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Review

Circular Economy in the Textile Industry: A Review of Technology, Practice, and Opportunity

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Abstract

Rapid expansion of the global textile industry has accelerated both resource consumption and the scale of associated waste streams. An emerging body of recycling technology research aims to mitigate these impacts by enabling more circular material supply chains. While technologies are well described in a technical sense, literature focuses heavily on chemical methods and provides limited assessment of their physical and practical potential in the context of contemporary textile market conditions. This paper reviews these technologies in technical terms, and then establishes a qualitative framework for material value retention and waste avoidance potential with which to evaluate their efficacy. Analysis highlights that few recycling technologies are demonstrably compatible with either the attributes of post-consumer textile waste streams or the pace and scale of deployment necessary to address consumption and disposition patterns. We also highlight that both mechanical and chemical recycling are capacity constrained, and generally yield low material retention and solid waste avoidance potential per unit mass relative to other circularity strategies. Given these constraints, we posit that systems-level shifts in product and business model design may be useful as strategies to both reduce impacts upstream and mitigate waste volume, in turn supporting improved recycling rates.

Keywords: textile waste; polymer recycling; chemical recycling; post-consumer waste; circular economy; lifecycle extension; closed-loop supply chain

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1. Introduction

Growing demand and evolving consumer preferences have driven trends in the textile industry towards materials and products with high volume, low cost, and rapid market cycles [1]. These trends accelerate both disposal at end-of-life (EOL) [2] and new textile manufacturing to satisfy growing market demand [3], creating significant environmental impacts. New textile manufacturing, for example, requires high material and process energy inputs. Considering that synthetic materials in particular are in many cases derived from fossil oil, gas, and chemical production, some estimates suggest that textile manufacturing accounts for as much as 10% of global industrial greenhouse gas (GHG) emissions [4], making it the fifth largest single-sector contributor [5,6]. At end-of-use (EOU) and EOL, nearly three quarters of all discarded textile products end up in landfill systems globally [7]; in the United States, this share is closer to 85% [8]. Unconfined decomposition in landfills contributes to major ecological and human health effects including water system contamination [9–11] and microplastics accumulation [12–14].

These patterns are challenged by the characteristics of global fiber demand. Globally, two-thirds of fiber production by mass is synthetic—including 52% polyester, mostly in the form of polyethylene terephthalate (PET); 5% polyamides (PA), often identified generically as nylon; and 5.7% cumulatively in other synthetic types, e.g., polyacrylonitrile (PAN), polyether-polyurea copolymer (elastane), and polypropylene (PP). Conversely, only about a third of global production is a from natural materials—23% cotton; 6.4% man-made cellulosic fibers (e.g., rayon); 5.9% other plant-based fibers (e.g., linen, hemp, jute); and 1% wool [1]. It is thus evident that contemporary textile consumption is driven heavily by synthetics, both in uniform composition and in variable-ratio blends, the most prevalent of which is polyester-cotton.

These characteristics create considerable challenges to improving resource efficiency and reducing solid waste impacts in the textile industry. Accordingly, much research effort focuses on developing material recycling technologies that might be applicable or adaptable to textile products [15,16]. Although technical and economic barriers are acknowledged throughout this landscape, proposed processes are often claimed to hold high potential to advance the circular economy in the textile industry. However, few process-focused studies assess realistic waste avoidance potential in the context of actual market volume and material mix characteristics. This gap enables unsustainable practices to continue under the belief that waste impacts can be easily avoided.

2. Methods

This paper enables this contextualization by first providing a high-level overview of recycling technologies currently practiced in and applicable to EOU/EOL textile product industries, as derived from published research literature (Section 3). We then review the landscape of EOU/EOL textile collection and sortation technologies and deployed industrial systems through the lens of the recycling technology review, assessing the degree to which existing and emerging recycling technologies may be both technically and logistically compatible with textile waste diversion (Section 4). Finally, we present a framework for understanding the material conservation and waste avoidance value of different circular strategies applicable to the textile industry, characterizing broadly accepted and emerging practices in terms of inputs, outputs, efficiency, and challenges (Section 5). Through this lens, we identify key areas of opportunity in textile circularity, respectively highlighting investments in recycling technology, product design, and system design elements that may improve both resource efficiency and waste avoidance (Section 6).

3. Recycling Technology Landscape

We first provide a technical review of extant recycling technologies applicable either to textile products specifically or to prominent material types used in textiles, categorizing by deployment scale under current market conditions.

3.1. Mechanical Recycling, Textile-Specific, Commercial Scale

Mechanical recycling of textile waste from all sources (post-industrial, pre-consumer, and post-consumer) is well established for a variety of materials. Process inputs must first be prepared for mechanical recycling by isolating textile material from any non-textile materials—e.g., zippers, buttons, and rivets—that may damage equipment or contaminate process outputs. Given the wide variation in designs, product types, construction, and materials in EOU/EOL consumer textile streams, this preparatory step is difficult to reliably automate and thus in many cases requires manual intervention, increasing process complexity and cost. Prepared textile materials are then subject to one of two pathways: fabric recycling or fiber recycling.

3.1.1. Mechanical Fabric Recycling

Fabric recycling entails the reapplication of whole finished fabric in a new textile product; a closed-loop process. Commercial deployments are few, and are currently limited to the diversion of post-industrial and pre-consumer wastes to new manufacturing operations. Example business models include material suppliers (e.g., FabScrap) [17] who sell bulk recovered fabrics to consumers and small textile manufacturers, as well as product manufacturers (e.g., Cotopaxi) [18] who use these same material sources in new products. In either case, current business models rely solely on unused post-industrial and pre-consumer fiber and fabric waste (i.e., deadstock), and are practically successful because material type, origin, and characteristics are all known and consistent within these streams. Although potential embodied value retention and material efficiency are high, these streams account for less than a tenth of overall textile waste volumes [7,19].

Fabric recycling from post-consumer textile products is technically possible. While the process itself has low technological sensitivity to (and therefore high technological tolerance for) material diversity and blended fiber types, these characteristics still create practical challenges for market scalability. Specifically, textile product design itself typically requires material uniformity within a given product or its components. Post-consumer waste streams' wide variability in design, condition, material composition, and myriad other variables therefore render industrial scalability a considerable logistical challenge under current market conditions. Accordingly, there are no observed commercial-scale deployments of mechanical post-consumer fabric recycling for closed-loop applications in US or European markets.

3.1.2. Mechanical Fiber Recycling

In contrast, fiber recycling is well established. Fibers can be recycled from existing textile products by shredding, cutting, and tearing until fabric structures are reduced to constituent fibers. At best, recovered fibers may then be re-spun into new yarns; however, mechanical processes shorten the fibers, limiting their strength and thus suitability for yarn spinning on their own. Consequently, new yarn production using mechanically recycled fiber typically requires mixing recovered fibers with virgin material [20].

Industrial deployments of closed-loop mechanical fiber recycling are recorded for both cotton and wool in European markets [21], supported by simple process infrastructure and high-purity outputs that facilitate integration with existing textile manufacturing value chains. Fabrics that are constituted from mechanically recycled natural fibers may be mechanically recycled again, but output fiber will be degraded such that it cannot be reused in closed-loop applications to produce new fabric, even when blended with virgin material [22]. Fiber degradation also severely constrains closed-loop potential for synthetic materials. While technically possible, mechanically recycling synthetic textile fibers into new woven fabrics creates major tradeoffs in material strength that limit durability and intensify water resource pollution due to microfiber shedding during washing [23]. Accordingly, there are few closed-loop mechanical recycling applications for EOL synthetic fibers at the commercial-scale [7], and those that exist blend only a small amount of recovered post-consumer material with virgin material in new fabric manufacturing [24]. Instead, mechanically recycled fibers of all types are more widely used in non-textile (i.e., open-loop) applications such as soil amendments in commercial agriculture (natural) [25–28], thermal insulation in commercial and residential construction (natural and synthetic) [29–31], and reinforcement for composite building materials (synthetic) [32–38]. Such applications are widespread and economically scalable outlets for post-consumer textile waste streams in particular, as they are less sensitive—though not entirely insensitive—to heterogenetic

characteristics that challenge other recycling technologies, e.g., colorants, coatings, and blended materials.

3.1.3. Thermomechanical Polymer Recycling

Both fabric and fiber recycling technologies are applied to textile products at EOU or EOL, creating material feedstocks for either textile or non-textile product applications. In contrast, thermomechanical polymer recycling is most commonly applied to non-textile products at EOU or EOL, and resultant material may serve as feedstock for many applications, including new textile production. Eligible polymer materials are subjected to the same kinds of mechanical processes—shredding, cutting, and tearing—and then melted. Molten polymer may then be used for dimensional solid products manufacturing (e.g., injection or blow molding) or extruded into new fibers for textile yarn spinning.

Thermomechanical polymer recycling requires high-grade, heterogeneous, thermally stable, solid polymer inputs. Consequently, application at scale is limited to industrial contexts in which EOL material waste streams readily meet these criteria—most notably PET bottles for consumer goods packaging [39]. Despite its potential, only 26% of EOU bottle-grade PET by mass is effectively recycled in the US market, corresponding to recycled material feedstock for only 7.4% of new PET production annually [40]. Recycled PET (rPET) has been used to produce PET textiles at commercial scale for decades [41,42], and indeed continues to account for the largest share of the total rPET end use market in the US [43]. However, rPET use accounts for only 6.5% of total synthetic fiber consumption in textiles within the US market [43,44]. Globally, less than 15% of total polyester fiber production—less than 8% of synthetic fiber overall—comes from rPET [1].

