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Recycling of Textile Waste – Sustainable Practices

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Abstract

Reusing and recycling textile fabric waste is one of the most important factors in the shift to a circular economy in the textile industry. The need to recover fabric waste stems mainly from the viewpoint of resource recovery and the harmful effects of disposal and landfilling on the environment. This study explicitly evaluates the current approaches and the status of textile waste recycling technology and addresses the issues that come with them. The emerging recycling trends have been discussed. Textile waste can be mechanically recycled to create new fibers with the same or different uses from the original materials. While biological recycling employs enzymes and microorganisms rather than chemicals to depolymerize old textiles. Chemical recycling uses chemicals to generate monomers for new textiles or other materials. Thermal recycling uses gasification, hydrothermal liquefaction, and pyrolysis to recover energy and fuels from waste textiles. Unblended cotton is the fiber type examined the most for recycling, followed by cotton and polyester blends. Open-loop recycling is the most popular method of fabric waste due to its cost-effectiveness, followed by chemical and closed-loop recycling.

Keywords: Circular textile solutions; Fibre separation; Environmental impact; Textile industry; Waste management

Introduction

The Textile and Clothing industry (T&C) is the second largest industry in the manufacturing sector. The exploitation and depletion of resources (raw materials, water, energy), air pollution, solid wastes, effluent discharges, and greenhouse gas emissions are all connected to its value chain. Rich sources of textile waste, such as waste from the production of textiles and apparel, commercial services, and consumption, have sparked worries about creating innovative circular textile solutions across the globe. In recent years, the management and disposal of textile waste have become a more pressing global issue [1-3].

Often, the only viable recycling methods for textile trash are energy recovery through incineration and second-hand international trade. Furthermore, the shortened lifespans of garment products due to quick fashion cycles and higher urban consumer spending power produce a sizable amount of post-consumer textile waste in the form of used or second-hand clothing. Post-consumer textile waste is primarily generated from domestic sources and comprises textiles that the owner no longer requires in the condition that they were. Since there are no other avenues for valorization, the most typical methods of disposing of ripped or soiled textiles that are no longer usable are landfilling or incineration. Many of the resources that make up this garbage are recyclable and useful [4,5]. The world has been dealing with environmental problems linked to the ongoing usage of natural resources, such as textile waste [6]. This paper reviews the concerns and challenges of managing waste better.

Environmental Concerns

The environmental consequences of waste generation are far-reaching and dire [7-9].

- Polluted Landscapes: Textile production and waste disposal contaminate water bodies with dyes and chemicals, wreaking havoc on aquatic ecosystems.
- Microplastic Menace: Synthetic fibers shed from discarded clothes infiltrate our oceans and food chain, jeopardizing marine life and human health.
- Landfill Legacy: Mountains of textiles decompose anaerobically, releasing potent greenhouse gases like methane and occupying valuable land that could be repurposed.
- Exploitative Practices: Garment workers in developing countries often face abysmal working conditions, low wages, and even exploitative child labour.
- Economic Inefficiency: Discarded textiles represent a colossal waste of resources and missed opportunities for circularity and sustainable practices [10].

Using efficient waste management techniques in the textile sector is necessary to address these issues. The industry can lessen the adverse effects of solid waste on the environment while simultaneously increasing operational sustainability and

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efficiency by maximizing resource reuse, enhancing wastewater treatment, cutting air emissions, and encouraging recycling activities [11].

Within this context, the circular economy model, which is predicated on eliminating waste and pollution and extending the life of products and materials through reuse, repair, remanufacturing, and recycling, is becoming increasingly significant.

As a result, resources are used more effectively, and new products made with virgin raw materials are either less necessary or not needed at all. The adoption of a circular model requires the recycling of textile waste. The focus is recycling textile trash to ensure sustainability and reduce environmental effects.

Objective

1. To gain an overview of the current techniques and advancements for recycling procedures in the textile recycling industry.

2. The remarkable selectivity of enzymes, which act as bio-catalysts, means certain fiber materials can be extracted from multi-component textiles using these techniques. Textiles become more recyclable as their complexity decreases.

Methodology

Secondary data sources have been sourced from online journals and review articles for case studies to understand some of the best practices used in the recycling industry.

Approaches in Textile Recycling

Numerous approaches exist for recycling textile waste, each with strengths and limitations [12].

