

Exploring Advanced Recycling Pathways for Textile Waste: Unlocking Value-Added Opportunities

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ABSTRACT

Managing fashion and textile waste is a major challenge in many countries. This paper delves into the burgeoning interest and academic focus on the progress of futuristic fashion. The fashion industry is creating new possibilities for digital integration and sustainable practices by blending contemporary materials with technological innovations and managing textile waste through various recycling methods. This paper provides an extensive overview of different categories of textile waste, origin of their generation, reusing proficiency of the textile industry, and the challenges associated with these valorization practices. Adding to that, this paper articulates on the key approaches including composting and development of cellulose nanocrystals to manage the waste as an opportunity of converting into value added products through mechanical, chemical and biological methods. Plant-based textile products, such as cotton, jute, hemp, and linen, come from a variety of sources but are often not properly utilized after use, leading to landfill and incineration problems. These materials are important alternative energy sources and unique sources for various bioproducts applied in many fields. Over the past two decades, significant attention has been directed toward reusing, recycling, and recovering various biomass wastes to create high value-added bioproducts. The conversion of plant-based textile waste into high-value nanocellulose biomaterials and high-quality compost offers a promising solution to the environmental problems associated with landfilling and incineration. This paper investigates innovative preparation methods and explores diverse applications to not only mitigate waste but also contributes to the development of sustainable and high-value products. This review highlights the need for ongoing research and collaboration between academia and industry to fully realize the potential of nanocellulose and other bioproducts derived from biomass wastes.

Keywords: Textile recycling, Chemical methods, Upcycling, Downcycling, Value-added products, Valorization.

INTRODUCTION

The textiles and apparel industry ranks among the largest and fastest-growing global industrial sectors due to factors such as population growth, rising consumer demand, the diverse applications of textiles, and advancements in mass production efficiency. In 2016, this sector generated annual revenues of \$1.3 trillion (FashionUnited, 2016), with the global clothing industry as its primary consumer (MacKenzie, 2016). Between 2000 and 2015, annual production nearly doubled, exceeding 100 billion units, and apparel consumption is projected to grow by 63% by 2030. This surge is significantly driven by the fast fashion segment, characterized by rapid production cycles, frequent style changes, and lower pricing strategies that offer consumers a wider variety of choices (EllenMacArthurFoundation, (2017)).

The growing awareness of the adverse effects of the current linear "take-make-dispose" system has mobilized stakeholders and policymakers to drive a transition towards a circular economy. This includes closed-loop systems that minimize waste, energy, and emissions across the entire production lifecycle (Lehmann et al., (2017), EllenMacArthurFoundation, (2017)). Addressing these challenges involves advancements in material and process technologies at all stages, from raw material extraction to waste management. Alarming statistics reveal that 87% of end-of-life textiles are disposed of in landfills or through incineration, making textile waste a pressing global issue.

Textile recycling technologies are pivotal in shifting from a linear to a circular model, with fibre-to-product innovations leading the way (EllenMacArthurFoundation, (2017)). Methods such as mechanical, chemical, and biological recycling are critical in mitigating the environmental impacts of post-consumer waste and greenhouse gas emissions. Globally, the fashion industry generates approximately 92 million tonnes of waste annually, with fast fashion significantly contributing to the problem through overproduction and excessive material waste. Shockingly, less than 1% of textiles are recycled into new garments, underscoring the urgent need for improved waste management practices (Picvisa Machine Vision Systems, 2023). The objective of this paper is to explore advanced textile recycling technologies by leveraging upcycling and downcycling strategies to tackle the pressing issues of waste disposal, ultimately contributing to a more sustainable future for the industry.

BACKGROUND

International studies highlight that over 150 million tons of textile waste are generated globally each year, with cotton waste contributing around 30% (De-Silva and Byrne, (2017)). Despite the theoretical recyclability of 95% of textile waste (Turemen et al., (2019)), actual recycling rates remain alarmingly low (Burton, (2018)). For example, in developed nations like Germany and the UK, the recovery rates for waste cotton

textiles fall below 30% (Wu et al., (2016), Palme et al., (2014)), while China reports rates of less than 10% (Wu GH. et al., 2015). Most cotton textile waste is managed through incineration or landfilling, both of which present significant environmental challenges. Incineration releases toxic gases, contributing to air pollution, while burial causes the leaching of chemical dyes into soil and water, resulting in contamination (Weber et al., (2017), Sezgin et al., (2021)).

