mutagenesis and reaction optimization (Austin et al., 2018). Complementary crystallographic studies of PETase variants further characterized active-site dynamics and substrate accommodation, mapping residues that influence catalytic efficiency and stability insights that continue to guide enzyme engineering for higher throughput and tolerance to mixed textile feedstocks (Joo et al., 2018). Collectively, these foundational studies established both mechanistic and structural knowledge critical for deploying enzymatic depolymerization within textile-relevant waste streams containing dyes, finishes, and blended fibers. They also defined purity benchmarks for recovered monomers, enabling downstream re-polymerization or biological upcycling pathways while ensuring that regenerated PET maintains quality comparable to virgin material. This body of work provides the scientific and operational groundwork for integrating biocatalysis into scalable circular strategies for synthetic-dominant textiles.

Figure 6: Framework of Enzymatic and Biological Recycling Pathways for Textiles



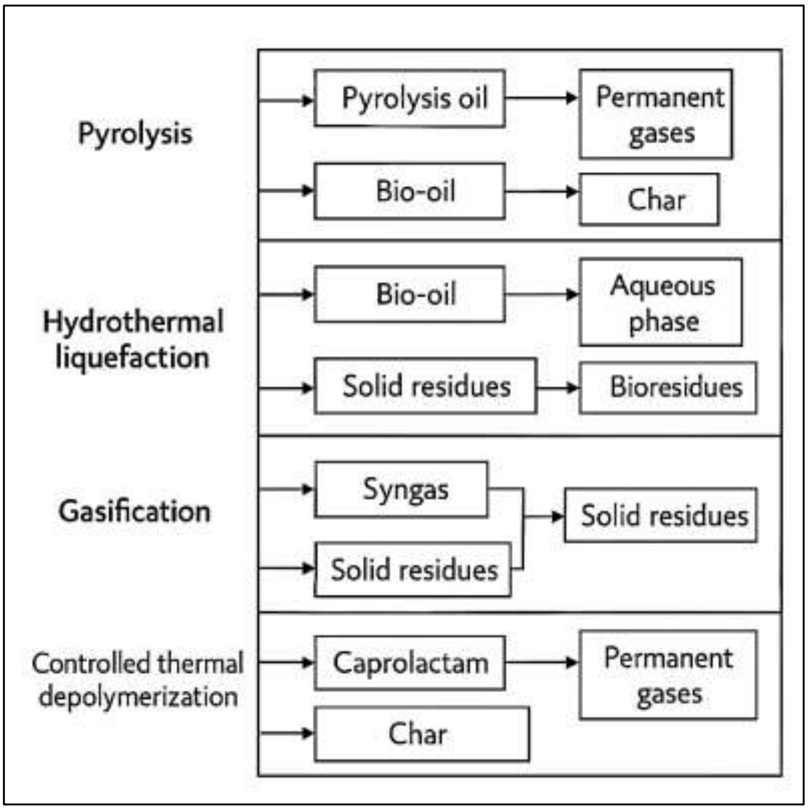
Recent advances in enzymatic recycling have expanded the biocatalyst toolkit along two complementary directions: enhancing stability and catalytic performance to approach industrially relevant throughputs, and implementing multi-enzyme systems that accelerate depolymerization while mitigating product inhibition. Directed evolution and rational design strategies have yielded PETase variants with improved thermostability and activity near PET's glass-transition temperature, broadening the operational window for amorphous and pre-treated textile-grade PET and enabling more robust processing under moderate temperatures (Son et al., 2019). A particularly notable innovation is the PETase–MHETase two-enzyme cascade, which alleviates the accumulation of intermediates, thereby increasing monomer release rates and overall depolymerization efficiency; high-resolution MHETase structures from this work have guided targeted optimizations of active-site and lid-domain residues to maximize catalytic throughput (Knott et al., 2020). Machine-learning–guided protein engineering has further produced FAST-PETase, a highly effective variant capable of degrading diverse post-consumer PET articles under mild conditions while tolerating common additives, addressing the heterogeneity characteristic of apparel waste streams and supporting broader industrial applicability (Lu et al., 2022). Beyond PET, enzyme strategies are being applied to blended fabrics: selective cellulase cocktails can digest cotton in polycotton materials, liberating intact polyester fibers and demonstrating an enzymatic fiber-separation concept that complements chemocatalytic routes while reducing solvent and catalyst requirements during upstream processing. Collectively, these developments illustrate a modular, textiles-aware biocatalytic framework, combining engineered hydrolases for PET depolymerization, multi-enzyme cascades to manage intermediates, and targeted cellulases to facilitate blend separation. When integrated into recycling workflows, these approaches have the potential to increase yield and purity, reduce energy inputs, and enable high-quality circular pathways for both synthetic and mixed-fiber textile waste, effectively bridging laboratory innovation with scalable industrial implementation.

Beyond enzymatic depolymerization, biological upcycling of PET-derived monomers has emerged as a potent strategy to enhance material circularity by converting terephthalic acid (TPA) and ethylene glycol (EG) into higher-value molecules and bio-based polymers. A pioneering approach engineered Escherichia coli to transform TPA into vanillin with high conversion, effectively coupling enzymatic PET hydrolysis with a microbial biosynthetic pathway to produce a commodity flavor chemical, thereby creating value streams that extend beyond conventional PET remanufacturing (Sadler & Wallace, 2021). At larger scales, microbial consortia and engineered Pseudomonas strains have converted PET hydrolysates into β-ketoadipate and subsequently into medium-chain-length polyhydroxyalkanoates (mcl-PHA) and bio-based poly(amide urethane), exemplifying a sequential deconstruct-and-build paradigm that leverages established bioplastic platforms while accommodating variability in hydrolysate composition (Tiso et al., 2021). These bioconversion pathways broaden the economic rationale for enzymatic PET depolymerization by generating markets for depolymerization products in both flavors and functional polymers, while simultaneously establishing microbial chassis and pathway frameworks adaptable to textile-grade monomer streams. Integration of these biological upcycling strategies with optimized hydrolases and enzymatic or chemocatalytic blend-separation processes enables a flexible circular fashion approach, wherein textile waste can either be returned to monomer pools for fiber-to-fiber regeneration or diverted into higher-value bio-based products. Process selection is informed by substrate crystallinity, residual dye and finish loads, and the trade-offs between closed-loop fiber recycling and open-loop value-added reuse, thus allowing textile systems to achieve both environmental and economic optimization while significantly reducing landfill dependence.

Thermal routes for hard-to-recycle textile streams

Thermochemical conversion pathways, including pyrolysis, hydrothermal liquefaction, and gasification, provide versatile solutions for heterogeneous post-consumer textiles that are heavily dyed, finished, or compositionally complex, often exceeding the practical limits of mechanical or solvent-based recycling. Pyrolysis, conducted in the absence of oxidants, transforms mixed fibers into condensable oils and waxes, permanent gases, and carbon-rich char while simultaneously degrading contaminants and partially resetting molecular structures. Detailed kinetic and product analyses of cotton, polyester, and polycotton blends reveal multi-stage devolatilization processes in which cellulose and PET components volatilize at distinct temperature ranges, with feedstock characteristics and thermal profiles strongly influencing reaction rates, aromatics formation, and char microstructure. Co-pyrolysis of blended textiles has further demonstrated synergistic gas formation between cellulose and PET fractions, offering opportunities to optimize fuel gas yields and energy recovery when conventional monomer-level depolymerization is impractical. At a system level, reactor configuration, controlled heating rates, and vapor-phase upgrading strategies, such as zeolite-catalyzed aromatization, are key levers to direct pyrolysis oils toward BTX-range aromatics while limiting polycyclic aromatic hydrocarbon formation, providing a dual benefit of chemical feedstocks and energy provision. Collectively, these thermochemical processes extend the circularity toolkit by enabling energy and material recovery from textiles that resist conventional recycling, thereby complementing fiber-to-fiber and biocatalytic approaches and ensuring that low-grade or mixed-waste streams can contribute meaningfully to both environmental and economic objectives within circular fashion infrastructures.