- **Primary approach:** Transforming discarded textiles directly into new products.
- **Secondary approach:** Converting textiles into fibers for further processing.
- **Tertiary approach:** Breaking down polymers for regeneration into new fibers.
- **Quaternary approach:** Utilizing waste for energy generation through incineration.

The ever-growing volume of textile waste presents a significant environmental challenge. Fortunately, various effective recycling strategies are being worked upon, each offering unique advantages and limitations for sustainable resource recovery [13].

Closed Loop Recycling

Traditional textile waste separation methods often relied on energy-intensive mechanical or chemical processes. However, a bio-inspired revolution is emerging, harnessing the power of microorganisms to achieve precise and sustainable material segregation. Biological separation utilizes enzymes and fungi with targeted biodegradation capabilities. These microscopic actors selectively break down specific fiber types within a blended textile, enabling efficient separation of cotton from polyester, wool from nylon, and other combinations [14,15]. This targeted approach minimizes collateral damage to desired materials, resulting in purer recycled fibers compared to traditional methods. The process includes:

Pretreatment: Textile waste is often pretreated to improve enzyme accessibility and enhance process efficiency. This may involve mechanical shredding, chemical washing, or physical modifications.

- Enzyme selection: Specific enzymes are chosen based on the targeted fiber types and desired breakdown products. For example, cellulases digest cellulose (found in cotton), while laccase enzymes break down lignin (present in natural fibers).
- Enzymatic hydrolysis: The selected enzymes are introduced to the pretreated textile waste, catalyzing the deconstruction of targeted fiber components. This process typically occurs under controlled temperature and pH conditions.
- Product recovery: The resulting breakdown products, such as glucose from cellulose or monomers from polyester, can be further processed or refined into various valorized materials [16].

Case Study 1 - Biological Recycling of PET: While numerous scientific advancements have identified microbes capable of PET degradation, Carbios, a biotech company, has developed an enzyme process technology that can break down PET (the material in polyester clothes) back to its building blocks. Carbios has found microbes from readily available resources like ordinary leaf-branch compost. They transformed cutinase LCC into a superior PET degradation catalyst through a series of targeted modifications.

Traditional recycling processes gradually degrade the quality of PET with each cycle. This ultimately limits the number of times a material can be reused and often relegates it to lower-grade applications. The enzymatic approach breaks PET down to its fundamental building blocks at the molecular level. This creates virgin-quality PET, ready to be reborn into brand-new clothes, bottles, or other products. This closed-loop system represents a circular economy for polyester, where the material can be continuously recycled without sacrificing quality.

While translating their innovation into reality, they are collaborating with PET manufacturer Indorama Ventures to build the world's first commercial-scale bio-recycling plant for PET plastic in France. This facility, expected to be operational by 2025, will process local plastic waste, potentially impacting how we manage plastic across various industries. This facility aims to reduce plastic waste reduction, with a processing capacity estimated at a staggering 50,000 tons of plastic waste annually. They have collaborated with major sportswear brands like On, Patagonia, Puma, and Salomon. Together, they aim to create the first large-scale system designed to recycle used polyester clothing into new garments [17].

Case study 2 - Fibre Regeneration from Textile Waste: Fiber regeneration offers a promising solution for cotton waste garments. This closed-loop upcycling technology involves transforming used cotton fabrics into pulp. The pulp is then dissolved using a solvent. N-methylmorpholine N-oxide (NMMO) is environmentally safe and completely dissolves cellulose without degradation. Subsequently, the pulp can be blended with wood pulp to create lyocell-like fibers. This approach reduces the demand for virgin cotton production, which is resource-intensive [18].

For garments containing a blend of cotton and polyester, phosphoric acid pretreatment can be employed in separation?. This method effectively separates the materials, enabling the recovery of 100% polyester and a high yield of glucose (79.2%)

under optimized conditions. This not only diverts waste from landfills but also creates valuable resources for other applications.

Another promising avenue for textile waste management involves the utilization of fungal cellulase. Studies have demonstrated the feasibility of cellulase production using submerged fungal fermentation (SmF) on textile waste. This process facilitates the hydrolysis of textiles, resulting in glucose recovery (up to 44.6%). This approach addresses textile waste and generates valuable bioproducts like glucose.

