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Developments in Recycling of Polyester Textile Waste

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Abstract

The textile and garment industry's fast fashion model, driven by cheap production and consumer demand, has shortened garment lifespans and increased clothing waste. Utilizing water, energy, minerals, colorant, and several harmful chemicals has loaded Mother Earth with immense consumption of resources. Synthetic fibers, particularly polyester, dominate the industry, contributing to carbon emissions and environmental pollution. Despite the potential for recycling, textile waste often ends up in landfills. Implementing circular economy techniques could significantly reduce greenhouse gas emissions and resource consumption. However, the current recycling rates for textiles are low, especially in developing countries. Additionally, the presence of microplastics from polyester in the environment poses a threat to organisms. The industry is shifting towards a circular economy model, aiming to create a closed loop where textiles can be reused and waste is minimized, thus saving resources, and reducing environmental impacts.

Keywords: Polyester recycling; Textile waste; Closed loop; Challenges in recycling; Recycling via stakeholders

Introduction

The textile and apparel sector is one of the key drivers of the global economy and employment. However, it also appears to be tremendously contributing to environmental contamination. As handloom was taken over by power loom, low-cost raw material, and large-scale manufacturing resulted in the cheap availability of garments, leading to the evolution of Fast Fashion. This business model aims to reduce lead times and purchase cycles since novel patterns and designs emerge each season to meet trends and satisfy consumer needs. As a result, clothes now have a shorter lifespan and are frequently worn less than seven times before being thrown away. It is projected by a study that 100 million tonnes of clothes will be bought yearly by 2030, surpassing the current level of about 60 million tonnes [1].

The share of natural fibers is declining, while the proportion of synthetic fibers is increasing to more than 70%. Textile production is expected to consume 300 million tonnes of fossil fuels and contribute 26% of carbon emissions by 2050, representing a 206% and 1200% jump over 2015 [2].

Polyester fiber contributes to over 54% of the world's fiber production market share. After experiencing a modest reduction in output owing to COVID-19 in 2020, global polyester fiber production grew from 57 million tonnes to 61 million tonnes in 2021. In contrast, recycled polyester (rPET) fiber production increased from 8.4 million tonnes in 2020 to almost 9 million in 2021. Although "polyester" is a general term for all polymers with ester linkages in their polymeric chain, in the garment industry, "polyester" refers to one of these materials known as polyethylene terephthalate [3].

Textile waste contributes significantly to landfill; nevertheless, most textiles can be recycled, allowing fibers and energy to be regained. According to a recent study, circular economy techniques have the potential to decrease global Green House Gas (GHG) emissions by over a third while lowering resource consumption by more than a quarter if adequately implemented [4]. The statistical data states that the standard recycling rate of disposed textiles in developed countries is roughly 16%, whereas only 10% or less of waste textiles are properly recycled in developing countries. According to the Ellen MacArthur Foundation, nearly 97% of clothing materials are derived from virgin resources, and only 1% of the 3% of recovered materials are recycled textiles. The microparticles of such synthetic fiber are ubiquitous in both marine and terrestrial environments and accumulate in live organisms through food and water because post-consumer waste is difficult to process [5].

Recycled polyester fiber is mainly made by recycling PET plastic bottles; however, it can also be made by recycling other pre-consumer processing residue and post-consumer plastics, such as discarded polyester textile waste. As a result, the industry is shifting from a linear economy to a circular economy, in which textiles can re-enter the life cycle rather than being wasted, forming a closed loop that saves resources and reduces environmental impacts.

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Challenges in the Recycling of Polyester Textile Waste

Considering the fragmented, globalized structure of textile and garment distribution networks, as well as the numerous fibers used, whether natural, synthetic, or blended, efficient recycling of textile waste is a tricky proposition and comes with the greater amount of energy needed to conduct recycling that raises the circular system's overall energy consumption [6].