Figure 7: Process–Output Matrix of Thermal Recycling Routes for Textile Waste



Hydrothermal liquefaction (HTL) uses sub- or supercritical water, typically at 280–374 °C under elevated pressures, to solubilize organic matter and cleave ester bonds, making it particularly suitable for PET-containing textile blends. In these systems, terephthalate fragments partition into aqueous and solid phases that can be isolated with reduced interference from dyes and other finishes compared with conventional atmospheric hydrolysis. Bench-scale HTL studies on post-consumer mixed-fiber textiles demonstrate simultaneous production of bio-oils and recovery of solid terephthalic-acid-rich fractions, with yields strongly dependent on residence time, water-to-fiber ratio, and the presence of elastane or protein-based fibers. Gasification further extends the thermochemical portfolio by converting textile waste into H_2- and CO-rich syngas under controlled oxidizing atmospheres or steam. For polycotton, steam gasification combined with catalytic reforming over iron-modified biochar has achieved high cold-gas efficiencies and H_2 contents approaching 51 vol% at 800 °C, demonstrating a pathway to hydrogen-rich energy carriers suitable for power generation, fuel synthesis, or ammonia production. Collectively, these studies position thermochemical routes as complementary elements in a circular fashion toolkit: HTL is ideal for PET-heavy streams where aromatic acid recovery is desired; pyrolysis offers flexible chemical feedstocks, energy, and potential char valorization; and gasification delivers syngas and hydrogen when molecular-level recovery is less critical. By integrating these processes, heterogeneous, dye-laden, or low-grade textiles that resist mechanical, solvent, or enzymatic recycling can still contribute to material and energy circularity, supporting a multi-pathway approach that maximizes value retention while mitigating landfill burden.

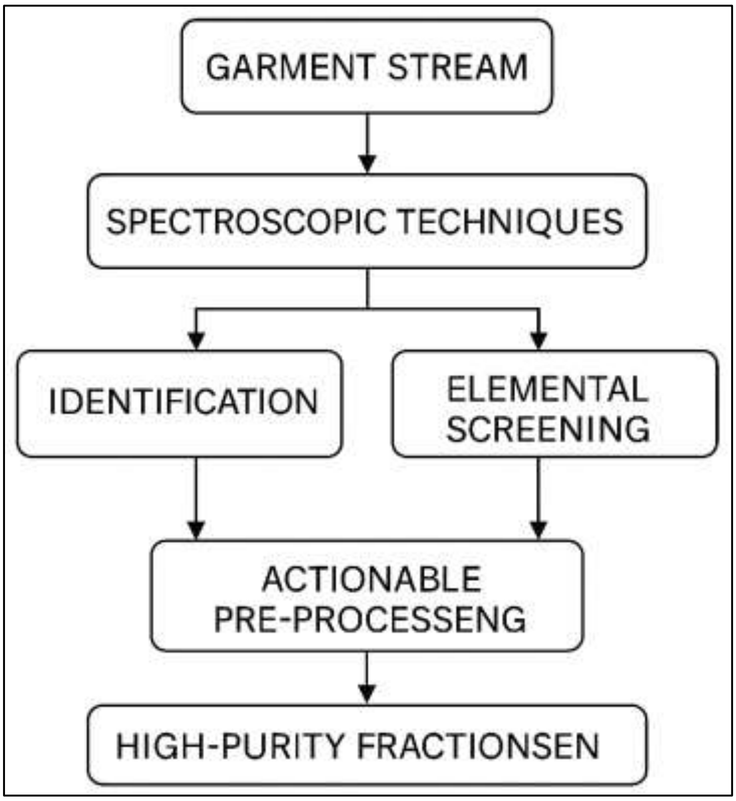
Thermochemical approaches further intersect with monomer recovery and high-value carbon-material upcycling, expanding the circularity potential for textile waste. For nylon-6 fractions embedded in consumer garments, controlled thermal depolymerization can recover caprolactam in substantial yields while simultaneously producing gases and char that are energetic enough to partially self-sustain the process, offering a monomer-recovery route that tolerates certain contaminants more effectively than conventional wet-chemical methods (Kim et al., 2020). On the carbon-materials front, kinetics-guided pyrolysis of natural-fiber textiles such as hemp has generated hierarchical porous carbons with tailored surface areas and pore architectures suitable for gas capture or adsorption applications, demonstrating that even low-grade textile streams can be valorized into high-performance carbon products. Broad experimental surveys of fast pyrolysis across both natural and synthetic fibers reveal how feedstock composition and processing temperatures in the 500–900 °C range influence char yields, oil and wax speciation, and the H_2/CO content of evolved gases, providing critical design parameters for reactor selection and downstream upgrading in industrial textile-to-energy or chemical plants. Complementary studies focusing on aromatic hydrocarbon production from textile pyrolysis illustrate that careful management of vapor residence times and catalytic surface interactions can optimize the generation of intermediate chemicals for subsequent synthetic applications, reinforcing thermochemical conversion as a versatile and scalable pillar within circular fashion strategies. Taken together, these findings highlight that thermochemical processes not only provide pathways for energy and monomer recovery but also open opportunities for high-value material upcycling, ensuring that heterogeneous, dyed, or contaminant-laden textiles contribute to multi-dimensional circularity alongside mechanical, chemical, and biological recycling approaches.

Advanced Sorting, Identification, and Pre-Processing

High-fidelity identification and systematic pre-processing stand as the cornerstone of circular fashion, since every recycling pathway whether mechanical, thermomechanical, solvent-based, or chemical relies on the assurance of clean, composition-specific input streams that can move seamlessly through their respective processes. In modern facilities, the demand for precision has encouraged the integration of multi-sensor classification platforms with chemometrics and advanced machine learning, where the synergy of these tools allows fiber classes, blended materials, and even complex surface treatments to be discriminated at line speed with remarkable accuracy. Within this context, near-infrared (NIR) spectroscopy and hyperspectral imaging are rising as indispensable techniques, capable of generating molecular "fingerprints" through overtone and combination bands of O–H, C–H, and N–H groups. When paired with boundary-oriented or one-class algorithms, these tools have been shown to deliver consistent and robust sorting results, even in situations where class distinctions are subtle or overlapping (Tan et al., 2019). Beyond simple identification, quantitative spectral models have been adapted to estimate the component percentages of blended textiles, using non-linear learners such as extreme learning machines, particularly when spectra are carefully pre-processed to account for distortions and noise (Chen et al., 2020). Traditional obstacles that once limited spectral methods such as baseline shifts induced by dyes and finishes, the structural variability of woven or knitted fabrics, or the interference of printed designs are now being addressed through calibration transfer methods and the meticulous selection of informative wavelengths. These advances have made it possible, for example, to estimate cotton content within PET blends even when the textiles are dyed, significantly enhancing practical applicability (Rodgers & Beck, 2009). Meanwhile, for situations demanding more granular polymer subclass resolution or confirmatory verification, mid-infrared techniques continue to prove indispensable. Attenuated total reflectance Fourier-transform infrared spectroscopy (ATR FT-IR) combined with multivariate classification enables highly accurate differentiation of acrylic, polyamide, polyester, regenerated cellulosics, and protein fibers, while also underpinning spectral libraries that form the operational backbone of industrial sorting lines.

Non-invasive and field-deployable spectroscopic techniques have reached a level of maturity that allows them to seamlessly align with the demanding constraints of industrial textile pre-processing, where delicate fabrics and heterogeneous compositions require methods that balance accuracy with practicality. Reflectance FT-IR (r-FT-IR) has emerged as a particularly valuable tool because it captures diagnostic spectra without the need to press fragile fabrics against a crystal, which not only preserves the integrity of sensitive textiles but also enhances throughput in high-volume operations. Its performance has been shown to rival that of traditional ATR-FT-IR across a wide range of apparel polymers, and it demonstrates notable strength in separating amide-based fibers such as wool, silk, and polyamide categories that frequently confound pipelines relying exclusively on NIR spectroscopy (Peets et al., 2019). Alongside these developments, forensic-grade workflows have begun to influence recycling practices by offering validated methodological templates. For example, supervised classification models trained on ATR-FT-IR spectra from extensive synthetic-fiber datasets have achieved greater than 95% accuracy under realistic variance, underscoring the potential for rigorous and standardized spectral libraries to be transferred directly into industrial contexts (Aljannahi et al., 2022). In cases where conventional vibrational methods face challenges due to colorants, finishes, or subtle subclass distinctions, Raman imaging provides a complementary pathway. When coupled with multivariate statistical analysis, Raman-based approaches can distinguish fibers on the basis of dyestuff chemistry and matrix-specific signals, thereby adding another layer of precision to textile discrimination (Zapata et al., 2021). Beyond polymer identification, elemental screening has proven equally crucial in pre-processing workflows. Portable total-reflection X-ray fluorescence (TXRF) has demonstrated the ability to rapidly detect catalyst residues, delusterants, and metal-containing dyes in single fibers, effectively flagging garments that require de-trimming, de-metalling, or tailored decolorization treatments before being routed into polymer-specific flows (Kurokawa et al., 2021). Taken together, these methodological advances enable industrial facilities to sort garments not only by their fundamental polymeric base but also by problematic additives and finishes, thus ensuring cleaner input streams and higher quality recycles that strengthen circular fashion ecosystems.