Thus, the use of even high-grade EOU synthetic polymer as a feedstock for thermomechanical recycling toward new textile production remains limited, despite the availability of enough EOU material to serve a much higher share. The use of synthetic polymer waste that is already in textile form as a feedstock for thermomechanical recycling is even less common, as required feedstock attributes mean that textile products of any origin are not well suited. Commercial-scale technologies for fiber-to-fiber recycling of PET textile waste do exist as adaptations of conventional processing technology (e.g., VacuFil® Visco+); however, the use of textile waste as a feedstock limits process capacity and enables the production of only textile-grade fibers as an output [45,46]. Because higher throughput and higher-value products may be achieved by using solid polymer inputs, the application of these technologies to textile waste materials is economically unattractive. Further, textile waste types eligible for thermomechanical polymer recycling are limited to those with readily achievable material purity. These include mostly polyester (e.g., post-industrial scrap) and nylon (e.g., EOL ocean fishing nets). While such streams are reliably homogeneous, they account for only a small share of total textile waste flows. There are no known commercial applications that use post-consumer textile garment waste—the largest contributor to global textile waste flows by an order of magnitude—as the primary feedstock for thermomechanical polymer recycling.

Given these physical challenges and multiple possible non-textile and/or non-woven applications for post-consumer textile materials, estimates suggest that, globally, less than one percent of all EOU/EOL textiles by mass—and less than five percent of recovered EOU/EOL textile fibers—are actually recycled back into new woven textile products [7,19,47].

3.2. Chemical Recycling, Textile-Applicable, Commercial Scale

Beyond mechanical fabric, fiber, and polymer recycling, the only other commercial-scale textile recycling process is chemical recycling. In chemical recycling, polymer bonds present in both synthetic and natural material types are broken down, leaving behind

constituent monomers. Because monomers are the basic building blocks of polymers, recovered monomer material may then be used in new polymer manufacturing processes. In this sense, chemical recycling processes are not specifically textile recycling processes. Rather, they are monomer recycling processes that are potentially applicable to all manner of polymeric feedstocks—e.g., solid consumer plastics, wood pulp—including textile wastes. Significant focus in chemical recycling technology research and development is given to both PET polyester and polyamides, due largely to their volume share dominance across consumer products sectors and subsequent contributions to post-consumer waste challenges. In this section, we review monomer recycling processes currently deployed at the commercial scale for textile industry waste streams.

3.2.1. Hydrolytic Monomer Recycling

For polyamides (i.e., nylon), the most prevalent monomer recycling process is PA-6 hydrolysis, whereby input materials are depolymerized via the application of high temperature water, pressure, and chemical catalysts. Isolated monomers may then be reconstituted into new polymers, which in turn can be used to draw new fibers for textile applications. A critical challenge is that the same properties that make materials like PA and PET useful for textiles—namely, high thermodynamic stability—also make them difficult to depolymerize [48,49]. Consequently, hydrolytic monomer recycling requires high-intensity process inputs in energy, heat, time, and consumable materials. The simplest form for PA-6—neutral hydrolysis—uses only water as its primary solvent, but requires process temperatures between 200–400 °C and pressures between 160–350 bar sustained over 1–6 h [50]. Similar process parameters are required for neutral hydrolysis of PET [51–53]. Depolymerization may be achieved at lower pressure and temperature, but requires tradeoffs in using either alkaline or acidic primary solvents, additional process time (5–24 h in both PA-6 and PET cases), and reagent complexity and toxicity [54,55].

Hydrolytic monomer recycling is practiced at scale and successful across commercial product markets, particularly for PA-6, e.g., Aquafil ECONYL® [56] and Bureo NetPlus® [57]. While exact input material composition ratios are not publicly disclosed, current technologies require high shares of the target polymer in process feedstocks; a characteristic more reliably achieved through more uniform material origins, e.g., recovered ocean fishing nets and industrial carpet tiles made from 100% PA-6. Accordingly, post-consumer garment waste is likely used only to a minor extent in these processes, if at all; reliable material flow analyses of commercial-scale chemical monomer recycling operations by feedstock type and source are not available.

3.2.2. Alcoholytic Monomer Recycling

A considerable share of PET monomer recycling is achieved using ethylene glycol (i.e., glycolysis) and, to a lesser extent, methanol (i.e., alcoholysis) due to lower process temperature, pressure, and time requirements and higher yield efficiency than baseline hydrolysis [58–61]. These processes are likewise commercially viable and practiced at scale (e.g., Teijin ECOPET® [62] and Loop Industries [63]) but are subject to the same limitations as hydrolysis on tolerance for post-consumer garment-type textile waste as inputs. While also technically possible to depolymerize PA-6 using glycolytic or alcoholytic processes, high temperature, pressure, and process time are still required. Relative to neutral hydrolysis, the detrimental impacts of a more complex underlying solvent are not justified by benefits in process economics, and little evidence exists of commercial-scale deployments for PA-6.

3.2.3. Ammonolytic Monomer Recycling

While hydrolytic and alcoholytic (including glycolytic) monomer recycling processes are technically applicable, more robust materials used in the textile industry require somewhat more intense processes. In particular, PA-6,6 requires both high temperature conditions and a considerably stronger solvent—ammonia (i.e., ammonolysis)—to achieve sufficient depolymerization and thus recycled material yield [64–67]. Ammonolytic monomer recycling is currently deployed at the commercial scale for the recycling of PA-6,6 carpet materials (e.g., Ascend Materials Cerene™ and Universal Fibers®) [68–71]. Given the scale of applications and broad tolerances around product characteristics, industrial carpeting is one of the few markets in which closed-loop recycling via chemical depolymerization is viable at scale. However, ammonia is a powerful solvent with considerable detrimental effects on both human and ecological health [72]. Accordingly, some major manufacturers in this market increasingly rely on alternative materials to PA-6,6 with more benign recovery processes, namely PET and PA-6. Industry leaders like Interface® and FLOR®, for example, use PA-6 sourced from Aquafil's ECONYL® product line, which is produced from a variety of recycled inputs, including but not only EOU carpet tiles [73,74]. Although ammonolysis is also applied to PET at the laboratory scale, the benefits of doing so in light of other process costs and impacts are not well documented, given that lower-intensity processes provide similar monomer recovery yields [75].

3.2.4. Cellulosic Polymer Recycling

Rayon is a genericized term referring to a "manufactured fiber composed of regenerated cellulose" [76]. Fibers may be produced from any cellulosic origin, including, e.g., virgin or recycled wood or bamboo pulps. Like chemical monomer recycling of synthetic materials, rayon production process are not therefore solely textile recycling technologies, although EOU/EOL cotton textile products may also serve as process feedstocks. The most historically prevalent rayon fiber production technology is the viscose method [77], which uses alkaline (i.e., lye) dissolution to partially depolymerize cellulose into an alkali cellulose solution, which is then treated with carbon disulfide to form sodium cellulose xanthate, an intermediate polymer precursor. When neutralized with sulfuric acid, treated xanthate regenerates cellulose polymers, creating hydrogen sulfide and carbon disulfide byproducts. After drawing into cellulose filaments, these byproducts are then removed using a sodium sulfide solution, and any remaining contaminants are oxidized with sodium hypochlorite or hydrogen peroxide.

Process chemistry inputs and byproducts of viscose rayon production are known to present considerable human health hazards to those involved in the manufacturing process [78]. Similarly, process complexity and the required degree of depolymerization limit material efficiency. In contrast, the lyocell rayon process uses simpler process chemistry, dissolving fiber pulp to isolate cellulose polymers directly using N-methyl morpholine N-oxide (NMMO) [79]. By achieving a lower degree of depolymerization, and thus avoiding some subsequent repolymerization steps, the lyocell method avoids considerable human and environmental health risks associated with the viscose rayon process chemistry [80]. A similar direct-dissolution process using a cuprammonium solution is no longer used due to the considerable environmental impacts—surface water heavy metal toxicity, soil acidification, marine eutrophication, etc.—of its inputs and byproducts [81].

Large-scale rayon production has been commercially successful in US and European markets for several decades. However, almost all rayon production has historically used plant fiber pulp—namely, wood, bamboo, and eucalyptus—as the primary feedstock. Although these pulps may include high recycled material input rates, they are effectively virgin raw material inputs in rayon production. The emergence of post-consumer textile

waste as a potential input for rayon manufacturing is relatively recent and remains limited in demonstrated capacity. Although some major manufacturers are undertaking initiatives to this end, these efforts are pilot scale. Wood and other plant pulp remain the primary input materials [82,83], but public funding has been awarded to support research and development collaboration between material suppliers and rayon producers toward incorporating increasing shares of post-consumer cotton textile waste (e.g., Södra OnceMore®, Lenzing REFIBRA™) [84,85]. Several startup companies have emerged with the aim of producing lyocell rayon-based consumer garments using post-consumer textile waste as the primary if not sole material input. However, startups either remain in pre-production scale stages (e.g., Evrnu Nucycl®) [86], or have struggled to operate independently at production scale, and either must collaborate with (e.g., Circ®) [87] or are absorbed by conventional production networks (e.g., Renewcell CIRCULOSE®) [88,89].