Recycling requires action from all parties throughout the supply chain, including fibre-to-fabric manufacturers, processing houses, brands and e-commerce sellers, customers, national and local governments, and nongovernmental organisations. The market share of chemically recycled polyester is anticipated to increase in the next years due to new operations beginning the commercial production of the material and other businesses in the research and development stage. Recycling waste from clothes, whether taken from pre-consumer or post-consumer, which causes closed-loop recycling, is a complex concept due to several factors that have been further discussed in detail.

Quality of the collected Waste

Many mechanisms, including contamination, dilution, dispersion, deterioration, and process losses, unavoidably change substances into a state of high entropy, where they are effectively lost for technical use. Hence, material cycles cannot be completely utilised in the closed loop. Contamination of the polyester textile waste is the main factor of degradation of its chemical and physical characteristics during re-processing. Lowering these contaminants' levels results in higher-quality recycled fiber [7].

- **Blends -** The textile recycling process has restrictions, particularly on blended fabrics. No technology can now deal with such material mixtures efficiently on an industrial level. Few researchers suggested a new classification of fibers based on the bonds and chemical groups that impart the physical and chemical properties to the fiber for better segregation in the primary recycling stages.

- **Color contaminants from dyes and pigments -** The substantial processing costs associated with textile recycling are partly due to a lack of cost-effective technologies for removing colors from textiles. To completely remove color from waste polyester fibers, recycling must include sorting, depolymerization, color separation, polymerization, and solution/melt spinning, Removing dye from polyester fibres can be done by treating the textile waste with a dye-stripping solvent at a temperature below which the polyester fibres do not disintegrate, but where the crystalline lattice of the polyester fibre swells and allows the dye to get released [8].

The dyes in the fibers might pose major environmental issues because synthetic dye structures are engineered to be difficult to break down to achieve good colour fastness. Dye destruction causes structural damage to polymers, alters the dyeability of recycled textiles, causes uneven dyeing, and affects the environment. More significantly, rigorous extraction procedures such as high temperatures (>150°C), long extraction times, and degradative solutions make the procedure uneconomic to the industry. The Gibbs energy of dye dissociation from textiles must be reduced to remove colours from fibers. It is feasible to disrupt dye-polymer bonds and significantly increase the chemical potential of dyes in fibers so that the chemical potential of dyes in all areas of fibers exceeds that in solution [9].

- **Hazardous Chemicals from Finishes -** An accumulation of toxic substances may impede recycling. Hazardous chemicals are required because technical textiles must meet stringent functional requirements. Most studies believe that textile waste delivered to recycling lacks environmental constraints; nonetheless, such textiles can contain powerful hazardous chemicals that require additional treatment [10]. There is a lack of data and information about the chemicals and potentially hazardous substances used in textile manufacturing and processing [11].

- **Trims and Accessories -**Zippers, buttons, labels, patches, etc., are examples of additives and trimmings. This complicates the sorting and dismantling of the garment recycling procedure even more [12].

Recycling Technologies

- **Mechanical recycling -** can result in manufacturing fabric, yarns, or fibers for use in novel products. The discarded cloth is dismantled, and the fabrics are chopped into smaller pieces. It is then fed into a revolving drum to complete the breakdown and obtain fibers. This is referred to as garnetting. The fabric flakes can also be melted and extruded. The resulting fiber properties of length, fineness, strength, polymer, and colour decide the quality and the novel product. Consequently, the fiber length is shortened, lowering spinnability and yarn strength. Most polymer recycling systems rely on mechanical processes restricted to comparatively pure polymers; such mechanical processes result in end-products with inferior thermomechanical characteristics [13].

- **Chemical recycling -** Textile waste is chemically recycled once de-buttoned, de-zipped, and shredded. Chemical recycling aims to reduce polymers to alternative levels, such as monomers or oligomers, by chemical reactions. Chemical recycling (16% recycling) of textile waste can be accomplished in two ways: (i) polymer extraction/dissolution and purification; and (ii) fiber depolymerization into monomers and their re-polymerization into virgin grade polymers which creates the Closed-Loop Recycling (CLR) if the product added back into the manufacturing unit [14].