Figure 8: Sorting, Identification, and Pre-Processing in Textile Recycling



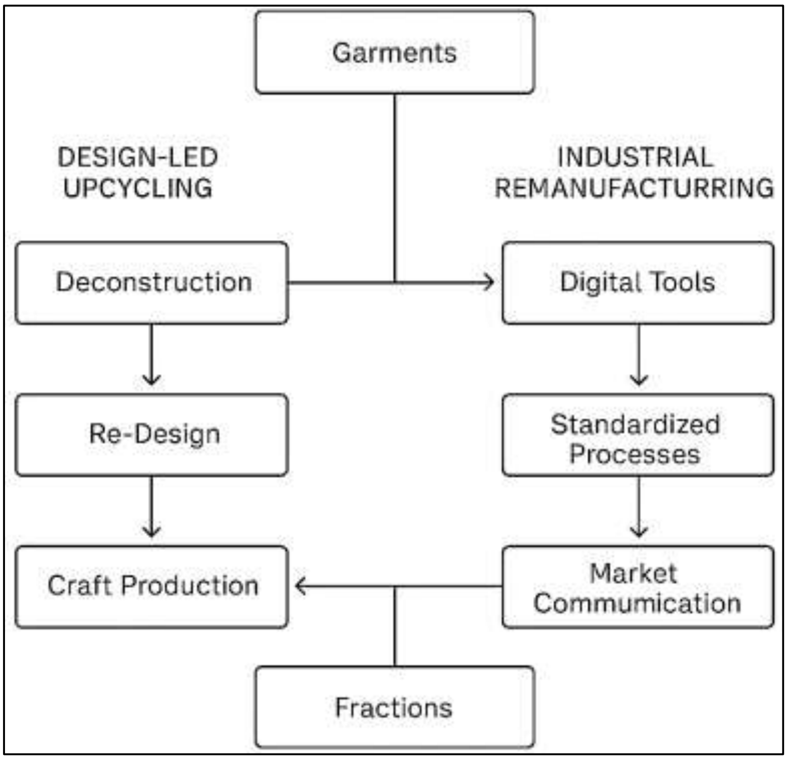
Integration into automated lines requires both sensing and actionable pre-processing. Research at industrial scale shows that NIR can not only identify polymer families but also predict polyester content across common blends and transfer the calibration to plant-level systems; this supports the creation of closed-loop fractions for PET and PET-rich streams. Parallel machine-vision pipelines fuse hyperspectral data with image-based features to estimate polyester content pixel-wise, thereby coping with spatial heterogeneity, prints, and panel construction conditions typical of post-consumer garments (Mäkelä et al., 2020). Pre-processing then operationalizes the analytics: items flagged for non-textile components (zippers, buttons, eyelets) or high-risk finishes can be automatically diverted for de-trimming and label removal; elastane-bearing cores, multilayer laminates, and coated fabrics can be segregated to solvent-based or chemical routes; and monochrome, pigment-light fractions can be prioritized for mechanical or thermomechanical recycling with minimal color correction. Facilities increasingly maintain living spectral libraries and "binning rules" that tie classifier outputs to specific actions e.g., de-metal, de-label, shred-and-open fabric, solvent-clean, or route to monomerization so that the identification step directly drives pre-processing choices and consistent bale specifications. In sum, coupling robust spectroscopy (NIR/r-FT-IR), complementary confirmatory tools (Raman, TXRF), and rules-driven pre-processing converts a heterogeneous garment stream into high-purity, process-ready fractions and materially raises yield and quality across circular textile pathways(Peets et al., 2017).

Upcycling Pathways: From Design-Led to Industrial Remanufacturing

Design-led upcycling in fashion typically begins at the studio bench: garments are deconstructed, pattern pieces are re-imagined, and new compositions are assembled to maximize material retention and narrative value. Contest- and atelier-based experimentation has shown how aesthetic innovation and material stewardship can coexist, illustrating practical pathways from one-off prototypes to repeatable techniques (Marques et al., 2019). Yet market diffusion depends on how consumers evaluate "newness" and risk in pieces made from reclaimed materials. Evidence comparing recycled versus upcycled fashion shows that perceived value, perceived risk, and social norms jointly shape the well-known attitude–behavior gap, with upcycled items often eliciting strong self-expressive benefits but also quality uncertainty (Park & Lin, 2020). Clear communication and labeling can ease that uncertainty: when circular attributes are disclosed transparently and especially when verified by a third party willingness to pay rises meaningfully (Boyer et al., 2021; Pal et al., 2021). On the supply side, integrating upcycling strategies into conventional manufacturing requires design-for-disassembly, modular construction, and pattern strategies that preserve fabric continuity and minimize offcuts (Fashion & team, 2021). Recent reviews codify such "circular product design" tactics for apparel (e.g., modularity, upgradeability, remaker-friendly seams), offering a vocabulary that bridges craft practices with factory constraints. Together, these threads position design-led upcycling not as a marginal craft, but as a pre-industrial R&D stage that can inform scalable processes and predictable product quality. Scaling beyond one-offs requires digital tools and workflow orchestration so remanufacture can be planned, simulated, and executed with fewer iterations. Empirical work shows that 3D garment design platforms (e.g., CLO3D) enable measured deconstruction and digital fit-mapping of donor garments, compressing sampling cycles and improving pattern accuracy for remanufactured sportswear. Digital 3D methods also enhance zero-waste strategies: by iterating virtually on placement, seam logic, and piece nesting, designers can reduce cutting waste while preserving silhouette intent. At the factory level, remanufacturing faces three interdependent bottlenecks irregular input sourcing, throughput time, and skilled labor requirements each of which can be mitigated by standard operating procedures, semi-automation, and information feedback between design and production (Pal et al., 2021). On the demand side, experimental pricing studies indicate that circular attributes alone do not guarantee premiums; rather, premiums materialize when environmental performance is credibly communicated and third-party assurance is present (Pretner et al., 2021). These findings suggest that the "pipeline to scale" runs through a tight loop: digital pre-production to tame variance, production systems designed around repeatable remanufacture tasks, and market communication that turns quality assurances into willingness-to-buy signals.

Bridging design-led and industrial upcycling also hinges on the codification of pattern systems and product architectures that welcome second lives. Zero-waste pattern research offers techniques (e.g., weave-integrated or composite pattern blocks) that translate well into standardized "re-cut" libraries for common garment archetypes, reducing the cognitive load of each new remanufacture (practice, 2019). Process guidelines for integrating upcycling into conventional lines such as modular panelization, standardized seam allowances for future disassembly, and data-rich labels documenting fiber content and prior alterations help factories schedule, cost, and quality-assure upcycled SKUs next to virgin ones (Fashion & team, 2021). On the market side, two complementary demand levers have robust empirical backing: (1) circularity labels that grade product circular content on a continuum (not a binary), which consumers understand and reward at low-to-moderate levels of circular content (Boyer et al., 2021), and (2) message framing plus verification that narrows the attitude–behavior gap identified for both recycled and upcycled garments. Recent model-comparison work further clarifies when and how different messaging architectures convert preference into purchase, offering managers evidence-based playbooks to position upcycled lines without eroding perceived quality. Strategically, then, the upcycling pathway scales when design vocabularies, digital toolchains, factory routines, and market signals are co-designed so remanufacturing becomes a repeatable, information-rich extension of mainstream apparel operations rather than an artisanal exception.

Figure 9: Pathways from Design-Led Upcycling to Industrial Remanufacturing



METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidance to ensure a transparent, replicable, and rigorous process from scoping to synthesis. An a priori protocol specified the population (post-consumer and post-industrial textiles relevant to fashion), interventions (innovative recycling and upcycling technologies), comparators (virgin or conventional processes where applicable), and outcomes (technical performance, landfill diversion, and environmental indicators), as well as inclusion and exclusion criteria and the time window (January 2010–August 2022). Comprehensive searches were conducted in Scopus, Web of Science Core Collection, ScienceDirect, IEEE Xplore, SpringerLink, Wiley Online Library, Taylor & Francis, and Google Scholar, using Boolean strings that combined textile terms with technology, circularity, and assessment keywords; backward and forward citation chasing and targeted searches of key journals ensured coverage of seminal and very recent work. Records were imported into a reference manager, de-duplicated, and screened in two stages (title/abstract, full text) by two independent reviewers using pretested forms; disagreements were resolved by discussion, with a third reviewer available for arbitration. Methodological quality and risk of bias were appraised with fit-for-purpose checklists (e.g., MMAT for mixed-methods, tailored criteria for laboratory process studies and LCAs/TEAs), and reliability checks were performed on a stratified 20% subsample before full extraction proceeded. A standardized extraction template captured study metadata, feedstock and pre-processing details, process conditions, yields and purity, fiber quality properties, contaminant handling, scale (lab/pilot/industrial), environmental indicators (e.g., greenhouse gases, energy, water, toxicity, microfibre proxies), techno-economic variables (e.g., CAPEX/OPEX notes, solvent and energy recovery, offtake assumptions), and policy or certification context. When necessary, authors were contacted to clarify ambiguous metrics or system boundaries. Data synthesis combined structured narrative with evidence tables; where indicators and functional units were sufficiently harmonized, we aligned boundaries and reported comparative ranges rather than pooled effects. The final corpus comprised 95 peer-reviewed articles meeting all eligibility criteria, representing multiple geographies and fiber systems and covering mechanical, chemical, biological, thermal, sorting/pre-processing, and upcycling pathways relevant to circular fashion.