From a lifecycle perspective, the apparel industry is one of the most ecologically impactful sectors due to its substantial resource demands (Peterson, 2014, EllenMacArthurFoundation, (2017), K. Niinimaki and L. Hassi, 2011). Emerging concerns include the release of microplastics, predominantly synthetic fibres, into marine environments (GreenBlue Institute, 2017, Gies et al., (2018)). These microplastics, which constitute 34.8% of primary microplastics in oceans, are primarily released during the laundering of synthetic textiles and can contaminate potable water systems (Boucher and Friot, (2017)). The apparel industry's value chain highlights critical phases in figure number 1 (Figure 1) - raw materials, usage, and end-of-life—as areas requiring significant sustainability improvements.

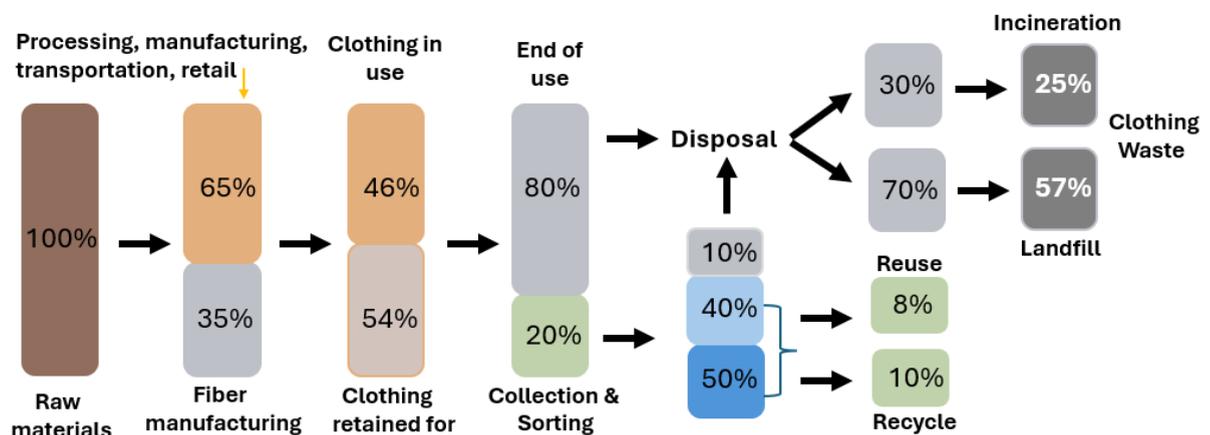


Fig. 1 Material waste in apparel flows from raw inputs to disposal at the end of its lifecycle (estimates)(Lehmann et al., (2017))

It is estimated that 87% of materials used in clothing production are either landfilled or incinerated, representing an annual loss of approximately \$100 billion in untapped opportunities opportunity (Katherine, (2018), EllenMacArthurFoundation, (2017)). Moreover, only about 20% of clothing is collected for reuse or recycling (Lehmann et al., (2017)), and less than 1% of textile materials undergo closed-loop fibre-to-fibre recycling (EllenMacArthurFoundation, (2017)). These inefficiencies in the End-of-Use phase, coupled with other stages in the value chain, underscore the need for enhanced circular economy practices.

Currently, recycling of waste cotton textiles primarily relies on mechanical and chemical recovery methods (Yu X. et al., 2021, Haule et al., (2016)). Mechanical

recycling is cost-effective, scalable, and simple, but often produces low-performance, low-value products such as filling, sound insulation, or heat insulation materials. To address these limitations, researchers like Fan et al. have developed innovative applications, including producing three-dimensional fibre needle-punched composites from denim waste for furniture manufacturing, thus adding value to recycled materials (Wang et al., (2022), Meng X. et al., (2021)).

Textile Waste

In 2015, global apparel waste was estimated to reach 83.5 million tons, which exceeded 90% of the total global fiber production of 94.5 million tons in 2016 (Lehmann et al., (2017), TextileExchange, 2017) . Textile waste primarily falls into two categories: pre-consumer (post-industrial) and post-consumer waste. Pre-consumer waste includes materials generated during industrial and commercial processes, such as textile scraps, excess inventory, damaged or defective materials, and production samples. Whereas post-consumer waste consists of items at the end of their lifecycle, such as recalled inventory, consumer-disposed products, or returned garments. The associated figure number 2 (Fig. 2) outlines the typical material flow and chemical waste streams observed during the manufacturing and use of apparel. These waste streams include both physical and chemical byproducts that emerge throughout the garment production and disposal stages. This emphasizes the critical need for strategies to minimize waste generation and implement effective recycling practices to reduce environmental impact.