3.2.5. Pyrolytic Monomer Recycling

Pyrolysis involves exposing waste materials to high heat in the absence of an oxygenic atmosphere, yielding solid, gaseous, and liquid components that may be recovered. Pyrolysis is widely proposed as an alternative to incineration or the treatment of myriad waste types [90–92], including plastic materials [93,94].

For natural fibers, the primary valuable outputs are bio-gas and bio-oil, which—although demonstrated at the laboratory scale as viable ingredients in bio-based plastic materials—are predominantly viable only for subsequent combustion toward heat and energy recovery [95]. Natural fiber pyrolysis may also yield biochar, which has some value as an agricultural soil amendment, though commercialization remains limited [96].

For PET and PA materials, the liquid output component is chemically and structurally similar to the crude petroleum products from which the input materials were originally derived. This oil contains a naphtha fraction, which may in turn be used to produce new monomers and subsequently regenerate polymers [97,98]. In this sense, pyrolysis goes further back in the manufacturing value chain than any other recycling process—effectively omitting only the crude oil extraction process—forfeiting nearly all embodied value, and creating considerable air and water resource pollution in the process [99]. Further, the fraction of input waste material that may be eligible for monomer regeneration is low; most material mass is converted to unusable waste byproducts, and of recovered usable material, approximately 15–20% by mass is recoverable naphtha, while the remainder may only be used as precursors for non-polymer petrochemical industry applications (e.g., lubricants and fuels) [100]. Plastic pyrolysis oil is also typically low-quality, and must therefore be mixed with mostly virgin material in the production of new monomers and polymers, markedly constraining the magnitude of manufacturing impacts that may actually be offset [100,101].

Pyrolytic plastic recycling is practiced at commercial scale, primarily by non-textile plastic products manufacturers, who use recovered pyrolysis oil only as a minority raw material ingredient in new petrochemical product manufacturing [100]. Although proposed in laboratory research, particularly for blended-fiber materials, there is no evidence of post-consumer textile wastes serving as an input for pyrolytic recycling at scale [102–104]. For PA-6,6 in particular, myriad secondary reactions beyond target depolymerization occur, dramatically reducing yield efficiency and increasing waste product generation [105–107]. While in some cases, such as PA-6, it is technically possible and demonstrated at the laboratory scale to recover monomers directly, yield is exceptionally low, inhibiting commercial scalability [108].

3.3. Chemical Recycling, Textile-Applicable, Laboratory Scale

3.3.1. Aminolytic Monomer Recycling

Research efforts to reduce the energy intensity of chemical monomer recycling focus largely on minimizing the temperature and pressure required to achieve depolymerization. To this end, polymer science research has long explored the potential to catalyze solvolysis processes using various amine group substances—potent compounds derived from ammonia—as the primary solvent. This process chemistry is most applicable to PET, which accounts for the majority of textile fiber production globally, suggesting considerable waste avoidance potential. Indeed, historical research does demonstrate reaction catalysis at near atmospheric temperature and pressure, with reduced reaction time and high yield [108–113].

However, after an extensive (over 60-year) research history, complete depolymerization under low-intensity reaction conditions via aminolysis remains possible only at the laboratory scale, and is only demonstrated on high-purity, homogenous material inputs, i.e., bottle-grade PET. Under more variable material quality and process control conditions typically present at the industrial scale, only superficial aminolysis (i.e., partial depolymerization) is demonstrably achievable [114]. In theory, partial reactions may be a desirable characteristic of aminolysis in that they may to some degree support controlled fiber degradation for direct polymer (rather than monomer) recovery. However, because aminolysis is ultimately a depolymerization process, recoverable polymers from partial reactions are inherently weakened from their input state. Consequently, recycled material must be blended with virgin inputs for any practical polymer application; a limitation that both constrains the potential for material efficiency and produces new polymer materials of poorer physical performance than fully virgin alternatives.

Ultimately, then, this process has about the same technical potential as any other chemical monomer recycling process, and is similarly subject to impact tradeoffs. Namely, lower process energy intensity (and thus cost) may be achieved, but these benefits come at the expense of output material quality and process reliance on high volumes of volatile organic compounds, posing real threats to both human and environmental health.

3.3.2. Enzymatic Depolymerization

Enzymatic depolymerization uses organic enzymes to metabolize polymeric materials, and is used in multiple ways [115–119]. The simplest example is as a means of waste removal via accelerated biodegradation. A more complex form is supporting hydrolysis (neutral or alkaline) or other solvolysis for polymer recovery and recycling by reducing process intensity (e.g., required temperature, pressure, time, and chemistry), though not by a significant magnitude [120,121]. A possible benefit of this technology in the textile industry context is that it theoretically supports higher tolerance for blended fiber types by using enzyme mixtures. Differently targeted hydrolases may be applied either in concert or in sequence to independently metabolize natural and synthetic components within the same material without degrading either one [122]. This holds considerable potential to alleviate current barriers in material separation that at present markedly limit the recyclability of blended-fiber textiles, which account for a significant share of total textile waste volume.

Although scientifically interesting, enzymatic depolymerization technologies are subject to practical limitations that severely constrain industrial scalability. Enzyme mixtures that may address the blended material barrier are themselves also a barrier, as the development of individual hydrolases—let alone mixtures—remains in its infancy and is a slow-moving research space. Even if achieved with some efficiency and reliability, the need for multiple different enzymes to complete reactions increases process complexity, time, and costs, challenging the economic viability of industrial-scale application [123].

Further, some processes remain only proposed as possible but not practically demonstrated, even at laboratory scale—supported primarily by mathematical biochemistry models in an academic setting. For example, in order to make polymer chains accessible to effective enzyme activation, enzyme-assisted PET hydrolysis still requires high temperatures. While physically plausible, this implicitly requires thermophilic hydrolases (which are uncommon) specifically oriented to PET; a combination of characteristics that may not exist at all [124]. In the absence of enzymes that can withstand high heat, depolymerization with known PET-applicable hydrolases requires long reaction times and generally reduces yield quality, limiting industrial viability [125].

In light of these challenges, there are no known industrial-scale applications of enzymatic depolymerization of either natural or synthetic materials in any industry sector. Suggestions that scalability may be possible generally target solid, non-textile plastic wastes, as these streams are more easily sorted and separated to create homogeneous feedstocks. The high sensitivity of both enzymes and environmental process parameters to specific material types in turn suggests low capacity to tolerate post-consumer textile wastes as inputs, as these material streams typically include highly mixed, variably blended, and often inseparable material types.

3.3.3. Ionic Liquid Depolymerization

Further toward the frontier of polymer science, researchers have more recently begun to explore the potential to catalyze depolymerization processes for both natural and synthetic materials using ionic liquids, a term used to describe salts (i.e., ionic compounds) that remain in the liquid state at ambient or near-ambient conditions without decomposing or vaporizing [126]. Ionic molecules that contain a positively charged (i.e., cationic) hydrogen atom are particularly labile; the strength of polar forces in turn readily catalyzes reactions with organic compounds (e.g., hydrocarbon polymers) even in the absence of high temperature or pressure. As a result, ionic liquids are powerful solvents [127,128]. Ionic compounds are by nature usually nonflammable, chemically and thermally stable, and have low vapor pressure (i.e., are not volatile) [129]. The combination of these attributes enables their use in solvolysis reactions at high temperature but without the need for high pressure, lowering process energy intensity and thus both cost and environmental impacts. In addition, ionic liquids have high density and uniquely adjustable solubility, characteristics that facilitate separation from organic reactants and thus support both high yield [130] and catalyst reusability [131].

Given these attributes, the application of ionic liquids to depolymerization for polymeric material circularity is a rapidly expanding research space. While lower-impact conjugates of the commercially viable lyocell process for cellulosic monomer recycling show promise, none are commercialized [132–135]. Similar processes for monomer recycling of PET have been developed, but likewise remain at laboratory scale [136,137]. A particularly severe constraint on scalability is the cost of both ionic liquid materials and the infrastructure required to produce them, which is in many cases material-specific. Given these challenges, ionic liquids are often expensive compounds to manufacture, meaning their industrial application is best justified in markets where products are themselves high-value; priorities include manufacturing industrial machinery, pharmaceuticals, batteries, fuel cells, and solar panels [138].

3.3.4. Metal Complex Catalyst Depolymerization

Metal complex catalysis has been deployed industrially for many decades. The most prominently familiar application at scale might be the automotive catalytic converter for internal combustion engine exhaust. In this example, platinum-rhodium metal catalysts

reduce NO_x molecules to form less-harmful N_2 and O_2, and platinum-palladium metal catalysts oxidize both CO and uncombusted hydrocarbons to produce less-harmful CO_2 and water. In quite a similar way, solutions of tailored metal complexes—i.e., compounds comprising a metal atomic center bound to any variety of ligand molecules—may leverage ionic molecular forces to catalyze the depolymerization process [139].

In recent years, researchers have developed metal complex catalysis processes for depolymerization of several synthetic material types, including polycarbonates [140–143], polyesters [144–146], PLA [147–149], and nylons [150–154]. This body of research reflects the degree to which metal complex catalysts may be tuned to treat specific material types that are often challenging to address with other chemical recycling processes. However, it must be noted that all of these processes were developed around high-grade, high-purity material inputs; there are no widely accessible studies that demonstrate applicability for heterogeneous waste streams or blended materials, and likewise none that explore potential to accommodate textile material inputs specifically. Further, few metal complex catalyst technologies for plastic waste depolymerization and monomer recycling are observably deployed at industrial scale [155].