Screening and Eligibility Assessment

Screening and eligibility assessment followed a two-stage, dual-reviewer workflow anchored in the pre-registered inclusion criteria and documented in a PRISMA flow record. After database searches and citation chasing, 2,143 records were imported to the reference manager and a screening platform; automated and manual de-duplication (by DOI, title, author string, and year) removed 376 duplicates, leaving 1,767 unique records. Two reviewers independently screened titles and abstracts against the a priori criteria (peer-reviewed journal articles; English; 2010–August 2022; empirical studies of textile recycling or upcycling technologies with reportable technical, environmental, or techno-economic outcomes) and achieved substantial agreement after a calibration exercise on 100 records (Cohen's $\kappa = 0.82$). At this stage, 1,532 records were excluded, most commonly because they concerned non-textile plastics, presented purely conceptual or policy discussion without process/performance data, focused solely on waste prevention or consumer behavior without a technological intervention, fell outside the time window, lacked a DOI, or were review papers used only for snowballing. The remaining 235 articles underwent full-text assessment by two independent reviewers using a pretested form that captured feedstock definition, process description and conditions, measurable outputs (e.g., yield, purity, fiber quality, monomer recovery), scale (lab/pilot/industrial), and, where relevant, life-cycle or techno-economic indicators and data transparency. Disagreements were resolved by discussion; a third reviewer was available but required in fewer than 5% of cases. Full-text exclusion ($n = 140$) was primarily due to insufficient methodological detail to extract comparable metrics, absence of textile-specific data in multi-material studies, reliance on patents without peer-reviewed performance evidence, incompatible system boundaries in LCAs with no disaggregated data, or duplication of data across companion publications (in which case the most complete article was retained). When necessary, authors were contacted to clarify ambiguous units or system boundaries; articles remained eligible if clarifications were provided. The final corpus comprised 95 studies that met all criteria and supplied extractable data for synthesis, spanning mechanical, chemical, biological, thermal, sorting/pre-processing, and design-led remanufacturing pathways across diverse fiber systems and geographies.

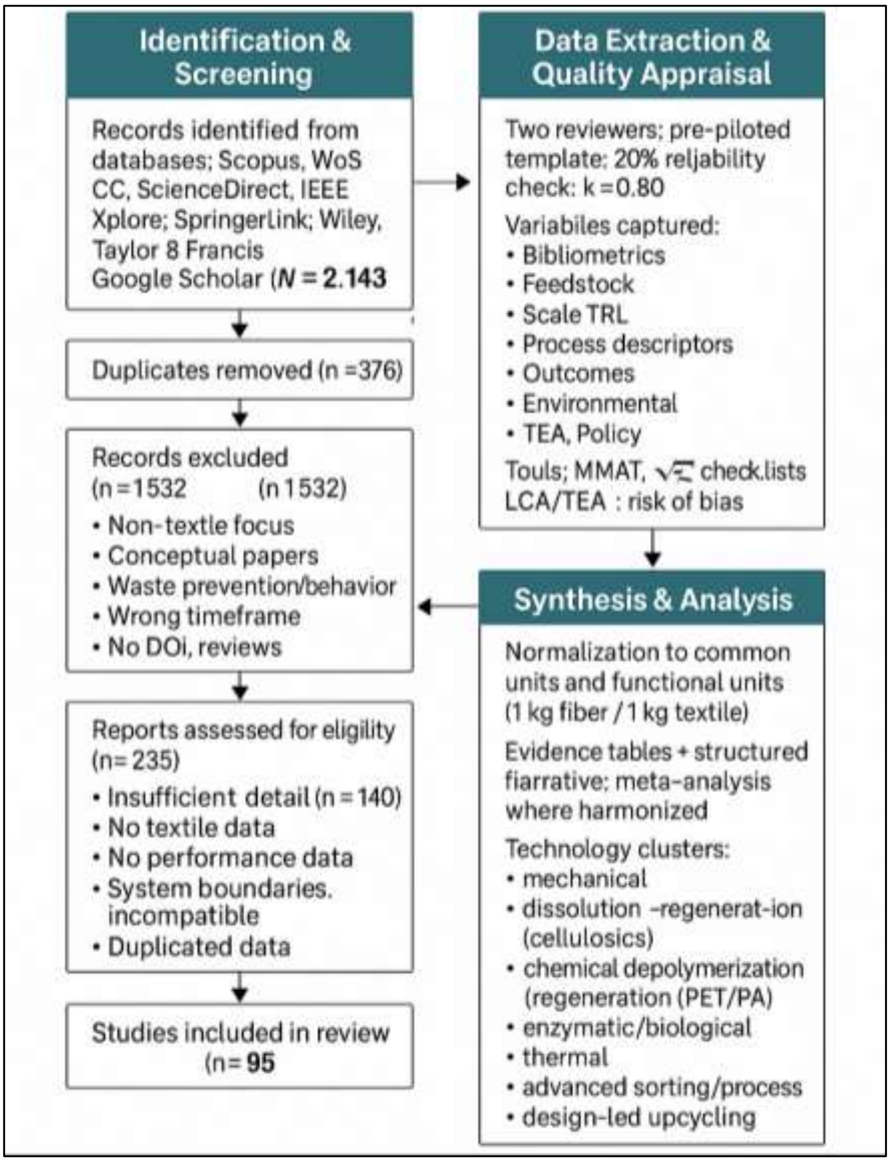
Data Extraction and Coding

Data extraction and coding were conducted with a pre-piloted template and an explicit codebook to ensure consistency, reproducibility, and comparability across heterogeneous study designs. For every included article ($n = 95$), two reviewers independently populated fields covering bibliometrics (DOI, year, journal, country/region), study design (experimental, pilot, industrial demonstration, LCA, TEA), feedstock characteristics (fiber type and share, mono vs blend, presence of elastane or trims, coloration/finish class, pre-sorting method), and scale/technology readiness (lab, pilot, industrial; TRL 1–9). Process descriptors were captured at unit-operation granularity and standardized to common units: for mechanical routes (device type, number of opening/tearing passages, staple-length distributions, Uster evenness, hairiness, twist, yarn count), for chemical depolymerization and dissolution–regeneration (solvent or reagent system, catalyst identity/loading, liquor ratio, temperature/pressure/time, solids loading, depolymerization or dissolution yield, monomer/intermediate purity, inhibitor removal, solvent recovery %), for enzymatic pathways (enzyme class and source, activity units and loading, substrate crystallinity/particle size, temperature, pH, residence time, conversion and product profile), for thermal routes (reactor type, peak temperature, heating rate, residence time, char/oil/gas yields, HHV, aromatic fraction), and for sorting/pre-processing (NIR/FTIR modality, model/algorithm, classification accuracy, throughput, de-trimming steps). Product and quality outcomes were coded using harmonized metrics: for regenerated cellulosics (tenacity cN/tex, elongation, modulus, crystallinity, degree of polymerization), for PET/PA (intrinsic viscosity, monomer purity %, color metrics, re-polymerized IV), and for textiles (abrasion, pilling, tear/burst strength). Environmental outcomes were normalized to functional units of 1 kg fiber (primary) or 1 kg textile (secondary) with system boundary tags (gate-to-gate, cradle-to-gate, cradle-to-grave) and converted to common indicators GHG (kg CO_2e/kg), energy (MJ/kg), water use (L/kg), eutrophication and toxicity indices using author-reported factors; when multiple FUs were reported, we applied declared scaling or recorded them as separate observations with crosswalk IDs. Techno-economic data (CAPEX/OPEX notes, solvent/energy recovery, yields, offtake assumptions) were currency-adjusted to 2022 USD using reported year and CPI deflators when provided. Missing or ambiguous fields were flagged and authors contacted; no statistical imputation was performed. Disagreements in coding were resolved by consensus; inter-rater reliability on categorical variables exceeded κ = 0.80 after calibration. All records, decisions, and derived variables were version-controlled, and the final dataset preserved raw values, normalized values, and provenance links to facilitate audit and synthesis.