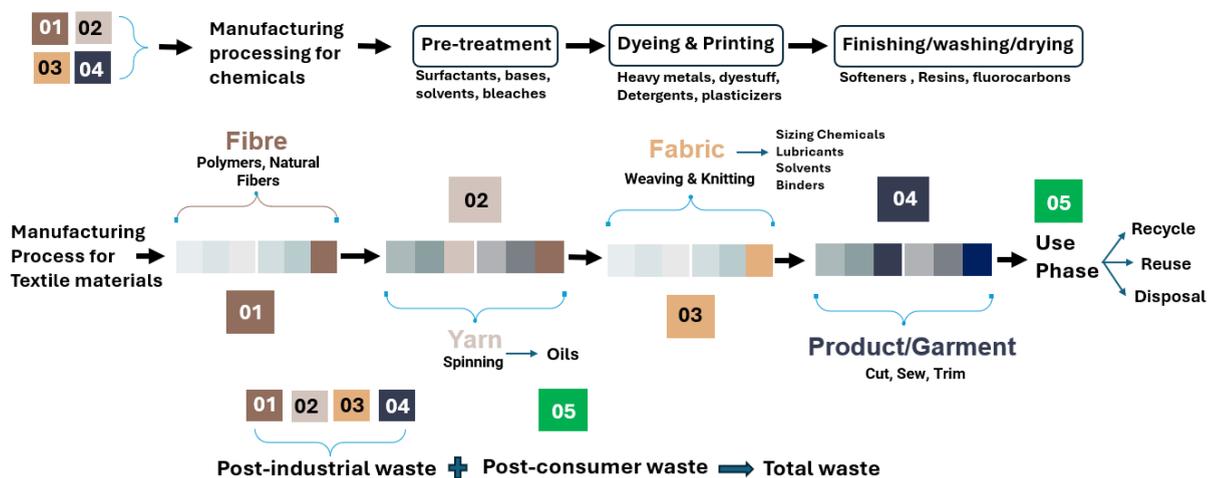


Fig. 2 Material and chemical waste flows during apparel manufacturing and use. Modified and reproduced from (TextileExchange, 2016, Safer Made, 2018).

METHODOLOGY

This paper examines strategies for utilizing natural and synthetic post-consumer waste through various recycling technologies and methods, focusing on upcycling and downcycling.

The following topics are discussed in this paper

- Identification of existing and emerging textile recycling technologies through mechanical, chemical and biological methods.
- Comparison of Upcycling and Downcycling Strategies for Post-Consumer Textile Waste
- Identification of key enablers for textile recycling adoption, and greater sustainability in the textiles and apparel industry.
- Future prospective - collaboration between academic research and industry

This study considers both 'open-loop' and 'closed-loop' recycling technologies. Open-loop recycling involves breaking down textile materials (through processes like shredding or deconstruction) into lower-value input products or using them in non-apparel applications, such as insulation, industrial rags, or low-grade blankets (Bhuiyan et al., (2023)). In this approach, the full value of the material is not recovered. On the other hand, closed-loop recycling involves multiple cycles where the textile material is recycled into an equivalent product. The research in this paper draws from a literature review, industry reports, news sources, technical studies, and qualitative methods, including interviews with technology providers and researchers. However, due to limited data and proprietary issues, some gaps in the research remain.

Recycling technologies and its methods

Valorization of pre- and post-consumer textile waste, which includes waste generated during the fiber, yarn, fabric and garment manufacturing stages, presents significant opportunities for recycling and repurposing. The process of transforming waste into valuable products reduces environmental impact and supports the circular economy by promoting resource efficiency and sustainability. Figure 3 illustrates different recycling methods for natural textile or garment waste and their applications.