Hydrolysis -The sole method of chemical recycling with the resulting products Ethylene Glycol (EG) and Terephthalic Acid (TPA), i.e., the monomer from which the PET is formed, is hydrolysis. Considering that hydrolysis is an environmentally friendly method of converting waste PET into valuable products, it is not used on a large scale due to the high energy consumption (High temperature (200-250 C), Pressure (1.4-2 MPa), and time required for complete depolymerisation and low purity of the finished products [15].

Glycolysis - The two primary depolymerization techniques that have attained commercial viability are glycolysis and methanolysis. The glycolysis process carries the molecular breakdown of PET polymer by glycols in the presence of trans-esterification catalysts, primarily metal acetates (eg, Zinc acetate), where ester linkages are eliminated and substituted with hydroxyl terminals.

The advantages of this process are that it requires atmospheric pressure and a reasonably low temperature (19°C), and manufacturing can be done continuously. Hot water extraction, cooling crystallization, and adsorption can easily separate and purify glycolytic products, and the reagents and products are less volatile and safe. No acid or alkali wastewater is produced during the process. The downside of this procedure is that colors, if present in PET waste, are often not eliminated and take considerable time and energy [16].

A glycolysis method with green catalysts, such as Mg-Al double oxides pellets, is used to examine the circular recycling of polyester textile waste and the catalyst was recovered three times without losing its potential. Researchers have tried to replace the harmful catalyst known as metal acetates with $CaCl_2$, $NaHCO_3$, NaCl with similar results under similar experimental conditions. However, the obtained product would be sodium terephthalate, with can be precipitated with stronger acids such as H_2SO_4 [17].

Methanolysis - Under 20-40 atmospheric pressure and 180-280°C process, PET is depolymerised by methanol into its monomers known as ethylene glycol and dimethyl terephthalate. The advantage of methanolysis is that DMT is considerably easier to purify than BHET, lower-quality PET feedstocks are acceptable in the methanolysis process compared to the glycolysis method, and other products like methanol and ethylene glycol can be readily reused and recovered. However, the key feedstock for PET manufacturing is pure TPA, not DMT, which is the principal result of methanolysis. The hydrolysis of DMT to TPA adds significant cost to the process.

- **Solvent-based recycling -** Virgin and recycled polyester (rPET) are generally blended with natural fibers such as cotton, wool and viscose, or synthetic fiber such as nylon and elastane to improve textiles' functional and aesthetic properties.

Recycling such textile material by separating the PET eliminates the possibility of further recycling the material. However, in such cases, a solvent-based technique can be taken to separate and recover both components from textiles containing a mix of PET/rPET and other textile materials.

The primary technique describes a solvent introduced to blended polyester textiles at a high temperature. Aromatic esters and aldehydes, Di propylene glycol methyl ether acetate, are suitable PET solvents. Undissolved fiber from the solution is removed by hot filtering. Isopropanol serves as an antisolvent by precipitating the required polyester.

- **Enzymatic recycling -** Post-consumer waste generally includes a mixture of different natural and synthetic fibers in blended textiles, such as cotton-polyester, polyester-lycra, and polyester-wool. The separation of blends, where garments are often multicomponent, presents a major challenge to recycling as fibers must be separated into single components to enable effective recycling. Using cellulase and keratinase resulted in a complete breakdown of blends such as poly-cot, poly-wool undigested polyester fibers were recovered. The nutrient-rich keratin hydrolysate could be employed in microbial growth media, bio-fertilizers, or animal feed [18].

For the hydrolysis of PET, some enzymes (Lipase, Polyesterase, Cutinase, carboxylesterase) with esterase/hydrolytic activity have been frequently utilised and termed as biocatalytic recycling Surfactants and additives such as calcium, magnesium, and hydrophobins (cysteine-rich proteins) have also been found to improve enzymatic PET hydrolysis by providing simple access to PET polymers. Biocatalytic recycling not merely sustainably manages PET trash, but the products created by this process have the same qualities as virgin PET [19].