In addition, the potential benefits of this approach have considerable tradeoffs. Claimed potential benefits are namely that the use of organic solvents may be reduced or avoided, and that functional metallic materials are abundantly available on earth. However, while abundant, all of these metals are nonrenewable, and many have competing applications in industrial roles that may be more critical than breaking down plastic waste, e.g., electrical grid, medical, communications, and public transportation equipment. Several proposed processes also rely on hydrogen gas as an essential reactant. While producible from other compounds either exogenously (e.g., industry-scale methane steam reforming) or in-process (e.g., in metal complex catalysis, predominantly from isopropyl alcohol), doing so is an energy-intensive and often expensive process with accordingly considerable environmental impacts. Although some researchers suggest these impacts may be mitigated by using renewable or otherwise clean energy sources in hydrogen gas production, both existing grid infrastructure and industrial production capacity (in the United States and globally) are limited in their ability to support proposed systems at the scale necessary to address contemporary patterns of plastic waste generation. Similarly, the consumption of costly hydrogen gas resources to recover low-value materials that are not practically reused at a high rate offers comparatively little economic, environmental, or social benefit relative to other possible uses, e.g., fuel cell electricity generation.

3.4. Recycling Technology Summary

3.4.1. Mechanical vs. Chemical

While opportunities for mechanical fabric and fiber recycling are in many ways constrained by the process-associated loss of material quality, chemical recycling processes avoid this degradation effect by reducing feedstock materials to their most basic building blocks and reassembling them effectively from scratch. Consequently, many materials not eligible for fabric or fiber recycling—especially those that have been previously recycled by these means—may still be suitable for chemical recycling. While process intensity is high, the target outputs of synthetic monomer recycling are in many cases chemically and structurally identical to the outputs of virgin polymer precursor production from fossil fuels. Accordingly, resultant fiber strength and end material quality of chemically recycled polymers are practically equivalent to newly manufactured alternatives. In the PA-6 example, hydrolytic monomer recycling yields the caprolactam, which is the final building block of the PA-6 polymer (i.e., polycaprolactam) itself [50]. This avoids the need to produce new caprolactam, which, to illustrate, otherwise involves multiple process steps: separating

naphtha from crude oil, distilling cyclohexane, oxidizing with cobalt-based catalysts to produce cyclohexanone, forming cyclohexanone oxime via condensation reaction with hydroxylamine, and finally treating with acid to form caprolactam [156].

3.4.2. Material-Process Compatibility Limitations

Although practiced at scale and successful across commercial product markets chemical monomer recycling of PA-6, PA-6,6, or PET is seldom a closed-loop process. Additives used in the textile industry to achieve desired product attributes—e.g., coloring, ultraviolet light protection, oil/water repellence, and fire resistance—reduce both process yield efficiency and the quality of monomer solutions made from recycled textiles [157,158]. As a result, depolymerized synthetic compounds are commonly used as raw chemical materials for non-textile products such as fuels, lubricants, and low grade packaging, but are rarely used as precursors for new polymers, and even more seldom for new textiles [61,159]. Less than two percent of global nylon fiber production, for example, contains material of recycled origin [160]. Of that fraction, the share that is 100% recycled material is unknown, though likely miniscule, as producing new polymers often requires blending recycled monomer material with virgin material simply on the basis of cost and availability [161]. Likewise, the fraction of recycled nylon derived from post-consumer apparel waste specifically is also low, as more uniform materials like post-industrial waste, EOU carpets, and recovered ocean fishing nets provide a more efficient process feedstock [7,19].

Further, the widespread use of blended fabrics in consumer apparel severely complicates their use as feedstocks to monomer recycling. Whether for natural or synthetic inputs, monomer recycling technologies target only specific monomers; the opposing fraction of blended input fibers is in many cases substantially degraded in the process [162,163]. This not only creates an unusable byproduct—reducing waste avoidance potential—but also contaminates the depolymerization process, reducing conversion efficiency and recovered material yield. Consequently, process tolerance for blended fibers (for which there is little publicly available data) is typically low, rendering much post-consumer textile waste ineligible for direct monomer recycling altogether. Although research efforts to recover both natural and synthetic components of blended textile wastes in chemical recycling processes are growing, they remain experimental and focused on case studies that do not reflect the full breadth of diversity in material compositions and blend ratios empirically observable across the textile industry at large [164–168]. Thus, while monomer recycling of PET-, PA-, and even cotton-based textiles is supported to an extent by commercially demonstrated technologies, these technologies' capacity to accommodate post-consumer garment waste as a feedstock remains limited.

3.4.3. Impact Avoidance Limitations

It must also be acknowledged that while recycling is generally thought to be environmentally preferable to new material production, benefits vary widely. Mechanical recycling is almost always preferable to virgin material production. In contrast, comparative environmental impact assessment studies suggest chemical monomer recycling for several synthetic materials is only slightly better (and in some cases actually worse) than virgin production across categories including energy consumption, greenhouse gas emissions, land use change (which accounts for landfill waste impacts), ecotoxicity, and water consumption (Figure 1) [169,170].

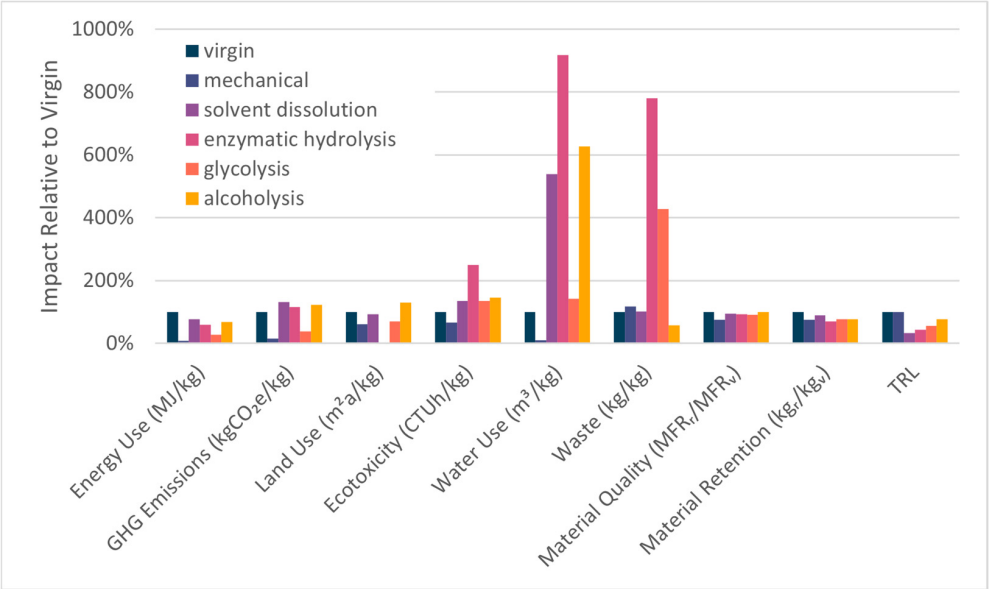

Figure 1. Lifecycle impact and technology readiness level (TRL) assessment of virgin polyethylene terephthalate (PET) production compared to various recycling technologies; data adapted from Uekert et al. (2023) [169], Table S1.

As a caveat, lifecycle impact assessment (LCIA) results are influenced by underlying assumptions made about energy and electricity grid fuel mix, as well as process efficiency, which can vary by location. Uncertainties that arise from these variables may especially affect the assessment of emerging technologies for which full-scale operational data are not readily available. Nonetheless, LCIA can provide meaningful input by identifying both critical impacts and process parameters to which impacts are especially sensitive.

3.4.4. Industrial Capacity Limitations

Finally, we note that even under ideal conditions in which textile waste streams are perfectly compatible with chemical recycling technologies, the scale of these waste streams far outsizes industrial capacity for chemical recycling at large (Figure 2). The U.S. generated 7.7 million metric tonnes (MMT) of synthetic fiber textile waste in 2021 [44,171]. The same year, total nameplate industrial capacity for chemical recycling of synthetic polymers in the U.S. was just 0.3 MMT per year [172], and likely even less, as most U.S. chemical plastic recycling plants have struggled to operate at their promised scale [173]. Importantly, this reflects the capacity for recycling synthetic materials of any origin, including clarified non-textile plastic waste streams, which in the U.S. amounted to 44.1 MMT in 2021 [174]. Likewise, the U.S. generated 7.8 MMT of natural fiber textile waste in 2021 [44,171] with an estimated industrial chemical recycling (i.e., rayon production) capacity of just 1.3 MMT [175,176]. The U.S. also generates over 65 MMT of solid wood waste per year [177], much of which goes to other recycling ends but is equally eligible—and indeed preferred over textiles—for use as a rayon production feedstock.

Indeed, textile waste generation from the U.S. market alone outpaces the entire global industrial capacity for chemical recycling of either synthetic (1.4 MMT/year) [172] or natural (6.5 MMT/year) [175] fibers of any origin. Given that higher-quality waste material streams—e.g., consumer products packaging, industrial wood pulp—are far more abundant and have existing industrial systems for homogenization, it is reasonable to assume that most chemical recycling capacity is dedicated to such materials. In this sense, even if all upstream barriers to textile recycling are alleviated—materials, design, collection, sortation,

material separation—existing chemical recycling infrastructure is not equipped to make a meaningful difference in textile waste avoidance simply on the basis of scale.