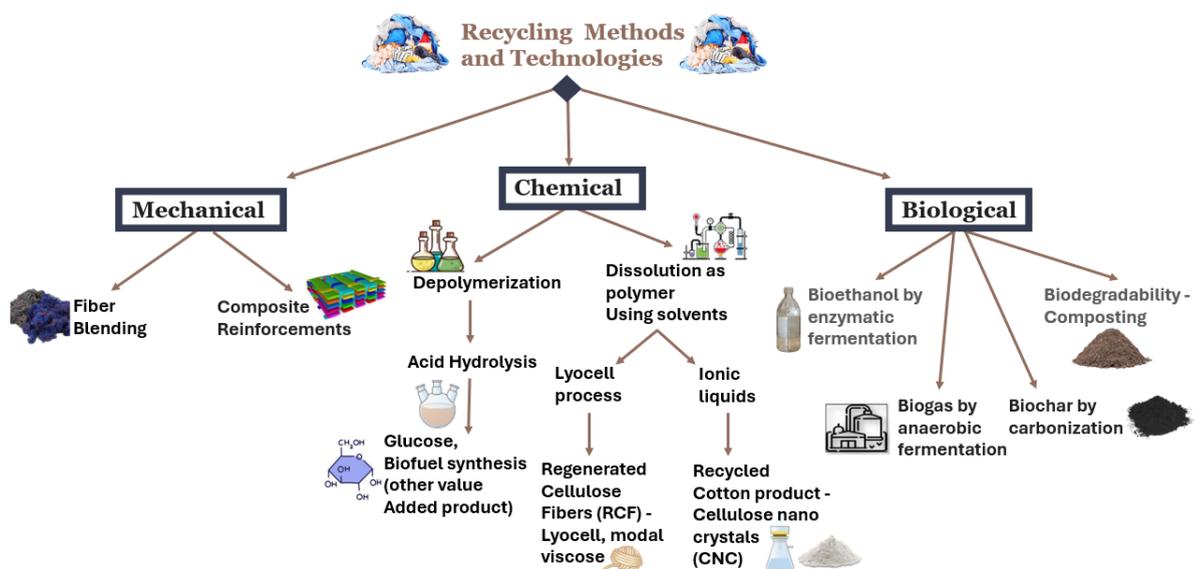


Fig. 3 Recycling methods and technologies

Mechanical recycling

The mechanical recycling process for cotton, used in apparel and other applications, involves re-spinning waste fibers through fiber blending and composite reinforcement techniques. During the sorting and shredding stages, the fibers become shorter and lose strength, leading to products with inferior properties compared to those made from virgin fibers. A study by Zhao et al. (2022) reported that recycled fibers produced via mechanical methods typically exhibit a 30–50% reduction in tensile strength. Consequently, these recycled fibers are suitable for manufacturing low-grade clothing and industrial textiles, such as insulation or padding materials. For instance, mechanically recycled cotton apparel waste can serve as a thermal insulation layer in high-performance clothing (Bhuiyan et al., 2023).

However, a significant barrier to the widespread commercial adoption of closed-loop re-spinning is the logistical challenge of collecting and processing sufficient material volumes to make the system viable (Hollins, (2014)). A process flow diagram, such as that in figure number 4 (Fig. 4), illustrates the pathways for mechanical recycling of cotton, including the production of re-spun fibers for apparel and blended materials for various uses.

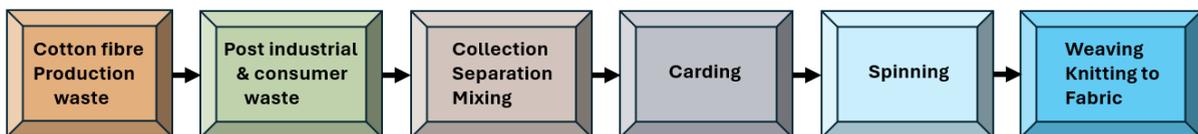


Fig.4 Mechanical recycling process of cotton (Li-Carrillo et al., (2016))

Chemical recycling

Chemical recycling effectively breaks down mixed fabrics, such as cotton blends, into monomers or solvents, enabling the creation of new fibers or the extraction of specific compounds (Saha, 2020). This method, particularly polyester recycling through glycolysis, offers an eco-friendly alternative to mechanical recycling, reducing CO₂ emissions by over 40% compared to virgin polyester production (Sharma and Jha, (2023)). Additionally, chemical recycling is more energy-efficient and achieves almost 99% recycling of chemicals, making it a more sustainable choice.

The chemical recycling of cotton focuses on dissolving cellulose, which can be approached through two main pathways: depolymerizing cellulose into glucose monomers for various applications like cellulose nano crystals (CNC) and regenerating cellulosic fibers (RCF) via solvent-based polymer dissolution (Li-Carrillo et al., (2016)). This process can also reduce reliance on toxic chemicals like carbon disulfide, traditionally used in viscose production, while producing fibers with qualities comparable to virgin materials (Morley, (2013)).

The two notable processes are used under solvent based polymer dissolution namely

- Lyocell (NMMO) and Ionic Liquid processes, which have been explored and developed in the recycling of cotton wastes into RCF like lyocell, viscose and modal. Figure 5, chemical recycling summarizes the different chemical-based processes for cotton fiber recycling.