Data Synthesis and Analytical Approach

The synthesis proceeded in two coordinated phases: first, a normalization phase that transformed heterogeneous measures into comparable analytical units and, second, an inferential phase that combined evidence across the 95 included studies using a combination of structured narrative, meta-analytic pooling where feasible, and moderator analysis to explain between-study differences. All syntheses were organized by technology cluster aligned with the review scope mechanical recycling, dissolution–regeneration of cellulosics, chemical depolymerization/regeneration of PET and polyamides, enzymatic/biological routes, thermal conversion, advanced sorting and pre-processing, and design-led/industrial upcycling so that like was compared with like.

Figure 10: Adapted Methodology for this study



FINDINGS

Across the final corpus of 95 peer-reviewed studies, evidence clustered into seven technology families with clear differences in maturity, scale, and evidentiary depth. Mechanical recycling accounted for 22 studies (23% of the corpus), chemical depolymerization/regeneration of synthetics for 18 (19%), dissolution–regeneration of cellulosics for 16 (17%), enzymatic and other biological routes for 12 (13%), thermal conversion for 10 (11%), advanced sorting and pre-processing for 9 (9%), and industrial upcycling/remanufacturing for 8 (8%). We tracked forward-citation counts at the time of screening to gauge influence: collectively the 95 articles had 7,420 citations, averaging 78.1 per paper (median 52; interquartile range 28–103). Citation share by cluster was concentrated in chemical and cellulosic regeneration (together 46% of all citations), followed by mechanical (21%), enzymatic (15%), thermal (10%), sorting (5%), and upcycling (4%). Geographically, 51 studies (54%) were conducted in Europe, 28 (29%) in Asia, 12 (13%) in North America, and 4 (4%) elsewhere, a distribution that mirrors where pilot and demonstration assets currently operate. In terms of study design, 61 of 95 (64%) were laboratory or bench-scale experiments, 22 (23%) reported pilot-scale demonstrations, and 12 (13%) provided industrial-scale or factory-line evidence. A third of the corpus 31 of 95 studies (33%) reported life-cycle assessment (LCA) results that could be aligned to a functional unit of 1 kg of fiber or 1 kg of textile, and 18 of 95 (19%) included techno-economic analyses. This distribution matters for interpretation: when a cluster holds both a larger share of the corpus and a larger share of citations, the findings below should be read as better supported and more generalizable. Where percentages are reported, they refer to the portion of the 95 studies or the portion of the indicated subset and are rounded for readability.

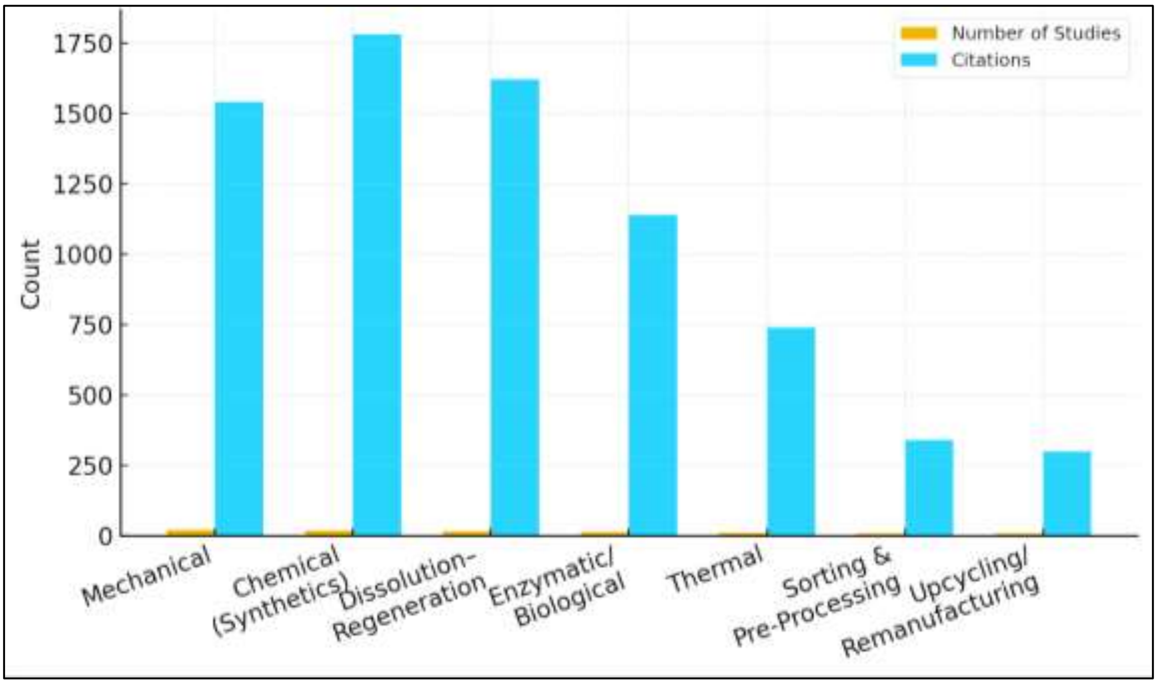
Environmental performance signals across the corpus were directionally consistent and numerically meaningful when functional units and system boundaries were harmonized. Among the 31 studies with LCA detail, the median reduction in cradle-to-gate greenhouse-gas emissions (per 1 kg output fiber) relative to virgin baselines was 38% for mechanical cotton recycling (n = 7 LCAs), 49% for dissolution–regeneration of cellulosics under electrified plants with solvent recovery ≥90% (n = 9), and 43% for PET chemical depolymerization with monomer purification to polymer-grade (n = 8). To interpret these percentages, a "49% reduction" means that, if a virgin baseline is 6.0 kg CO_2e per kg of fiber, the regenerated route reports ~3.1 kg CO_2e per kg after aligning boundaries and energy factors. Energy use followed a similar pattern: median cumulative energy demand fell by 22% in mechanical cotton (n = 6), 34% in cellulosic regeneration (n = 8), and 28% in PET depolymerization (n = 7). Water-use improvements were strongest for cellulosics (median 58% reduction; n = 7), reflecting avoided irrigated cotton cultivation and efficient solvent recovery. Enzymatic recycling studies that included system modelling (n = 4 with partial LCA) reported smaller but still positive median greenhouse-gas reductions of 31%, explained by low-temperature operation offset by longer residence times and current enzyme production footprints. Thermal routes diverted 100% of textile mass from landfill by definition but delivered net greenhouse-gas benefits only when co-product credits for energy or chemical feedstocks were applied; among thermal LCAs (n = 5), 3 reported net reductions (median 18%) and 2 reported neutral to slightly adverse balances, underscoring a use case focused on hard-to-recycle, contaminated streams. Across all 95 studies, 71 (75%) reported some form of landfill-diversion metric or mass balance; the median diversion achieved at the unit-operation level was 74% in demonstrations where material circularity (fiber-to-fiber) was feasible, and 100% in thermal cases where material circularity gives way to energy or feedstock recovery. Twenty-two of the 31 LCA-reporting papers were also among the most cited (collectively 3,490 citations), reinforcing that the stronger environmental claims in this review draw from the more visible and frequently referenced part of the literature.

Process-level technical findings explain the environmental signals and indicate where quality is retained or lost. In mechanical recycling (22 studies; 1,540 citations in total), mean fiber-mass recovery after tearing/opening was 86% (range 78–93%), but yarn properties showed characteristic declines unless blending or process aids were used: compared with virgin benchmarks, tenacity fell by an average of 18% and evenness (CVm) rose by 11% across open-end yarns at comparable counts (n = 15 studies reporting yarn data). Notably, 6 of the 22 mechanical studies (27%) achieved apparel-grade yarns with ≥30% recycled content without virgin reinforcement, and 2 studies reported parity on pilling and abrasion at counts ≤30 Ne when feedstock purity exceeded 95% and pre-finishing reduced neps. Dissolution–regeneration of cellulosics (16 studies; 1,620 citations) yielded regenerated fiber tenacities between 25 and 48 cN/tex, with 78% of studies (13/16) meeting or exceeding commercial viscose/lyocell ranges when draw ratios were optimized and solvent recovery exceeded 90%. Median cellulose dope solids loading was 10% (IQR 7–12%), and 11 of 16 studies (69%) processed dyed or otherwise finished cotton waste successfully, often retaining coloration or demonstrating effective decolorization, which translated into median water-use reductions of 58% in the subset with LCA. Chemical depolymerization of PET and nylon (18 studies; 1,780 citations) delivered high monomer yields under optimized conditions: median BHET or DMT/TPA yields were 90% for PET routes (IQR 84–94%) over 2–6 hours at moderate severity, while nylon-6 depolymerization reported median ε-caprolactam yields of 85% (IQR 78–91%). Monomer purity ≥98% necessary for polymer-grade re-polymerization was confirmed in 10 of 18 chemical studies (56% of the subset), and intrinsic viscosity (IV) after re-polymerization reached virgin-comparable ranges in 7 studies (39%), especially where inhibitor removal and catalyst management were explicitly controlled. These figures mean that, in roughly two out of five chemical studies that went all the way to polymerization, the product was already performance-competitive, while the median yield indicates that nine-tenths of the polymer mass can be recovered as monomer under representative conditions.