Case Study 3 - Enzymatic Separation and Recycling of Wool/Polyester Fabric Blends: The primary wool component, the keratin protein, has a stubborn structure that makes it difficult to break down. Additionally, mild treatment conditions are necessary to preserve the mechanical properties of the synthetic polymers and ensure that the recycled material satisfies performance requirements. Keratin accounted for 95% of wool by weight and exhibited a high degree of disulfide bonding, which confers rigidity and chemical resistance.

Recycling wool-synthetic textile blends effectively requires eco-friendly techniques. The research was conducted on the selective degradation of wool fibres and the recovery of synthetic fibres using the enzymatic treatment of wool/polyester fabric blends. Fabric blends were treated with a protease previously studied for its keratinolytic action in conjunction with reducing agents.

The two-step enzymatic method with sodium thioglycolate present produced the most significant results for wool fiber breakdown. Scanning Electron Microscopy (SEM) and weight loss measurements of the treated fabrics verified that the wool component had been completely removed. The mechanical characteristics and purity of the resultant polyester fibers were examined using infrared spectroscopy and nano-indentation. The polymer fibers left over after enzymatic treatment maintain the structural integrity and physical characteristics of virgin fibers. They can be utilized to make new clothes or other textile goods made of polyester [19].

Mechanical Recycling

Mechanical textile waste recycling is a cornerstone of the textile industry's circular economy, offering a cost-effective and adaptable solution for a diverse range of discarded fabrics. This established method leverages physical processes, including cutting, shredding, carding, and fiber separation, to deconstruct pre-consumer and post-consumer textiles into reusable fibers. Mechanical recycling begins with meticulous sorting and segregating materials based on fiber type, color, and contamination levels. This initial step ensures the purity and quality of the final recycled fibers. Once sorted, garments and other textiles undergo size reduction via powerful rotary blades, followed by a targeted tearing process that liberates individual fibers from their woven or knitted structures. However, mechanical recycling can damage fibers and shorten their length, impacting their suitability for yarn or non-woven production. Defining quality parameters for recycled fibers becomes challenging due to their shorter length and the presence of non-fiber remnants. Techniques such as lubrication during processing and strategic blending with virgin fibers can mitigate fiber degradation and enhance the properties of the final product.

The resulting recycled fibers, though potentially shorter due to mechanical processing, find diverse and valuable applications. Higher-quality fibers can be re-spun into yarns, forming the basis for new fabrics with minimal loss of functionality. Lower-quality fibers, imbued with the resilience of their past lives, offer alternative avenues for resource recovery. These "second-chance" fibers produce construction materials, automotive components, insulation products, non-woven fabrics, and decorative elements [20].

Chemical Recycling

Chemical recycling delves into the molecular realm, transforming textile waste through chemical reactions. This diverse approach encompasses the below strategies [21].

Dissolution technology: This process uses solvents to dissolve cellulose-based fabrics like cotton and viscose into their original chemical components. These molecules can then be repolymerized to create new cellulose fibers and restart the textile cycle.

Depolymerization: This advanced technology breaks down synthetic polymers like polyester and nylon into their monomers, the building blocks of the polymer.

Repolymerization: These monomers can then be repolymerized to create virgin-quality recycled polyester or nylon, suitable for high-performance fabrics.

Thermal Recycling: Thermal recycling offers a unique pathway for synthetic fibers, leveraging heat to melt and reshape them into new forms. This approach is particularly efficient for pre-consumer waste from production scraps, where consistency simplifies processing. Chips and pellets obtained through mechanical shredding undergo melt extrusion, a high-temperature process that reshapes the molten polymer into new fibers. This method offers advantages like versatility and cost-effectiveness, contributing significantly to recycling materials like polyester, nylon, elastane, polypropylene, and polyurethane. Using heat and no oxygen, pyrolysis breaks down organic molecules to create char, oil, and syngas. The gasification process involves partially oxidizing organic materials at a high temperature to produce syngas, which can then be used to make chemicals or fuels [22]. Recycling waste cotton, polyester, nylon, and other synthetic or natural fibers can be accomplished using either approach [23,24].