The Lyocell method

This method illustrated in figure number 5 (Fig. 5), uses N-methylmorpholine N-oxide (NMMO) to dissolve cotton fibers, producing regenerated fibers by processing the dissolved pulp (cotton waste) with other plant-derived pulp sources, such as wood, flax, or hemp. This method is ideal for 100% cotton fabrics.

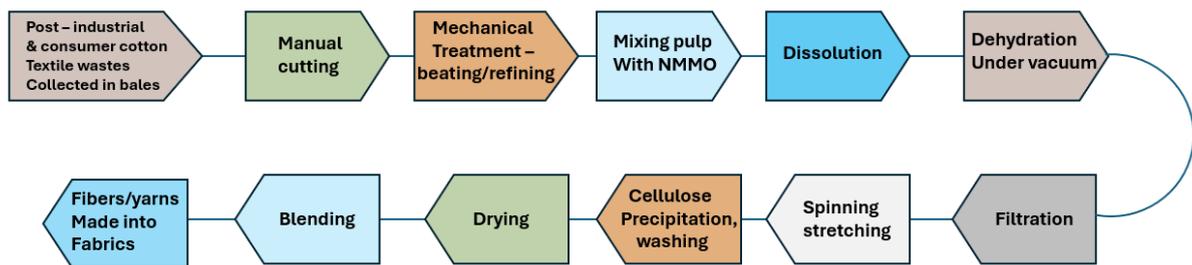


Fig. 5 Flowchart of lyocell process (Li-Carrillo et al., (2016))

Figure number 5 illustrates the Lyocell process, a chemical recycling method designed to transform post-industrial and post-consumer cotton textile waste into regenerated fibers. The process begins with the collection and pre-treatment of cotton waste, where finishes like easy-care treatments are removed using acid-alkali washing to ensure compatibility with recycling. Next, the textile waste is manually cut into small pieces (10x10 mm) and mechanically refined. The refined material is mixed with N-methylmorpholine N-oxide (NMMO), a cellulose-dissolving solvent, in a controlled ratio (1:10), along with stabilizers like n-propyl gallate. This mixture forms a spinning dope comprising 9% cellulose, 13% water, and 78% NMMO, which is homogenized under vacuum. The solution is then filtered to eliminate impurities, and cellulose is precipitated in water, washed, and prepared for spinning. During spinning, fibers are stretched under specific conditions (e.g., 115°C, 25 m/min winding speed) to enhance their tensile properties. The final stages involve drying the fibers at 60°C and blending them with other pulp materials, such as wood or flax, to create versatile outputs. While the process produces fibers comparable to virgin cotton, it requires pure cotton feedstock and involves high water consumption, presenting both advantages and challenges for sustainability.

The Ionic Liquid process

This process described in figure number 6 (Fig. 6), developed by researchers at Aalto University and the University of Helsinki, uses ionic liquid solvents like [DBNH]Oac (1,5-diazabicyclo [4.3.0] non-5-enium acetate) to recycle cotton waste into man-made cellulosic fibers (MMCs). These regenerated fibers demonstrate tensile strength

superior to native cotton and commercially available MMC fibers (Schuch, (2016)). Another ionic liquid, 1-allyl-3-methylimidazolium chloride (AMIMCI), has been used by Deakin University researchers to separate cotton from 50:50 polyester-cotton blends. Although still in development, this method shows promise for producing fully recycled cotton products or blending with other pulp sources to create regenerated cellulosic materials (R. De Silva. et al., 2014).

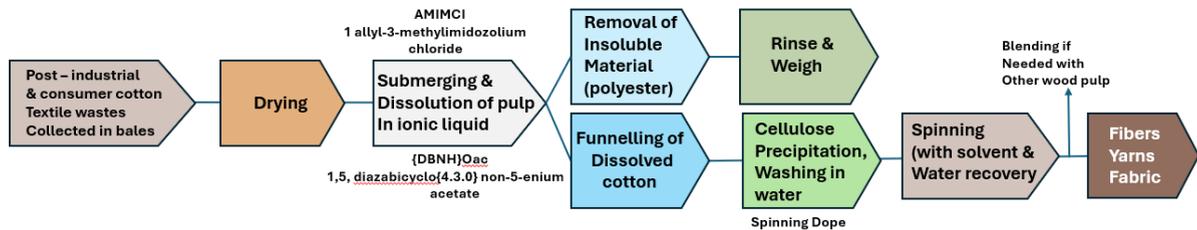


Fig. 6 Overview of ionic liquid process (Li-Carrillo et al., (2016))