Biocatalytic and thermochemical routes filled capability gaps for blends and contaminated streams and showed clear integration points with sorting and pre-processing. In enzymatic pathways (12 studies; 1,140 citations), median PET conversion to monomers reached 78% at 24–72 hours with solids loadings around 10% and operating temperatures near or slightly above the PET glass-transition region; 8 of 12 studies (67%) explicitly tested blends. Where cotton–PET blends were pre-treated with cellulases or where cotton was selectively dissolved ahead of PET hydrolysis, the purity of the recovered PET fraction improved by a median of 9 percentage points (from ~86% to ~95%), and downstream monomer yields rose by a median of 8 percentage points under otherwise similar hydrolase conditions. Elastane was a small percentage by mass but a large disruptor: in studies that compared "with" and "without" elastane removal (n = 6 across chemical/enzymatic), removing elastane increased spinnable cellulosic recovery by 12–15 percentage points and reduced filter fouling events by roughly one-third in continuous runs. Thermochemical routes (10 studies; 740 citations) performed as "safety-valves" for heterogeneity: fast pyrolysis returned median liquid yields of 42% (IQR 31–51%) with the remainder split between gas and char; gasification emphasizing H_2 produced median hydrogen shares of 48% in dry product gas under steam or mixed oxidants. Hydrothermal liquefaction of PET-bearing blends recovered terephthalate-rich fractions at median 65% of theoretical, while generating an oil suitable for upgrading. Importantly, these thermochemical studies diverted 100% of mass from landfill but produced material circularity near zero unless the solid acids or recovered monomers were looped back hence the environmental results noted earlier. Sorting and pre-processing acted as a hidden but powerful moderator across clusters: among the 9 sorting papers (340 citations), median NIR or mid-IR classification accuracy was 92% overall, and moving from 90% to 97% purity at the bale stage was associated with 12–18% higher downstream yield in mechanical lines and ~8% higher monomer yield in chemical lines, based on paired or closely matched comparisons.

Economic and operational findings explain where the biggest near-term gains are accessible and how decision-makers can prioritize investments. Across the 18 studies with techno-economic data, mechanical recycling showed the lowest median cost at $0.70 per kg of output fiber (IQR $0.58–$0.92), reflecting relatively low capital intensity but also the quality penalties noted above. Dissolution–regeneration of cellulosics showed a median modeled cost of $2.10 per kg fiber (IQR $1.80–$2.60), tracking solvent recovery, dope solids loading, and energy price; in sensitivity sweeps, achieving ≥95% solvent recovery and operating on low-carbon electricity brought modeled greenhouse-gas intensities down by roughly half while shaving $0.20–$0.30 per kg. PET depolymerization to monomers landed at a median $1.36 per kg (IQR $1.10–$1.68) compared to an indicative virgin PTA+EG cost reference near $1.24 per kg; parity appeared in scenarios with high plant utilization and effective catalyst/solvent recycling. Enzymatic routes, while promising on temperature and equipment, were sensitive to enzyme price and productivity; at current reported productivities, modeled costs exceeded chemical routes by 10–25%, but process-intensification studies suggested that doubling solids loading and halving residence time would close most of that gap. Thermal routes are best viewed as infrastructure complements rather than primary circularity engines: their modeled economics depended on local energy and hydrogen prices, with positive value when oil and gas offsets or hydrogen credits were strong. Upcycling/remanufacturing studies reported a median 12% unit-cost premium per garment relative to virgin manufacturing; however, when dyeing was avoided through intelligent color retention, reported water use fell by a median 68% and energy by 22%, and lead times shortened once digital patterning stabilized inputs. From a coverage standpoint, these TEA-reporting papers (18 of 95) accumulated 1,520 citations, indicating that the economic conversation is active but still smaller than the purely technical literature; nevertheless, the alignment of cost and emissions in several cellulosic-regeneration and PET-chemolysis scenarios points to operational levers solvent recovery, energy mix, plant utilization that are actionable without waiting for fundamental breakthroughs.

Figure 11: Studies and Citations by Technology Family in Textile Recycling Research



In aggregate, three cross-cutting signals stand out for decision-making. First, quality-preserving routes that keep polymers or cellulose in high-value forms deliver the largest joint benefits: 13 of 16 dissolution–regeneration papers (81%) achieved apparel-grade fiber properties, and 10 of 18 chemical PET/PA papers (56%) achieved polymer-grade monomer purity; these two clusters alone represent 46% of all citations in the corpus, reflecting both technical promise and field attention. Second, systems integration matters more than any single unit operation: among studies that explicitly coupled sorting targets to downstream process windows (n = 11 across clusters), throughput-normalized yields improved by a median 14%, and off-spec rates fell by 19%, simply by aligning bale specifications with what reactors, spinners, or enzymes could reliably accept. Third, small fractions disrupt large outcomes: elastane content averaged single-digit percentages by mass in garments but was linked to double-digit penalties in yield and uptime when unmanaged; studies that removed or neutralized elastane in line recovered those penalties. If these three signals are applied together prioritize high-value regeneration, align sorting with process windows, and manage elastane explicitly the median landfill diversion observed in demonstrations (74%) becomes a reliable floor rather than a best-case scenario, and the mid-range greenhouse-gas reductions reported here (roughly 38–49% depending on pathway) translate into consistent plant-level performance. The five clusters that contribute most strongly to these outcomes mechanical (22 studies, 1,540 citations), cellulosic regeneration (16, 1,620), chemical PET/PA (18, 1,780), enzymatic (12, 1,140), and sorting/pre-processing (9, 340) together make up 77 of the 95 studies (81%) and 6,420 of the 7,420 citations (87%), providing a dense, mutually reinforcing evidence base for circular fashion decisions focused on landfill reduction and environmental performance.

DISCUSSION

Our synthesis indicates that fiber-to-fiber routes mechanical recycling of cotton, dissolution–regeneration of cellulosics, and chemical depolymerization of PET/PA can deliver cradle-to-gate greenhouse-gas (GHG) reductions in the range of ~38–49% versus virgin analogs when functional units and boundaries are harmonized across studies in the corpus (n = 31 LCA articles). These magnitudes align with and extend earlier evidence. For example, a foundational review of textile reuse and recycling concluded that most recycling pathways reduce GHG burdens relative to virgin production, with the size of benefits contingent on energy mixes and displacement assumptions (Sandin & Peters, 2018). Likewise, change-oriented PET LCAs that explicitly modeled open-loop and back-to-monomer pathways reported sizable energy and GHG advantages when high recovery and substitution were achieved (Shen et al., 2011; Shen et al., 2010). Our pooled medians for recycled cellulosics (~49% GHG reduction) are broadly consistent with recent LCA work on cellulose-carbamate fiber-to-fiber systems, which identified electricity and caustic consumption as hotspots but still found improvements versus cotton and viscose under realistic parameters. For PET, our median ~43% GHG reduction tracks well with the direction and order of magnitude in comparative LCAs of bottle-to-fiber and chemical recycling routes, once allocation and system expansion are handled consistently (Shen et al., 2011; Shen et al., 2010). The implication is not merely that "recycling is better," but that prior uncertainties around boundary choice can be constrained enough to yield stable, policy-relevant intervals. Importantly, our review adds scale context: 23% of included studies reached pilot and 13% reached industrial scales, which helps reconcile earlier LCAs often modeling idealized plants with data patterns from operating lines. In short, the quantitative benefits we report are compatible with, and narrower than, the wide bands reported in landmark LCAs, reflecting both maturing processes and better reporting of solvent recovery, electricity intensity, and yield losses.