Recovery of Polymers from Blends: Chemical recycling holds immense potential for diverse textile waste streams, including

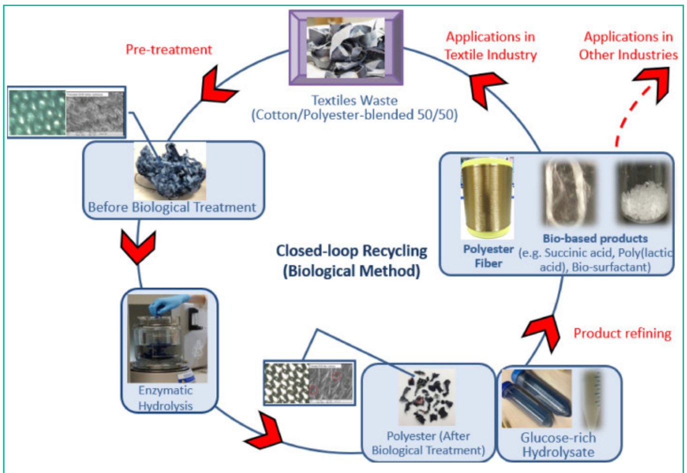

Figure 1: Closed Loop Recycling.
Source: Novel bioprocess for recycling textile waste won the Gold Medal in the International Exhibition of Inventions of Geneva, 19 Apr 2018.

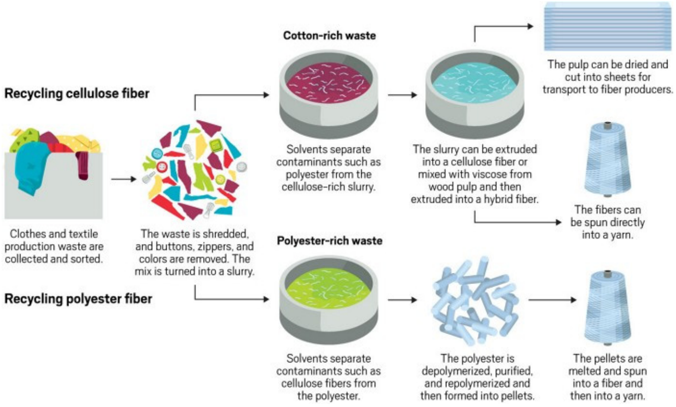

Figure 2: Recycling of Polyester/Cotton Blend.
Sources: Ambercycle, Renewcell, C&EN research. Credit: Yang H. Ku/C&EN/Shutterstock**.**

blends of natural and synthetic fibers. For example, cotton and polyester blends can be chemically separated, as illustrated in Figure 2, allowing each component to be recycled efficiently through its respective method. This targeted approach maximizes resource recovery and minimizes waste.

Recovering bio-oil and monomers from textile waste without the requirement for sorting or colour removal is possible with the hydrothermal liquefaction process. After post-consumer polyester and cotton textiles were subjected to hydrothermal liquefaction, it was discovered that a blend of 95% cotton and 5% polyester produced the most significant bio-oil production (26%) at 325°C under alkali conditions. However, more terephthalic acid was created by a 50% cotton/50% polyester blend.

Textile waste can also be processed using the hydrothermal method. In a study, waste cotton textiles pretreated hydrothermally at 320°C for 60 mins resulted in 23.3% bio-crude oil yield. Furthermore, carbon-rich biochar was created, which has potential applications as an electrocatalytic carbon material or an alternative solid biofuel. Hongthong discovered that when different nylon polymers were added to the hydrothermal liquefaction of macroalgae for the production of biofuel, Fucus serratus would hydrothermally liquefy at 350°C, completely degrading nylon 6 into caprolactam and partially degrading nylon 6,6 into cyclopentanone. This suggests that certain nylon textiles may be broken down and their monomers recovered [25].

Open-Loop Recycling

Open-loop recycling is a key element of the textile industry's circular economy, focusing on reintroducing post-consumer textile waste into different product value chains. Unlike closed-loop recycling, which repurposes fibers within the textile industry, open-loop strategies offer diverse opportunities for resource recovery and value creation. This approach transcends the limitations of garment recycling, enabling the incorporation of recovered textile materials into entirely new product categories [26]. For instance, PET fibers from recycled bottles can be used in construction, insulation, automotive components, furniture padding, and ropes.

Shredded textile waste can be used as insulation for buildings, cars, and furniture and as a filler for carpet underlay, providing cushioning and noise reduction. Discarded textiles can be recycled into absorbent wipes and cleaning cloths for industrial use. This replaces non-reusable options and avoids relying on virgin materials.