Biological recycling

Biological recycling, or bio-recycling, utilizes biochemistry like enzymes and microbes such as bacteria or fungi to speed up the reactions and breaking down of an organic matter into its basic components for reuse (Reddy and Yang, (2015)). These processes are crucial in enabling sustainable recycling pathways for natural and synthetic fibers. This process is environment-friendly and complements chemical and mechanical recycling methods. In this process, the selection of enzymes plays a critical role in ensuring efficient degradation based on fiber type, processing conditions, and recycling goals. Several key enzymes play a vital role in textile recycling by breaking down fibers into simpler monomers. For instance, cellulase enzymes target plant-based fibers like cotton, hydrolyzing β -1,4-glycosidic bonds in cellulose to release glucose and cellobiose. These cellulase enzymes are usually a combination of multi-enzyme complexes with different functions and targets that catalyze the breakdown of cellobiose molecules from cellulose chains at their ends. Vehviläinen et al., (2020) introduced Biocelsol technology, which involves activating dissolving-grade pulp as an initial step in producing regenerated cellulose fibers. Unlike the traditional viscose process, this method has the notable advantage of avoiding the use of carbon disulfide, making it a more environmentally friendly alternative (Vehviläinen et al., 2020). Proteases act on animal fibers such as wool and silk, breaking peptide bonds to produce amino acids or peptides. Lipases are used for synthetic fibers like polyester, catalyzing the hydrolysis of ester bonds to yield monomers such as terephthalic acid and ethylene glycol. Additionally, laccases focus on dyed and treated textiles, oxidizing phenolic and non-phenolic dye compounds to aid in detoxification and color removal (Sharma and Jha, 2023). There are a lot of benefits of using enzyme-based recycling in textiles including enzyme reduces reliance on harsh chemicals and energy consumption is lower when compared to thermochemical processes. Additionally, it allows for selective degradation and preserving valuable components. In addition to recycling fibers into raw materials, biological recycling facilitates

downcycling approaches. Cotton and other textile waste can be converted into compost, biofuels (e.g., bioethanol), biochar through carbonization (oxidative combustion), or biogas via anaerobic digestion, using fermentation technologies. These processes provide an avenue to replace fossil fuels with renewable alternatives (Rajaeifar et al., 2015; Nigam and Singh, 2011).

Comparison of upcycling, downcycling and recycling strategies for post consumer textile waste

These strategies have been utilized in valorization of textile and post-consumer textile waste as a solution mentioned in Table 1. This table outlines upcycling and downcycling strategies for utilizing natural and synthetic post-consumer textile waste, along with the corresponding recycling technologies and methods.

Table 1. Comparison of upcycling and downcycling strategies for post-consumer textile waste

| Strategy | Fiber Type | Examples/Methods | Recycling Technologies | References |
|-------------|--------------------|---|--|---|
| Upcycling | Natural Textiles | <ul style="list-style-type: none"> - Cotton Waste: Converted into high-performance cellulose nanofibers for composites or bioplastics. - Wool: Reclaimed wool used in durable textiles or insulation panels. | <ul style="list-style-type: none"> Mechanical Treatments: Processes that maintain fiber integrity. -Enzymatic Treatments: Biochemical methods to enhance fiber properties. | (Picvisa Machine Vision Systems, 2023, Managed, (2024)) |
| | Synthetic Textiles | <ul style="list-style-type: none"> - Polyester (PET): Chemically recycled into virgin-grade polyester yarns using depolymerization. - Blended Fabrics: Hydrothermal separation to isolate synthetic fibers from natural ones for reuse. | <ul style="list-style-type: none"> Depolymerization Techniques: Breaking down polymers to their monomers for repolymerization. - Hydrothermal Separation: Using water under high temperature and pressure to separate fiber types. | (Picvisa Machine Vision Systems, 2023) |
| Downcycling | Natural Textiles | <ul style="list-style-type: none"> - Cotton and Linen: Shredded and repurposed as stuffing for furniture or padding for | <ul style="list-style-type: none"> - Mechanical Shredding: Physically breaking down fibers into lower-value products. | (Picvisa Machine Vision Systems, 2023) |