While these bio-recycling strategies are likely to provide environmental benefits, an in-depth analysis of the environmental consequences associated with these new systems is required. It is critical to assess and enhance the life cycle environmental implications of such new technologies to avoid unintended consequences, such as the use of a specific chemical for processing textile waste, when they are subsequently scaled up.

Ways to Promote Recycling Through Stakeholders

The textile industry, with a global business of $2.4 trillion global industry works with one of the longest supply chains. It is based on a complex, diverse, decentralized supply chain that includes numerous actors, including raw material, yarn, fabric, knitwear producers, finishing, apparel firms, brands, retailers, customers, and recycling agents. Each level of the supply chain generates unavoidable textile waste hence, different aspects can be undertaken through different stakeholders, which promotes recycling [20].

Closed-loop recycling has had greater success in garment manufacturing with pre-consumer waste than post-consumer waste recycling. Because pre-consumer waste is easily identifiable, making segregation easier, can be virgin and homogenous in fiber and colour, and hence, the resulting reclaimed fiber will be of superior quality for re-entering into the supply chain.

- **Designer aspect -** Designing goods and services for a circular economy has the potential to significantly reduce primary resource requirements while increasing the accessibility of secondary materials for continued use in the economy [21].

Product design is the main criterion that can either excel or impede textile waste recycling. Designers and manufacturers can design the product on a recycling-based concept termed Design -2- Recycle, which can substantially reduce the environmental impact.

Designing a textile product with a longer service life quality could encourage reuse over recycling. The material can be made either of a single fiber, or the virgin fibers can be blended with the recycled fiber of the same fiber, Avoiding using mixed material reduce the hindrance in closed-loop recycling and energy consuming separation and purification process of blends [22].

The finishes applied on the garment for functionality and aesthetic purposes should be fluorocarbon – free and when possible, employ C-0 chemistry to assure water and dirt repellence.

The trims and accessories (zippers, buttons, labels, etc) should be attached with a material/ thread that can easily be dissolved in some special solvent, reducing labour-intensive segregation.

- **Manufacturing aspect -**The textile material should be manufactured near the consumption area to minimize the transportation in the loop. Fiber degradation begins during consumer use, such as washing and wearing. Hence, the manufacturer and brands become responsible here in providing appropriate labelling of wash care and informing the consumer about textiles' caring and re-mending aspects. One option to reduce the carbon footprint associated with the whole life cycle of polyester is to manufacture these materials using bio-based feedstock rather than fossil fuels [23].

- **Consumer aspect -** The consumer should take care of the laundry aspect during the consumption period of the product. Furthermore, it is critical to raise customer knowledge to encourage ecologically friendly textile product adoption.

Summary

Recycling polyester textile waste poses several challenges. The variety of garments in terms of style, materials, and fiber types makes sorting and dismantling for recycling labour-intensive. Contamination, the blending of fibers, color contaminants from dyes, hazardous chemicals from finishes, and trims and accessories complicate recycling.

Mechanical and chemical recycling are the leading technologies used prominently in the industry. Mechanical recycling involves depolymerization and repolymerization of the polymer, which are then used to create new products. However, this process can result in low-quality reclaimed fiber and limit the raw product to virgin material. Chemical recycling aims to reduce polymers to monomers or oligomers through chemical reactions, diversifying end-product applications. Hydrolysis and glycolysis are common methods, but they have drawbacks such as high energy and time consumption, making them uneconomical for the industry. Methanolysis and solvent-based recycling are other options, but each method has limitations. Enzymatic recycling is being explored as a potential solution for separating mixed fiber waste. Enzymes, such as Cellulase, Keritnase, and Polyesterase, have shown promise in breaking down polyester fiber into monomers and separating blends. This approach contributes to developing a circular economy by creating value from waste.

Efficient textile waste recycling requires collaboration among all stakeholders in the supply chain, including producers, manufacturers, customers, and governments. Implementing circular economy techniques can significantly reduce greenhouse gas emissions and resource consumption. Overall, addressing the challenges of polyester textile waste recycling is crucial for reducing the comprehensive impact of the textile industry on the environment and moving toward a sustainable future.

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