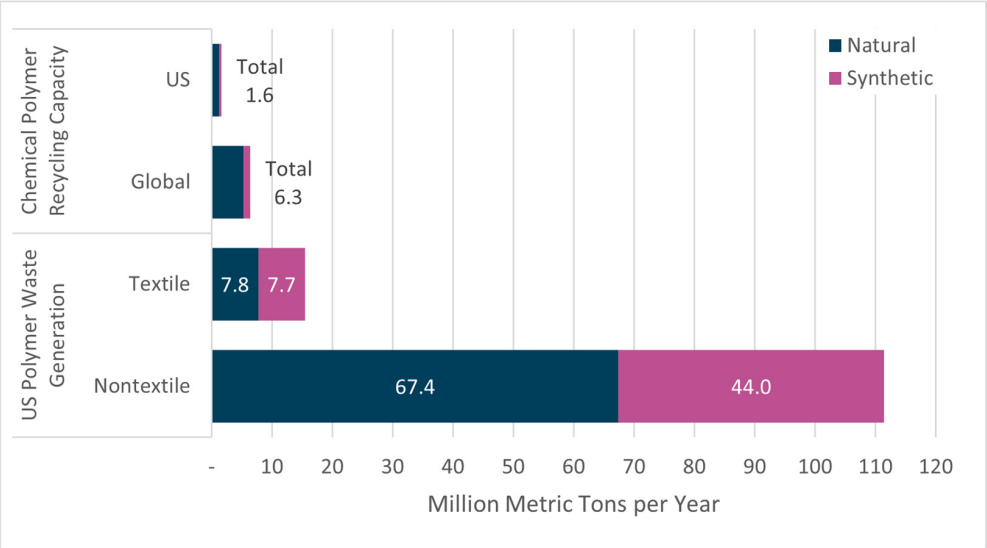

Figure 2. U.S. polymer waste generation by product and material type vs. U.S. and global industrial capacity for chemical recycling, by fiber type, using 2021 data [Tables S2–S4].

While some growth is planned, it is unlikely that industrial capacity for chemical recycling can either catch up to or keep up with ongoing patterns in textile consumption and waste generation. Indeed, since the 2021 reference year for the above data, U.S. textile consumption and waste generation have continued to grow, with increasing shares of both material flows represented by synthetic fibers [44]. Over the same period, synthetic material chemical recycling plants in the U.S. have fallen short of anticipated processing and production volumes by up to 90%, in some cases shut down, and even failed to materialize altogether [173].

4. Textile Waste Logistics Landscape

To utilize a waste stream as a feedstock, collection and sortation is necessary to produce a steady and reliable flow of input materials. As described in Section 3, virtually all recycling processes either practiced in or applicable to textile waste streams depend on homogenous inputs. Variability in textile products, particularly post-consumer products, therefore necessitates sorting textile waste by material type at a minimum, and may require sortation by other attributes depending on the intended recycling pathway.

4.1. Collection and Sortation

4.1.1. Collection and Sortation Challenges

Currently, sortation is functionally integrated as a part of collection processes in the US market; however, formal collection and sortation systems are few and far between, with no observable standards of industry practice. While commercial efforts may exist, EOU/EOL textile waste collection is neither widespread nor compulsory in the industry: as outlined above, less than 15% of EOU/EOL textiles are collected for recycling in the US market. There is also no market-scale municipality-driven infrastructure for EOU/EOL textile-specific waste collection and sortation, as there is for some other challenging waste streams, e.g., consumer electronics. In the absence of industry-scale producer responsibility or municipal systems for product takeback, collection efforts remain disjointed and material flows remain both decentralized in nature and uncertain in character [178].

Private, independent third parties provide some capacity to fill this gap. The most prevalent of these are commonly non-profit organizations—e.g., Goodwill Industries and Salvation Army—that enable closed-loop direct reuse of finished consumer apparel. Such firms typically collect via generalized bins at disparately located drop-of sites that are unattended and unmonitored, meaning current collection is fragmented and unreliable [179]. Consumer disposition also does not follow meaningful patterns in either timing or product type. As a result, collection volume varies widely and unpredictably. Further, there are few published guidelines for accepted materials, and little to no consequences to consumers for disposition of unacceptable items, creating vulnerability to waste stream contamination. Together, these conditions limit collector knowledge of the volume, schedule, and characteristics of incoming materials, creating systemic inefficiencies.

Automated sortation process technology at scale is similarly limited. Sortation is typically accomplished by human visual inspection and manual sorting. This reliance on manual sortation supports neither the pace, capacity, nor reliability required to convert mixed textile waste into clarified feedstock streams [180]. Combined with the wide diversity and relative inconsistency of product condition, these processes generate considerable material fallout. In addition, the scale of secondary user demand in markets served by the non-profit reuse model is far outweighed by the scale of collected post-consumer textile waste volume, even when accounting for unusable fallout. Consequently, large shares of collected textile wastes—both usable and unusable—are sent to landfill anyway, or increasingly exported from the U.S. to low-income regions in the Global South [181].

4.1.2. Collection and Sortation Technologies

There is thus a clear need for growth, consistency, and specificity in textile waste collection and sortation technologies. For collection, Internet of Things (IoT) technologies hold considerable potential to streamline collection and improve the quality of collected material streams. To this end, collection sites may leverage remote sensing and monitoring technologies to track when consumers deposit waste materials, what those materials consist of, and when collection sites are ready for pickup. Similar digital technologies in computer vision and control may be leveraged to restrict the disposition of unacceptable or superfluous materials. In this way, collection may be integrated with some degree of upstream sortation by consumers themselves.

The technology to enable upstream sortation already exists. Producers may use computer-readable barcodes to convey product information—e.g., size, color, material type, fabric treatments, and manufacturing date—which can then be tracked by scanning individual product barcodes. Post-consumer waste collectors may then leverage existing digital database and enterprise resource management (ERM) technologies for a variety of control measures. Requiring consumers to scan products before disposition in collection bins, for example, may enable the restriction of accepted product and material types, limiting material stream contamination. Further, scanned information may enable collectors to better understand the characteristics of incoming products, facilitating sortation by product and material type, increasing throughput capacity and enabling both reuse stream demand matching and recycling stream material homogenization. These technologies collectively support IoT frameworks for digital product passports (DPP) [182,183].

In addition, computer vision, machine learning, and automated material handling are all technologies that exist across myriad industries, and may be applicable to textile waste stream management to improve sortation capacity and efficiency [184]. Recent innovations to these ends include the use of visible spectrum imaging to identify product type and disruptor presence, and shortwave infrared imaging to detect material composition [185,186]. These

capabilities vastly improve not only the speed but also the accuracy of incoming material assessment, and are commercially demonstrated in the US [187].

4.1.3. Collection and Sortation Limitations

Such technologies are critical to building EOU/EOL textile waste processing capacity and efficiency sufficient to address the growing scale of textile waste streams. While many of these technologies already exist, there is little evidence of their use at scale in the textile industry, and most research on their applicability to textiles specifically remains laboratory-scale [188]. Further, some technical limitations remain. Although material collection and sortation infrastructure of similar nature and for similar material types does exist to some degree for municipal solid waste (MSW) recycling, current municipal recycling technology is not equipped to separate textiles from mixed MSW streams, much less sort textiles by specific material compositions [189]. In particular, recent research uses near-infrared (NIR) spectroscopy to identify specific material types within a mixed stream, information that may then be used to inform either manual or automated sortation processes [190,191]. However, complexities of textile design—blended materials, colorants, coatings (flame retardants, water resistors, insect repellents, etc.) can all limit the ability of NIR spectroscopy to accurately and reliably identify materials. Other material analysis technologies can detect these complicating materials, and have been demonstrated using textile product inputs at the laboratory scale. However, most processes require extensive sample preparation, expensive equipment, and significant processing time—limiting commercial scalability. Likewise, the application of machine learning to sort materials is dependent on robust training data, which is virtually nonexistent for textile products due to the breadth of industry diversity [192].

4.2. Material Separation

4.2.1. Material Separation Challenges

A major challenge for recycling textiles using any of the above technologies is that material uniformity is widely variable and often poor in textiles, particularly in post-consumer waste streams. While chemical recycling processes target specific materials, nonuniform materials in colorants, surface coatings, blended fibers, etc., are all subject to the degradative effects of process heat, pressure, and chemistry. Their inadvertent but unavoidable breakdown not only reduces process efficiency, but also compromises catalyst materials. This creates a waste stream and, by extension, necessitates linear material consumption to support a purportedly circular process. Applying any given chemical recycling process to a textile product in practice also results in monomer solutions that are heavily polluted by these contaminants. These solutions must in turn be purified in order to isolate the targeted material in a form suitable for subsequent repolymerization; requiring additional chemical material inputs and generating further process waste [193,194].