| | | | | |
|-------------------------------|---------------------------|--|--|---|
| | | <p>automotive seats.</p> <p>- Hemp Waste: Utilized in mulch mats, ropes, or construction materials like hempcrete.</p> | | |
| | Synthetic Textiles | <p>- Nylon Waste: Reused as carpet fibers or industrial ropes.</p> <p>- Polyester Blends: Ground into pellets for manufacturing items like containers, nonwoven fabrics, or geotextiles used in construction.</p> | Mechanical Grinding: Reducing fibers to pellets or smaller forms for non-apparel applications. | (Picvisa Machine Vision Systems, 2023) |
| Recycling Technologies | All Fiber Types | <p>-Mechanical Recycling: Shredding and re-spinning fibers, suitable for mono-material textiles.</p> <p>-Chemical Recycling: Enzymatic hydrolysis for cellulose; glycolysis for PET.</p> <p>-Thermal Recycling: Combustion or pyrolysis to convert waste into energy or chemical feedstocks.</p> <p>-Biological Recycling: Utilizing microbes or enzymes to degrade natural textiles into organic matter for agricultural use.</p> | <p>Mechanical Processes: Suitable for maintaining fiber quality in upcycling.</p> <p>- Chemical Processes: Allow for higher purity and quality in recycled fibers.</p> <p>- Thermal Processes: Energy-intensive, primarily for non-recyclable materials.</p> <p>- Biological Processes: Eco-friendly methods for natural fibers.</p> | (Managed, (2024), Picvisa Machine Vision Systems, 2023) |

By implementing these strategies and utilizing appropriate recycling technologies, the textile industry can significantly reduce its environmental footprint and promote sustainability.

Identification of key enablers for textile recycling adoption and sustainability in the textiles and apparel industry

The global textiles and apparel industry faces significant environmental challenges, including the generation of substantial waste and the depletion of natural resources. Recycling is a vital solution to mitigate these impacts. However, to promote widespread adoption of textile recycling and achieve sustainability, several key enablers must be addressed including - technological innovations, infrastructure and logistical development, economic and regulatory support, collaboration across the value chain, consumer awareness and behavior and digital and data-driven solutions.

Technological Innovations

Advances in recycling technologies are pivotal to achieving greater adoption. Chemical recycling methods, such as glycolysis, the Lyocell process, and ionic liquid technologies, have demonstrated superior efficiency in recycling mixed fibers into high-quality regenerated materials (Saha, 2020; Sharma & Jha, 2023). Biological recycling methods using enzymes and microorganisms, such as cellulases for cotton and proteases for wool, further complement chemical and mechanical techniques, enabling selective degradation and reduced energy consumption (Reddy, 2015; Vehviläinen et al., 2020). Mechanical recycling, though limited by reduced fiber strength, provides opportunities for producing industrial-grade materials, such as thermal insulation layers (Zhao et al., 2022; Bhuiyan et al., 2023).

Infrastructure and Logistical Development

A robust waste collection and sorting infrastructure is essential for ensuring an adequate supply of textile waste for recycling. Challenges such as contamination and material heterogeneity must be addressed by integrating advanced sorting technologies and scaling up material recovery facilities (Oakdene Hollins, 2014). Additionally, global collaboration is needed to harmonize practices for handling textile waste streams and optimize supply chain logistics.

Economic and Regulatory Support

Economic incentives such as extended producer responsibility (EPR) frameworks and tax benefits for sustainable practices can motivate stakeholders to adopt recycling technologies (Rajaeifar et al., 2015). Regulatory measures mandating recyclability standards and restricting hazardous substances are critical to ensuring environmental compliance and fostering innovation (Nigam & Singh, 2011).

Collaboration Across the Value Chain

Stakeholder collaboration, including partnerships between brands, recycling facilities, and policymakers, is key to scaling sustainable practices. Integrating recycling into circular business models, such as take-back schemes and resale platforms, enhances the economic viability of recycling initiatives (Sharma & Jha, 2023).

Consumer Awareness and Behavior

Educating consumers about the importance of textile recycling and encouraging sustainable consumption patterns are vital enablers. Transparent labeling and incentive programs, such as discounts for returning used clothing, can foster consumer participation in recycling efforts (Oakdene Hollins, 2014).

Digital and Data-Driven Solutions

Technological tools, including artificial intelligence (AI) and blockchain, offer transformative solutions for tracking textile lifecycles, optimizing recycling processes, and enhancing transparency (Sharma & Jha, 2023). For example, AI-based sorting technologies improve the efficiency and scalability of waste management systems. The adoption of textile recycling in the apparel industry hinges on addressing key enablers across technological, economic, and social dimensions. By advancing recycling technologies, building robust infrastructure, incentivizing sustainable practices, and fostering stakeholder collaboration, industry can significantly reduce its environmental footprint.