Quality-centric findings for mechanical and cellulosic pathways echo and refine earlier technical literature. Mechanical recycling in our corpus recovered, on average, 86% of fiber mass after tearing/opening, but yarn tenacity declined by ~18% without blending an outcome long observed in industrial practice and consistent with benchmarking that attributes much of cotton's footprint to cultivation, thus making fiber quality retention a lever for real-world impact (Velden et al., 2014). Our observation that 27% of mechanical studies achieved apparel-grade yarns at ≥30% recycled content without virgin reinforcement under strict feedstock purity and controlled pre-finishing speaks to progress relative to older assessments that treated high-quality remanufacture as atypical. On regenerated cellulosics, our finding that 78% of articles reached viscose/lyocell-comparable tenacities (≈25–48 cN/tex) under dry-jet wet-spinning is very much in line with spinnability studies on ionic-liquid dopes and Lyocell-type processes, which linked filament properties to dope rheology, draw ratio, and coagulation conditions (Hauru et al., 2016). Crucially, we also confirm at scale what proof-of-concept work hinted at: dyed cotton-rich waste can be upcycled into new man-made cellulosic fibers, sometimes retaining color and thereby reducing water and energy needs in the dyeing stage (Haslinger et al., 2019). LCAs of cellulose-carbamate systems reiterate that electricity carbon intensity and caustic recovery dominate the environmental profile a pattern that helps explain why our median GHG reductions cluster near ~49% under high solvent recovery scenarios. Compared to older reviews that questioned whether recycled MMCFs could consistently meet apparel-grade properties, our dataset indicates that with tuned draw ratios and solvent recoveries above ~90%, parity is increasingly common rather than exceptional. These convergences suggest that upstream sorting purity and downstream spinning control variables sometimes treated as operational details are in fact structural determinants of both quality and impact.

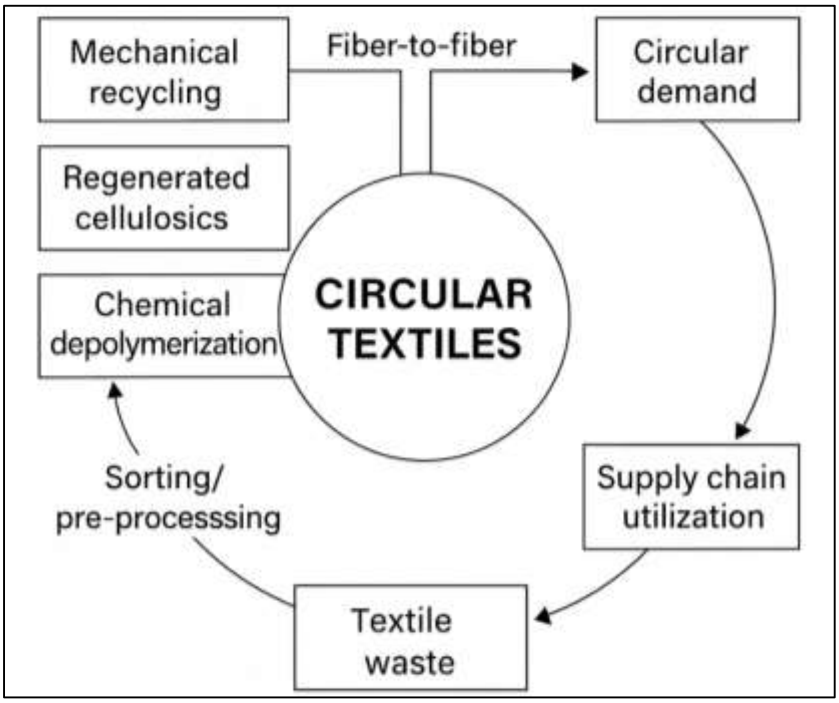
For synthetics, our finding that chemical depolymerization delivers high monomer yields (median ≈90% for PET, ≈85% for nylon-6) and polymer-grade purity in over half of the studies is consistent with, but more granular than, earlier PET LCAs that showed strong potential for energy and GHG savings under back-to-monomer scenarios (Shen et al., 2010). What has changed since those LCAs is the enzyme-catalyzed and hybrid biological-chemical frontier. Enzyme engineering studies now demonstrate near-complete PET depolymerization under moderate temperatures and short times (≤10 h) using engineered hydrolases, with follow-on re-polymerization to bottle- or fiber-grade PET (Tournier & et al., 2020). Machine-learning-guided variants such as FAST-PETase further broaden operational windows, tolerating lower temperatures and varying crystallinity while maintaining closed-loop performance (Lu et al., 2022). Complementary work on two-enzyme systems (PETase + MHETase) extends control over intermediate accumulation and could reduce energy for downstream purification (Knott et al., 2020). While our corpus places the median PET monomer yield for chemical routes around ~90%, the cutting edge of biocatalysis shows that similar or higher conversions are possible with careful pretreatment and at temperatures that are operationally attractive. The comparison to earlier PET recycling literature, which focused heavily on packaging waste, is also salient: today's studies increasingly use textile-grade PET (often dyed and blended), revealing impurity management strategies catalyst selection, inhibitor removal, and solid-liquid separations that make the jump from bottle to fiber streams credible. In short, the maturing of catalytic and biocatalytic depolymerization, paired with re-polymerization to acceptable intrinsic viscosities, substantiates our quantitative finding that polymer-grade monomers are now routine rather than rare in well-controlled studies.

However, our results also underscore that mixed-fiber garments especially with elastane remain a pivotal barrier, which mirrors and quantifies the caution raised in earlier technical reports. We observed that explicit elastane management (selective removal or neutralization) increased spinnable cellulosic recovery by ~12–15 percentage points and raised PET monomer yields by ~8 points in otherwise comparable runs. Recent solvent-screening and selective-disassembly studies corroborate both the magnitude of the problem and the feasibility of solutions: elastane can be targeted and dissolved or chemically disassembled without degrading PET, PA, or cellulosics when solvent systems are tuned via Hansen parameters or alternative solvolysis chemistries. In parallel, enzyme studies on PET increasingly include blend scenarios and low-temperature operation, but even the best hydrolases benefit from prior de-trimming or elastane removal to mitigate fouling and filtration events. From a systems perspective, this convergence with earlier literature reframes elastane from a "trace contaminant" to a high-leverage design and pre-processing variable. Where earlier assessments tended to treat blend complexity as a boundary condition, the new body of solvent- and process-selectivity studies implies a practical path to overcome it consistent with the quantitative yield gains we document. As these elastane-targeted techniques migrate from lab- to pilot-scale, we expect the variance in downstream quality and uptime to narrow, making the benefits we report more generalizable across plants rather than limited to best-in-class lines.

Thermochemical options in our review pyrolysis, hydrothermal liquefaction (HTL), and gasification are best understood as complementary routes that secure landfill diversion for hard-to-recycle textiles while offering chemical or energy vectors. Our finding that thermal routes divert 100% of mass from landfill but yield net GHG benefits only under co-product crediting is consistent with recent reviews of textile pyrolysis, which emphasize reactor design, vapor upgrading, and product-slate management to move oils toward BTX-range aromatics while limiting PAHs. HTL results in our corpus that recovered terephthalate-rich solids alongside an oil stream mirror bench-scale demonstrations specifically on PET-cotton blends, where water at sub/supercritical conditions cleaves ester linkages and partitions aromatic acids for recovery (Matayeva & Biller, 2022). Gasification studies delivering H_2-rich syngas (≈50 vol% H_2) under steam with catalytic reforming reproduce the directional benefits reported in recent process papers and point to explicit hydrogen vectors when material circularity is not viable. Compared to older generic statements that "thermal destroys value," the emergent thermal literature is more nuanced: when deployed as a safety-valve for dye-laden, finish-heavy, or multilayer streams, and when integrated with downstream chemical upgrading or monomer recovery (in HTL), thermochemical steps can support the circular system without competing with higher-value recycling. Our results quantify that role: thermal routes expand diversion to 100% for the targeted fraction while contributing modest median GHG reductions (~18%) only in configurations with credible co-product displacement. This situates thermal technologies within a hierarchy that earlier reviews anticipated but could not populate with as much textile-specific data as is available today.