4.2.2. Material Separation Technologies

A considerable body of extant research explores material separation processes by which target material may be physically isolated from nonuniform material mixtures, enabling the capture and use of homogeneous polymers—whether natural or synthetic—as feedstocks in further recycling processes. In the case of blended-composition textile fibers, separation by mechanical means is technically infeasible. Consequently, separation processes typically involve solvent-based dissolution-precipitation reactions, whereby either polymeric target materials or associated impurities (or both) are first dissolved and then filtered to remove any solid components [193]. Depending on input material and process chemistry, these solid components may be either the target product material or contaminant material. In the case where solid polymers are filtered out, these outputs may be suitable for mechanical or

thermomechanical recycling. Conversely, in the case where solid contaminants are filtered, resultant solutions are then subjected to either additional chemistry or temperature change to cause the precipitation of target monomers, which may then be eligible for chemical monomer recycling as a more homogeneous feedstock.

4.2.3. Material Separation Limitations

Although at least two decades of research have yielded myriad functional process parameters for multiple material types, virtually all of this work demonstrates process feasibility using post-industrial wastes [195–206]. While post-industrial waste products may exhibit individual material nonuniformity, the waste streams are themselves typically either completely or nearly homogenous. As a result, the parameters of nonuniformity within the waste products are known and consistent, allowing material separation processes to be developed around specific composition patterns. In contrast, the composition of post-consumer waste streams—especially in the apparel sector—is widely variable and seldom consistent, implicitly requiring multiple different processes.

This produces a major challenge to commercial viability for post-consumer textile waste mitigation, as the scale of required infrastructure systems makes it economically infeasible to build capacity for the diversity of material types presently used. This limitation highlights the importance of addressing both individual product and whole waste stream material composition challenges upstream in the manufacturing value chain, both in collection and sortation of EOL textile products into consistent material streams, and more fundamentally in the design of textile products themselves. Because neither of these are an evident priority in observable industrial practice or consumer behavior, there are no mainstream industrial-scale applications of such material separation technologies to post-consumer textile garment waste.

In addition, while both sortation and separation technologies have been demonstrated to reliably remove dyes and colorants [206–208], process efficiency, reagent recoverability, and output material quality are all sensitive to many other kinds of fiber additives. Flame retardants, water-resistant coatings, insecticides, abrasion and corrosion resistance films, and other amendments are widespread across textile product sectors, especially consumer apparel [209,210]. Such additives compound attribute heterogeneity in post-consumer waste streams. Even with effective sortation by material type, the presence of these disruptors are difficult to detect and thus may not be known, leading to contamination of chemical recycling feedstocks and thus poor performance.

Absent effective automated sorting and separation technologies, post-consumer textile waste streams will remain poor candidates for chemical monomer recycling. Accordingly, in the few cases where they are used as industrial-scale polymer processing feedstocks, they are virtually always a minority ingredient in a mixture involving considerably higher shares of either more homogenous recycled or newly manufactured material.

5. Circularity Assessment

5.1. Manufacturing Value Chain

In order to assess these technologies within a broader circularity framework, we first define the root textile manufacturing value chain. We generalize this value chain into steps broadly applicable across both synthetic and natural material types. In both cases, extracted raw materials are first processed to remove impurities, yielding a uniform target material. In cotton, for example, processing includes ginning raw linters to separate fiber from seed [211]. In nylon-6,6, crude petroleum is the fundamental raw material from which diamine and dicarboxylic acid monomers are derived [212]. These intermediate materials are then drawn into individual fibers: in cotton, by combing and carding ginned linters into

unidirectional fibers; in nylon, by combining and heating liquid monomers to form molten polymer chains (i.e., polymerization) which are extruded and solidified. In either case, individual fibers are then spun into yarn; yarns woven (or knit) into fabrics; and fabrics constructed into textile products. This process is generalized in Figure 3 below.

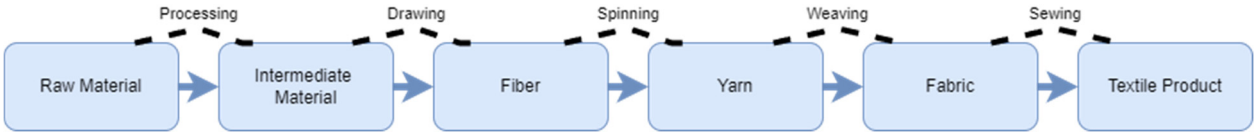

Figure 3. Textile manufacturing value chain.

5.2. Waste Origins and Embodied Value

Generally accepted circular economy principles hold that the highest impact avoidance potential—across economic, environmental, and social impact categories—is enabled by processes that retain the greatest share of a given product's final formative and functional value [213]. We consider this with respect to the manufacturing system value chain, where embodied value and environmental impacts increase at each stage of the production process [214,215]. In the context of a waste problem, then, the closer a given disposition strategy can keep a waste to its most recent stage in the value chain, the greater that strategy's waste avoidance potential. In this sense, understanding the waste avoidance potential of different EOU/EOL textile management strategies therefore requires understanding the origins of different waste types, their value characteristics, and the disposition pathways applicable to each.

Textile waste has three potential origins. The first is post-industrial, which includes finished materials that are either unused byproducts of the manufacturing process (i.e., prompt scrap) or unsold whole material stocks (i.e., deadstock fibers and fabrics). The second is pre-consumer, which includes manufactured textile goods that go unsold or unused for a variety of reasons—e.g., manufacturing defects, damage in transit, or overstock—and ultimately become retail stage losses (i.e., deadstock products). The final is post-consumer, which includes finished products discarded at EOU or EOL by private consumers and enterprise-scale users alike. Material flow analysis of the European textile industry suggests that post-consumer waste outweighs combined post-industrial and pre-consumer textile waste by an order of magnitude [216]. Thus, most textile waste is finished products, where value and impacts are embodied in both the material content itself and the processes required to produce the product's form and function.

5.3. Open- vs. Closed-Loop Disposition

Understanding waste origins and value characteristics, we subsequently characterize disposition pathways in the textile industry context. To this end, we define such pathways as either open- or closed-loop. Open-loop pathways are those that apply a waste to a different end use than that for which it was originally produced, resulting in changes to its inherent physical properties [217]. Closed-loop pathways are those that apply a waste to the same end use as that for which it was originally produced in the same general form. Although closed-loop is generally preferable to open-loop from a both value and environmental impact perspectives, both open- and closed-loop pathways exist at each stage of the manufacturing value chain. The primary determinant of a given pathway's preferability is the distance from origin of the manufacturing value chain. In this sense, the highest potential for waste avoidance is found in pathways that enable closed-loop reuse of an EOU/EOL textile product in its final form for the same functional application. Any strategy that achieves less than closed-loop reuse forfeits some portion of embodied value and impact and requires additional material and energy inputs to achieve the same

level of functional value as the original product. Such strategies consequently hold lower environmental impact avoidance potential relative to closed-loop reuse [218].

5.4. Recycling Hierarchy

Given these foundations, we define generalized pathways for post-consumer textile waste and position them relative to the manufacturing value chain, informed in part by an architecture described in Juanga-Labayen et al. (2022) [219]. These pathways include:

5.4.1. Closed-Loop Reuse

At the highest level, finished EOU/EOL textiles may redeployed (after repair, if necessary) after a partial or full use cycle to serve an additional partial or full use cycle in the same form and for the same use application. In addition to avoiding the solid waste output of the first use cycle, closed-loop reuse preserves all of a textile product's material, formative, and functional value, providing additional service time while avoiding the costs and impacts associated with producing new material and manufacturing a new product to meet that demand. Perhaps the most prevalent and visible form of closed-loop reuse in textiles is the secondary market for consumer garments, in which an original user donates or sells a product at EOU to a subsequent user, whereupon the product begins an additional use cycle.

5.4.2. Fabric Recycling

Fabric recycling involves recovering post-industrial fabric waste (i.e., prompt scrap) and/or disassembling finished EOU/EOL products to recover finished fabric. This supports open-loop reuse, wherein an EOU product may be used in whole or part to serve a similar but not identical purpose. In these cases, most of the product's material value is preserved, but only part of the formative and functional value are retained. In other words, the embodied impacts of producing fabric are retained, but those of producing the end product are forfeited. A common example of fabric recycling for open-loop reuse is the adaptation of EOU consumer garments into rag cloths for use in cleaning applications.

This arrangement means that additional demand in the original use application requires new material and product manufacturing, but the impacts of these processes are offset to some degree by serving demand in the secondary use application without incurring those production costs and impacts, as well as the partial avoidance of EOL solid waste outputs from the original use cycle. In the consumer example above, the garment must be replaced, but the impacts of producing and purchasing new cleaning cloths—as well as those of discarding the garment—are avoided. Often, characteristics of secondary use applications are such that the material and manufacturing impacts of new products designed for that application are less than those of new products that may serve its demand through open-loop reuse. Consequently, because offset impacts are lower, the net impact avoidance potential of fabric recycling is less than that of closed-loop reuse.

5.4.3. Fiber Recycling

Fiber recycling involves disassembling recovered fabric (from any waste source) but retaining original fiber structures. Recycled fibers may then be used in a myriad of non-textile (i.e., open-loop) applications. Recycled fibers may also, in theory, be reused for subsequent textile manufacturing (closed-loop). In either case, because recycled fibers must undergo additional manufacturing processes to produce finished products, an even smaller share of the original waste's embodied impacts and value are retained compared to fabric recycling and closed-loop reuse. Further, additional demand in the original waste's primary use application must be served by subsequent new material production and product manufacturing. All of these processes—both applied to recycled fibers and to new

materials—themselves also create waste. Thus, the net impact avoidance potential of fiber recycling is less than that of fabric recycling.