FUTURE PROSPECTIVE - COLLABORATION BETWEEN ACADEMIC RESEARCH AND INDUSTRY

Collaboration between academia research and industry offers a promising pathway for addressing textile waste through innovative recycling technologies. This partnership leverages academic research capabilities and industrial scalability to create effective solutions for textile recycling and sustainability.

Innovative Recycling Technologies

Academic institutions drive innovation by developing advanced recycling methods, such as chemical and biological recycling. For instance, the Swedish company Renewcell collaborates with researchers to scale up chemical recycling technology, transforming textile waste into Circulose®, a high-quality fiber. This partnership aims to recycle over 1.4 billion T-shirts' equivalent annually by 2030 (Tang, (2023)). Another example of innovative recycling technologies is Evrnu, a U.S.-based company, collaborates with universities to create NuCycl, a patented fiber engineering technology. This technology converts textile waste into high-performance fibers, supporting the production of new garments by major brands (Hussain, 2023).

Policy and Circular Economy

Academic research informs policymaking, encouraging industries to adopt circular economy principles. For example, studies emphasize the role of blockchain and AI in enhancing transparency and efficiency in textile waste management. This fosters better partnerships between textile manufacturers, recyclers, and retailers.

Scaling Solutions

Academic projects often focus on proof-of-concept work that industry can scale. For example, Worn Again Technologies collaborates with universities to refine technologies that separate and recycle mixed-fiber textiles, making them commercially viable.

Collaborative Programs and Funding

Government-backed initiatives like the EU's Horizon programs encourage collaborations between universities and industries, providing funding for innovative recycling projects.

The integration of academic insights and industrial expertise accelerates the adoption of scalable recycling technologies, gain access to real-world data and application opportunities, fostering environmental sustainability by producing higher-quality, eco-friendly products, positioning these collaborations as crucial for achieving sustainability goals in the fashion and textile industries.

CONCLUSION

The growing global demand for textiles has created significant environmental challenges, particularly in waste management and resource utilization. Current global fiber production has shown an upward trend, with virgin fibers dominating the market and recycled fibers comprising less than 10% of total production. This indicates a pressing need for effective recycling methods to mitigate the environmental impact of textile production and consumption. Global apparel waste in 2015 surpassed 90% of global fiber production, highlighting the critical challenge of managing textile waste effectively. The dominance of synthetic fibres raises concerns about microplastic pollution and non-biodegradability, emphasizing the need for sustainable production and recycling practices. Adding to that, proliferation of textiles made from fiber blends—such as cotton and polyester or elastane—poses significant challenges when it comes to recycling post-consumer textile waste. This is due to the labor-intensive separation process of the different fiber types and different conditions required for chemical and mechanical recycling. Chemical recycling technologies can help overcome complications associated with mechanical recycling of textiles and there are some innovative startups working on solutions to make high-value fiber blend recycling possible.

Mechanical recycling, often used for cotton, involves shredding and re-spinning fibers, resulting in shortened fibers with reduced tensile strength (30-50% lower than virgin fibers). While mechanically recycled fibers are suitable for low-grade applications like insulation and padding, logistical challenges and limitations in quality make widespread adoption difficult. Chemical recycling offers a more sustainable alternative by breaking down fibers into monomers or solvents, achieving nearly 99% chemical

recycling efficiency and reducing CO₂ emissions by 40% compared to virgin polyester production. Techniques like the Lyocell process and Ionic Liquid methods demonstrate promise for recycling cotton and blended textiles while producing regenerated fibers with superior properties. Biological recycling employs enzymes and microbes to degrade fibers into reusable components. This process is environmentally friendly, reduces reliance on harsh chemicals, and complements chemical and mechanical methods. Notable examples include cellulases for cotton, proteases for wool and silk, and laccases for dyed fabrics. Downcycling options, such as composting and biofuel production, also present opportunities for utilizing textile waste in sustainable ways.

To address the textile industry's sustainability challenges, it is critical to adopt a multi-pronged approach that combines mechanical, chemical, and biological recycling methods. Additionally, improving logistical frameworks for waste collection, scaling up emerging technologies, and fostering collaboration among stakeholders are essential steps toward a circular and sustainable textile economy. These advancements can significantly reduce textile waste, lower CO₂ emissions, and enable the production of high-value products from recycled materials, contributing to global sustainability goals.

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