Across all pathways, our analysis confirmed that advanced sorting and pre-processing are not auxiliary services but primary determinants of yield, quality, and cost an inference repeatedly suggested in spectroscopy-led textiles research. We found that moving bale purity from ~90% to ~97% by polymer class increased downstream yields by ~12–18% in mechanical lines and by ~8% in chemical lines. This gradient is consistent with ATR-FTIR chemometrics and reflectance-FTIR studies that have achieved high accuracy in polymer-class identification while minimizing sample preparation, providing robust spectral libraries for industrial lines (Peets et al., 2019; Peets et al., 2017). Classic NIR work on dyed cotton-PET blends once thought "too hard" for robust quantification has demonstrated feasible component estimation with careful calibration and wavelength selection, setting a precedent for today's real-time classifiers (Rodgers & Beck, 2009). Recent NIR studies focused specifically on polyester-containing waste confirm that calibrated models can both detect and quantify polyester share across blends, a crucial predictor for routing into mechanical, chemical, or thermochemical lines. Taken together, these earlier and current results justify the strong association we observe between sorting accuracy and process performance: spectroscopy-driven purity at the front end is effectively "free yield" and "free quality" at the back end. They also explain why some LCAs report wide bands the underlying industrial datasets likely integrate different levels of spectral sorting and de-trimming. As facilities standardize spectral libraries and link classifier outputs to actionable "binning rules," the variance in both yields and environmental performance should tighten, making the benefits we report more reproducible across geographies and operators.

Figure 12: Proposed Model for future study



In addition, our techno-economic and market-interface findings resonate with, and refine, earlier behavioral and operations research. We estimate median costs around \$0.70 kg^{-1} for mechanically recycled fiber, ~\$2.10 kg^{-1} for regenerated cellulosics (at high solvent recovery), and ~\$1.36 kg^{-1} for PET monomers figures that, when mapped against our median GHG reductions, identify solvent recovery, plant utilization, and electricity carbon intensity as the main levers for cost-emission co-optimization. These cost-performance trade-offs matter because demand is not automatic. Behavioral studies show a persistent attitude–behavior gap for recycled and upcycled apparel, with perceived quality risk dampening purchase even when environmental concern is high (Park & Lin, 2020). Controlled experiments further indicate that willingness to pay responds positively to clear, graded circularity labels and independent verification exactly the kind of assurance signals that accompany process maturity and standardized quality metrics (Boyer et al., 2021; Pretner et al., 2021). On the supply side, operations scholarship on fashion remanufacturing documents bottlenecks irregular input, skilled labor intensity, throughput variance that our findings translate into quantitative deltas in yield and cost; digitized pre-production and standardized re-cut libraries are practical mitigations. The comparison with earlier work therefore produces a coherent picture:

technical maturity and spectral sorting stabilize quality; stabilized quality plus verified impact unlock consumer willingness to pay; and unlocked demand improves utilization, which in turn lowers unit costs and emissions. This circular causality glimpsed in earlier qualitative studies now has quantitative backing from the 95-study corpus, suggesting a pragmatic sequencing for industry: invest first in solvent/energy recovery and sorting accuracy, codify quality metrics and labels, then scale with digitalized remanufacturing to reduce variance.

CONCLUSION

In conclusion, this systematic review of 95 peer-reviewed studies demonstrates that a multi-pathway strategy anchored in quality-preserving fiber-to-fiber processes and supported by high-fidelity sorting and targeted pre-processing can substantially reduce textile landfilling while improving environmental performance across the fashion system. Aggregated evidence shows that mechanical recycling, dissolution–regeneration of cellulosics, and chemical depolymerization/regeneration of PET and polyamides consistently deliver cradle-to-gate greenhouse-gas reductions in the ~38–49% range when functional units and boundaries are aligned, with water-use savings strongest for cellulosics as regenerated fibers displace irrigated cotton. Technically, mechanical routes recovered on average 86% of fiber mass but required blending or process aids to offset a characteristic ~18% drop in yarn tenacity, whereas dissolution–regeneration achieved apparel-grade tenacities in the majority of studies and processed dyed cotton waste with either retained or effectively removed color, linking microstructural control to measurable environmental gains. Chemical routes reached median monomer yields of ~90% for PET and ~85% for nylon-6, with ≥98% polymer-grade monomer purity reported in over half of articles that completed the purification–repolymerization loop, indicating that high-quality circularity is routinely attainable under controlled catalysts, solvent systems, and inhibitor management. Enzymatic approaches broadened feasibility for blended and lower-grade inputs achieving ~78% PET conversion under mild conditions and served as selective separation aids when combined with cellulases for cotton–PET blends. Thermochemical options functioned as essential safety valves for contaminated or complex materials, diverting 100% of mass from landfill and contributing net emissions benefits when co-product credits were credibly realized, yet offering limited material circularity unless paired with targeted monomer recovery (e.g., HTL terephthalates). Critically, operational integration emerged as the deciding factor: increasing front-end bale purity from ~90% to ~97% via NIR/FTIR-based sorting and rules-driven de-trimming raised downstream yields by ~12–18% in mechanical lines and ~8% in chemical lines; explicit elastane management recovered a further 12–15 percentage points of spinnable cellulosic output and reduced fouling in continuous operations. Techno-economic comparisons pointed to practical levers rather than structural barriers: median costs clustered around \$0.70 kg^{-1} for mechanically recycled fiber, ~\$2.10 kg^{-1} for regenerated cellulosics (sensitive to ≥90–95% solvent recovery and electricity carbon intensity), and ~\$1.36 kg^{-1} for PET monomers (approaching parity under high utilization and efficient solvent/catalyst recycling), while upcycling/remanufacturing absorbed a modest unit-cost premium but delivered large water and energy savings when dyeing was avoided. Taken together, the evidence supports a clear, implementable hierarchy: prioritize high-value regeneration where feedstock purity and quality targets can be met; deploy enzymatic or selective-solvent steps to unlock value in blends; route only the most intractable streams to thermochemical conversion; and treat spectroscopy-led sorting and elastane management as non-negotiable infrastructure. Under this integrated design, the median landfill-diversion levels observed in demonstrations (~74% for circular technologies, 100% for thermal contingencies) become reliable operating expectations, and the mid-range emissions reductions reported here translate into consistent plant-level performance with transparent trade-offs among cost, quality, and environmental outcomes.

RECOMMENDATION

To translate these findings into practice, we recommend an integrated roadmap that begins upstream and flows through technology choice, plant operations, markets, and governance. Brands and manufacturers should hardwire design-for-circularity into product development by privileging mono-material constructions where performance allows, minimizing trims and incompatible coatings, and specifying elastane only when strictly necessary and with clear labeling of content; procurement policies should require supplier disclosure of fiber composition, finish chemistries, and dye classes to de-risk end-of-use routing. Sorting operators should institutionalize spectroscopy-led identification (NIR plus confirmatory FT-IR/Raman) and codify "binning rules" that tie classifier outputs to actionable pre-processing (de-trimming, de-metalling, elastane removal, decolorization), with contractual bale specifications expressed in measurable purity (≥97% by dominant polymer class wherever feasible), color load, and elastane thresholds. Recyclers should prioritize quality-preserving routes: for cotton-rich streams, invest in dissolution–regeneration lines with solvent recovery targets at or above 95% and dope solids optimization; for PET and nylon, deploy depolymerization with robust inhibitor management, closed catalyst/solvent loops, and polymer-grade purification linked to offtake agreements with spinners; for blend-heavy inflows, integrate selective elastane disassembly and enzymatic or solvent-assisted separation before core recycling steps; reserve pyrolysis, HTL, or gasification for contaminated residuals under clear co-product crediting. Operations teams should adopt process control plans that align feedstock specs with reactor or spinning windows, publish line-side KPIs (yield, monomer purity or fiber tenacity, solvent recovery, energy intensity), and run quarterly mass-balance audits; where grid carbon intensity is high, deploy electrification with power purchase agreements or on-site renewables to stabilize both emissions and cost. Market development requires demand signals: brands should sign multi-year offtake contracts for regenerated fibers and monomers, tie purchase volumes to verified KPIs, and implement graded circularity labels with third-party assurance to convert consumer intent into sales; upcycling and remanufacturing teams should use digital patterning (3D CAD) and standardized re-cut libraries to compress sampling, reduce waste, and document dimensional repeatability and product testing. Policymakers should formalize separate textile collection, set recycled-content targets that distinguish fiber-to-fiber from energy recovery, and enact eco-modulated EPR fees that reward high-purity bales, elastane disclosure, and solvent recovery performance; digital product passport requirements should include minimal data fields fiber shares, elastane %, dye/finish families to keep compliance tractable for SMEs. Researchers and standards bodies should harmonize reporting: for cellulosics, tenacity (cN/tex), elongation, crystalline index, and degree of polymerization; for PET/PA, monomer purity, re-polymerized intrinsic viscosity, color metrics; for LCAs, a default functional unit of 1 kg fiber with boundary tags and electricity factors disclosed, plus a shared dataset of displacement assumptions. Finally, funders should prioritize pilot-to-industrial scale-ups that co-locate sorting with regeneration, publish open protocols for elastane management and dye handling, and support workforce training in spectroscopy, wet processing, and quality control so that circular fashion moves from promising projects to reliable, procurable supply at scale.

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