5.4.4. Polymer Recycling

Polymer recycling involves disassembling fibers but retaining constituent their polymers. Although conventionally associated with synthetic materials—e.g., plastics like nylon and PET—the term "polymer" simply refers to a substance comprising repeating chains of uniform molecules (i.e., monomers) linked together by covalent chemical bonds. In this sense, the cellulose molecules that make up cotton fibers are also implicitly organic polymers. Thus, the lyocell method of rayon production, which retains the cellulose structures of input materials and simply extrudes cellulosic polymer solution into new fibers, is a form of polymer recycling. In synthetics, perhaps the most established form is the production of polyester textiles from EOL PET bottles (open-loop), which are shaved into chips, melted, and extruded into new fibers [220].

In both natural and synthetic cases, reconstituted fibers must then be spun into yarn, woven or knit into fabric, and manufactured into finished textile products—all processes that require additional material and energy inputs and create additional post-industrial and pre-consumer waste. Once again, a greater share of the original waste's embodied material, formative, and functional value are forfeited, and a greater intensity of manufacturing process and waste impacts are generated both in meeting replacement demand.

5.4.5. Monomer Recycling

Monomer recycling involves disassembling polymers/oligomers but retaining constituent monomers. Processes similarly result in the destruction of polymer chain bonds, typically by applying exogenous heat, pressure, and organic chemistry to substantially raise system energy, yielding a mixture of monomers [221]. As illustrated in Figure 3, these monomers constitute the fundamental building blocks of all classes of polymer material, and as such may be used to produce new polymeric materials for any purpose, including new textiles. Virtually all chemical textile recycling technologies presented in extant literature—other than viscose and lyocell rayon methods—are monomer recycling methods.

Although monomer recycling theoretically preserves the integrity of monomer molecules such that reconstituted polymers exhibit little material degradation, depolymerization and repolymerization processes do not have 100% material recovery or conversion efficiency; thus, not all input waste mass is preserved in new material production. In addition, these processes themselves require considerable new material inputs, both in the form of process chemistry components and process energy fuels. Like all other recycling processes, reconstituted polymers must in turn repeat all subsequent steps of the manufacturing value chain in order to become new products, regardless of their final application—necessitating additional material and energy inputs, and generating additional post-industrial and pre-consumer waste. Thus, even if the intended end use is textile production, net impact and waste avoidance potential is lower than all preceding processes.

5.4.6. Energy Recovery

Energy-recovery is inherently open-loop, and involves extracting the embodied energy value of waste textile materials in any form. Examples include anaerobic digestion of post-industrial and some post-consumer natural fibers for biogas production [222–224]; fermentation of post-industrial natural fiber wastes and some high-cotton content post-consumer waste for ethanol production [168,225,226]; and incineration of mixed textile wastes of all types and phases for industrial process heat or electricity generation [15,227,228]. At this level, all material, formative, and functional value of the textile waste is forfeited, and a minimal share of replacement demand manufacturing impacts are offset. Similarly, although solid

waste mass is reduced, overall waste impacts are balanced by increased greenhouse and toxic gaseous emissions resulting from combustion.

5.5. Generalized Framework

At a high-level, this hierarchy architecture reflects diminishing efficiency of embodied material value retention and efficacy of waste impact avoidance (Figure 4). With each step down, the share of input materials that are not recovered (i.e., likely sent to landfill) increases, as do the new material and energy input requirements of both processing recovered material and producing new textile products to serve replacement demand. These conditions inherently constrain potential benefits in overall system cost and impact reduction. Even so, most of the reviewed fundamental process research focuses on chemical recycling—approaches with among the least impact and waste avoidance potential.

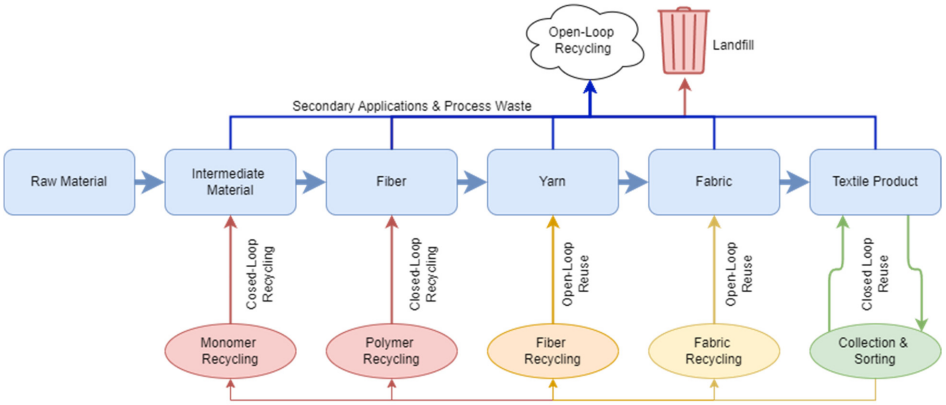

Figure 4. Textile recycling system framework.

5.6. Scale of Opportunity

In line with this analysis, a review of post-consumer textile waste management practices finds that a wide majority (60%) are suitable for direct reuse in the same application (i.e., closed-loop reuse), while 35% are suitable for redeployment in a similar application in which some portion of both material and formative value are retained (i.e., open-loop reuse) [219]. A small minority (~5%) are found to be truly waste with no formative value. In light of current practices, this suggests that the opportunity for improvement above current state is considerable. In this vein, Figure 5 illustrates the current state of EOU/EOL textile material mass flow by pathway using global industry data. Figure 6, in contrast, illustrates the potential mass flow given current trends in waste type and condition. While this distribution of potential post-consumer textile pathways reflects intensive structural and market shifts, the share of total output volume allocated to recycling in Figure 6 is far more compatible with industrial capacity limitations identified in Section 3.4.4.

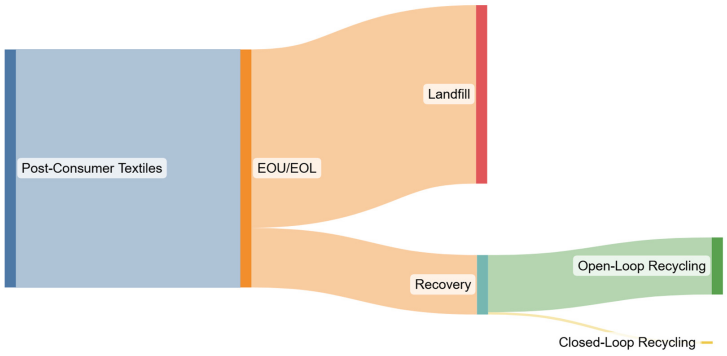

Figure 5. Current state of post-consumer textile material management reflecting global trends [Table S5].

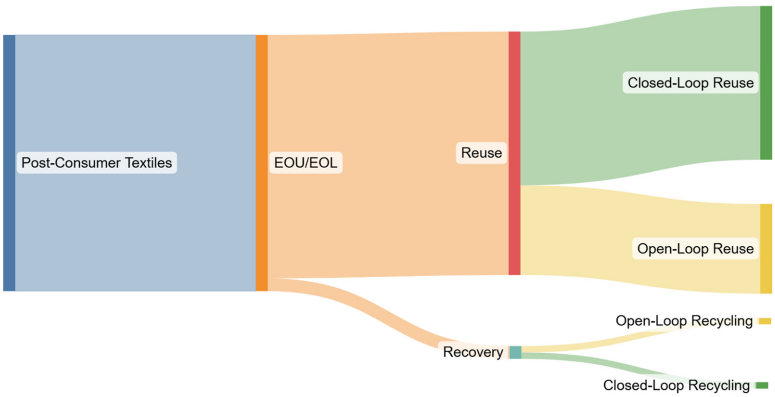

Figure 6. Hypothetical potential for post-consumer textile material management under current material and process technology conditions, according to a review by Juanga-Labayen et al. (2022) [219], Table S5.

6. Discussion and Conclusions

6.1. Critical Limitations in Chemical Recycling

From a purely technical perspective, chemical recycling processes are well-understood, and technologies are relatively developed. Considered in a vacuum, technical feasibility for all chemical monomer recycling processes is therefore relatively high: material recovery is technologically possible; recovered material may be used to produce new polymers; and this cycle may in theory be continuously repeated without loss of quality in newly produced material. However, practical feasibility is low: material and energy consumption are high; technology readiness for high-volume processing is low; process technology is highly material specific, while textile waste streams are heterogeneous and blended; recycling process outputs are far from immediately reusable as textile manufacturing inputs; recovered monomer outputs must generally be mixed with virgin inputs in new polymer production; new polymers that include recycled monomer content are seldom used for textile production; and even when they are, the cost of regenerated polymer-inclusive textiles is not broadly competitive with mostly or purely virgin alternatives.