Recycled textiles can be transformed or combined into:

- Automotive components such as soundproofing materials used in car doors, headliners, and carpets provide a lightweight and sustainable alternative to traditional materials.
- Geotextiles offer a durable and environmentally friendly solution [27].
- Non-woven materials like felt pads and filters. This creates new uses for waste materials and reduces reliance on petroleum-based products.
- Resins or polymers to create composite materials. These can be used for various applications, including building materials, furniture, and sporting goods.
- Can be used as mulch in gardens and landscaping projects in horticultural applications.

Although open-loop products do not return to the original textile value chain, they provide a valuable second life for discarded materials. Open-loop recycling promotes efficient resource management and contributes to a sustainable production landscape by leveraging their inherent properties and adapting them to new functionalities [28].

Anaerobic Digestion of Textile Waste

Bacteria naturally break down organic matter in an oxygen-free environment through a process known as Anaerobic Digestion (AD). These microorganisms create biogas, a blend of Carbon dioxide (CO_2) and Methane (CH_4), which is a renewable energy source. Textiles, primarily composed of natural and synthetic fibers like cotton, polyester, and nylon, are suitable feedstock for Anaerobic digestion.

Pretreatment: Textile waste goes through a pretreatment process to break down the fibers and enhance biodegradability. This may involve mechanical shredding or chemical treatment.

Digestion Tank: The pretreated waste is then introduced into a sealed digester tank lacking oxygen. Microbes in the tank start degrading the organic components of the textiles, producing biogas.

Biogas Capture and Utilization: The generated biogas is captured and can be used for various purposes, such as generating electricity, heating buildings, or fueling vehicles. AD diverts textile waste from landfills, reducing greenhouse gas emissions associated with decomposition and promoting a circular economy. Biogas from AD is a clean and renewable energy source, helping to reduce dependence on fossil fuels. The solid residue left after digestion, called digestate, can be used as a fertilizer due to its nutrient content [29].

Challenges for the Future of Textile Waste Management

Scaling up recycling technologies - Current recycling techniques frequently have trouble processing intricate blends or particular fibers, restricting their broad use. For a variety of textile waste streams, scalable and reasonably priced solutions are required [30,31].

- Consumer behavior - Sturdy educational programs and easily accessible substitutes are needed to encourage responsible buying patterns and shift fast-fashion behaviors.
- Economic viability- To encourage ethical behavior along the textile value chain, substantial funding and legislative assistance is needed to build an effective and sustainable waste management infrastructure.

• Global collaboration - International cooperation is necessary for effective solutions to handle the problem holistically and consider the various production and consumption patterns in different parts of the world.

• Microplastics - Textile fibers play a substantial role in the pollution caused by microplastics. Enhancing wastewater treatment technologies and creating materials with less fiber shedding require research.

Looking into the above challenges, the remedies can collaborate with similar manufacturing units with similar waste types. Combining the outflow of waste materials will ensure a substantial and continuous supply of recyclable raw materials. This will provide an early return on investment in the scaling up of technology. Consumers are sensitive to prices. Awareness about how recycling is done and how to reuse, recycle, remanufacture, and remodel can shift the preference to be sustainable. A mindset change will encourage consumers to see value in products that have been upcycled or products with recycled content in the retail space. Legislation and the effective enforcement of legislation will keep the manufacturers in compliance along the supply chain [32].

Summary

The textile sector faces several obstacles because of waste generation, such as environmental pollution and the loss of important raw resources. The industry is changing due to initiatives like recycling PET bottles, using regenerated textiles, and implementing effective waste management plans. Closed-loop recycling conserves resources like cotton, polyester, and nylon and lessens reliance on virgin materials and the environmental costs of their production (water use, energy consumption). On the other hand, open-loop recycling is a cost-effective solution for a wide range of textiles, especially those unsuitable for closed-loop recycling due to fibre blends or lower quality. However, it is important to recognize that recycled materials are typically downcycled into products of lesser value than original textiles.

Adopting sustainable methods can cut production expenses, lessen environmental impact, and increase operational effectiveness for the fashion sector. Collaboration among stakeholders, including manufacturers, brands, retailers, and consumers, is vital for driving change and creating a more sustainable fashion ecosystem. By embracing innovative solutions and fostering a culture of sustainability, the textile industry can contribute to a greener future while satisfying consumer demand for upcycled products and products with recycled content.

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