Indeed, most of these challenges are evident in all post-consumer polymer waste streams, including solid plastics for which strong material labeling, collection, sortation, and material separation systems already exist. Yet, even in these sectors—e.g., municipal solid waste streams—chemical recycling is not practiced nearly as widely as is technically possible. While overall plastic recycling in the U.S. reaches three million tons per year [229], it is vastly outweighed by U.S. new production (65 MMT/year) and plastic waste generation (35–40 MMT/year) [171,230–233]. This reflects an overall recycling rate across all materials and processes of 7.5% of waste generation, corresponding to input capacity for only 4.6% of annual production. Moreover, due to lower process cost and higher-grade outputs, much of this amount is likely attributable to thermomechanical recycling of solid bottle-grade packaging products—namely PET and high-density polyethylene (HDPE)—which account for up to 40% of total production and waste stream mass in each case [40,234]. In this sense, we contend that if chemical recycling truly held potential for market viability at the industrial scale, it would be observably implemented in sectors where key infrastructural and logistics challenges have already been addressed. A clear lack of activity in these sectors is therefore indicative of critical limitations.

Further, even if broadly accepted, the ability to significantly reduce either waste to landfill or net material consumption via chemical recycling is limited, as the amount of recovered material is balanced by the generation of process wastes, and the use of recovered material in new polymer production remains limited. In this respect, avoided environmental

impacts under current uptake trends may conceivably be offset and even outpaced by the growing consumption of (mostly virgin) polymers at large. Assessments of chemical recycling as a viable and sustainable approach to textile sector circularity under current conditions of product design, material production, and market consumption—as broadly stated in research literature—appear to consider only the depolymerization process itself as a frame of reference, providing an artificially limited view of systemic challenges. Considered in context, chemical recycling as a primary strategy is neither logistically nor economically feasible under present conditions, and cannot itself sustain existing production and consumption trends; a perspective acknowledged by plastics manufacturers themselves [235].

6.2. Upstream Potential: Circularity Assessment Framework

In light of these limitations, we must also consider how textile waste challenges may be addressed by examining waste stream trends through the lens of the circularity assessment framework.

Based on material properties prevalent across the industry, most post-consumer textile wastes are not suitable for fabric (i.e., mechanical) recycling, which enables closed-loop recycling and high-level circularity. Most post-consumer textile wastes are, however, suitable for open-loop recycling applications, e.g., mechanical fiber recycling for building, construction, or agricultural applications, or incineration for energy recovery. However, virtually all open-loop recycling applications are terminal. Considered in the context of the circularity framework in Section 4, this retains little embodied value and inhibits further circular potential for a given material stock. From a more granular perspective, open-loop recycling applications of this nature simply displace (rather than reduce) net waste to landfill associated with a given material stock by introducing a temporary intermediate user. When mechanically recycled textile material from open-loop applications reaches EOL, it is seldom eligible for subsequent mechanical recycling, and no more eligible for chemical recycling than in its prior form. Further, the sheer volume of available post-consumer textile waste likely significantly outpaces demand for open-loop recycled fiber and industrial production capacity for stated applications, constraining the viability of these pathways as waste mitigation strategies.

Finally, most post-consumer textiles are suitable for closed-loop reuse, i.e., lifecycle extension in a product's finished form that prolongs the period before it becomes waste. To this end, we prioritize both extending the first use cycle and enabling subsequent use cycles. Source reduction via closed-loop reuse reduces new material consumption and downstream waste to landfill—and the costs associated with each—both to the highest degree and with the highest efficiency of any available strategy. In this vein, emerging market trends suggest the market viability of such use and ownership models. Notably, closed-loop reuse is increasingly incorporated into mainstream business models in some consumer textile segments, e.g., Patagonia Worn Wear, Fjällräven Pre-Loved, Cotopaxi ReSale, Allbirds Rerun, and The North Face Renewed. These models may be valuable sources of insight on product design, process logistics, and system economics.

6.3. Uptake Challenges and Inevitable Waste

Considered together, these assessments of chemical recycling and other circular pathway potential in the textile industry under current conditions reveal several challenges. Although myriad circular technologies—including chemical recycling—are applicable to materials used in textile products, process specifications are in most cases material-specific. The growing prevalence of natural-synthetic blends in widely varying ratios therefore complicates the separation and recovery of individual materials, and limits the amount of textile waste that can be realistically recycled. Further, even when materials can be separated,

technologies applicable to individual material types are in many cases input-intensive, physically destructive, and variably efficient—creating process byproducts that themselves become waste and relinquishing much of the actual material value embodied in EOU/EOL textiles. These attributes create significant costs that limit both material recovery capacity and market scalability at large, ultimately constraining their potential as a sole strategy to address growing textile waste concerns in the global context.

We must then acknowledge that textile circularity must include in some way a shift in the market trends that create both these critical limitations to recycling and the volume of material that must be recycled. Toward the former, improving the compatibility of post-consumer waste stream attributes with demonstrated recycling technologies is a shift best enabled upstream by changes in both collection and sortation system infrastructure and—most impactfully—product design. Toward the latter, shifts in product design, use, and ownership models that support extended product lifecycles through repair, direct reuse, and fabric recycling may effectively slow the rate of consumption and disposition to better match the realities of industrial capacity for lower forms of thermomechanical and chemical recycling. Shifts in, e.g., material simplification, blend standardization, fabric additive mitigation, market cycle temperance, and post-consumer logistics technology may support both of these ends impactfully and, in turn, alleviate both compatibility and capacity barriers to systemic textile circularity.

However, such shifts are challenged by considerable static inertia across the textile market and industry. Textiles of all material types—and plastics in particular—are inexpensive to produce, as virgin material supply chains and new manufacturing infrastructure are well-established. Further, the textile industry operates within a market environment in which both producers and consumers currently face few (if any) direct consequences for material consumption and waste-to-landfill impacts. Accordingly, industry incentive to either fundamentally alter core business models or adopt high-cost recycling technologies to address these challenges is currently and is likely to remain low; evident in observable industrial practice, where virtually all forms of both closed- and open-loop recycling represent a small fraction of industry activity. Together, these conditions suggest that textile industry circularity is limited not only by current design practices, but also consumer behaviors and broader market structures.

6.4. Recommendations and Future Work

On their own, extant textile recycling approaches have little logistical potential for meaningful circularity, practical potential for commercial scalability, or net impact avoidance. However, all textile products and their constituent materials—even those whose lifecycles are extended through upstream circularity—will eventually but inevitably reach EOU and EOL. Raw material recycling technologies are thus still essential to a sustainable textile economy. We therefore contend that a systems-level approach that leverages potential improvements at all levels of the circularity hierarchy is necessary.

In this light, we propose symbiotic evolution of research and technology development priorities whereby recycling technology research system boundaries shift to consider the variable properties of post-consumer textile waste inputs and the challenges of building industrial capacity; and whereby efforts toward improved textile product and industrial system design shift to also consider the technical constraints of all recycling technologies, but chemical methods in particular.

However, achieving a well-balanced technology development research strategy requires better resolution of the physical characteristics of textile waste flows than is currently available. Although this review provides a high-level quantification of waste volumes by material class relative to available recycling capacity, neither this review nor other extant

material analysis efforts provide sufficient granularity in waste flow characterization to build a well-guided technology research agenda. This limitation constrains the ability to estimate the actual magnitude of impact reduction potential possible with recommendations highlighted through the lens of the recycling hierarchy. Indeed, technologies with high per-unit impact reduction potential may not yield significant net impact reduction at the population scale if they are applicable to only a small fraction of textile waste flows. Similarly, although we highlight that many apparently favored recycling technologies have low per-unit impact reduction potential, net impact reduction at population scale may be more meaningful if such technologies can be made to be compatible with a larger share of the total waste flow population.

With this in mind, we propose that immediate next steps in systems-level research should prioritize this high-granularity waste flow characterization. To this end, we advocate in particular for: mass flow analysis of textile production, particularly consumer apparel, by specific material composition including blend ratios; mass flow analysis of textile waste outputs to specific recycling processes and end uses by both waste origin and material type; mass flow analysis of textile waste streams compared to potential mechanical fiber recycling application demand by both waste origin and material type; and characterization of waste mass flows by attributes like color, fabric treatment, etc. The latter in particular may then provide a sound basis for prioritizing technical development of chemical recycling processes to address common material additives. Concurrently, imminent research should investigate product design, ownership, and business model shifts that extend product lifecycles; extended producer responsibility (EPR) frameworks and technologies, e.g., product passport; logistical, economic, and technical analysis of upstream collection and sortation systems; and economic analysis of structural shifts toward circular supply chain integration.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling10060225/s1, Table S1: Environmental impact metrics, virgin production vs. common chemical recycling methods, for selected polymer types; Table S2: U.S. textile product exports, by product category and fiber, in raw-fiber equivalent pounds; Table S3: U.S. textile product imports, by product category and fiber, in raw-fiber equivalent pounds; Table S4: Data source information for US vs. global textile consumption, textile waste, polymer waste, and total chemical polymer recycling capacity; Table S5: Sankey diagram input values.

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Abbreviations

The following abbreviations are used in this manuscript:

EOU	End-of-Use
EOL	End-of-Life
US	United States
GHG	Greenhouse Gas
MMT	Million Metric Tonnes
PE	Polyethylene
PET	Polyethylene Terephthalate
PA	Polyamide
PP	Polypropylene
HDPE	High-Density Polyethylene
NMMO	N-methyl morpholine N-oxide
PLA	Polylactic Acid
MSW	Municipal Solid Waste
LCIA	Lifecycle Impact Assessment
TRL	Technology Readiness Level
IoT	Internet of Things
ERM	Enterprise Resource Management
DPP	Digital Product Passports

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