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Biotechnological Solutions for Recycling Synthetic Fibers †

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Abstract: Biotechnology offers the potential for selective depolymerization of natural and synthetic fibers, isolation of components or recovery of monomers. This progress solves the problems associated with the regeneration of monomers from synthetic fiber blends, especially when contaminated or mixed fibers are involved. In addition, the recycling of used fiber products into higher value products not only keeps waste out of landfills, but also creates economic opportunities and reduces the need to produce new synthetic fibers. Synthetic fibers can be recovered by mechanical or chemical recycling, but biotechnological solutions with enzymes offer a better environmentally friendly alternative to harsh chemicals by selectively breaking down certain chemical bonds in polymers to obtain purer monomeric building blocks. Efficient biotechnological recycling, however, depends on the specific polymer, as different enzymes, microbial colonies, fungal hyphae, etc. can process different man-made fibers. Challenges arise with any type of fiber recovery, including enzymatic degradation, when suitable enzymes have not yet been discovered or when fiber blends impede accessibility and efficiency. This short review provides an overview of the possibilities of biotechnological solutions for synthetic fiber recovery.

Keywords: biotechnological solutions; synthetic fibers recycling; eco – friendly textiles; sustainable textiles; enzymatic degradation

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1. Introduction

As environmental awareness of sustainable practices increases, the textile industry is under increasing pressure to reduce its environmental impact. The widespread use of synthetic fibers, while contributing to diverse and affordable textile products, has led to a growing problem of waste accumulation due to their slow degradation [1,2]. Textile fiber recycling includes mechanical recycling, chemical recycling including pyrolysis, enzymatic hydrolysis, hydrothermal technology, ammonolysis, gasification, glycolysis, and decolorization to reduce the amount of textile waste that is incinerated or landfilled. Chemical treatment is an effective method of textile recycling in which chemicals are added to break down the complex textile polymer into smaller polymer molecules. Today, chemical recycling is a popular method for degrading polymers, solution-purified polymers, oligomers, monomers, or raw materials in gaseous or liquid form, all of which are products of chemical textile recycling. Re-polymerization can be used to renew polymers such as oligomers and monomers even in textile waste. In contrast, mechanical textile recycling has been used since the beginning of the industrial revolution. It is one of the cheapest and simplest recycling methods [3-5]. However, not all of these processes are suitable for recycling synthetic fibers in a sustainable manner. In response, biotechnological approaches have emerged as promising alternatives for recycling and degradation synthetic fibers. The use of microorganisms that degrade synthetic fibers in bioreactors is a viable approach for large-scale recycling [6,7]. This short review focuses on mechanical and biotechnological solutions (see Figure 1).

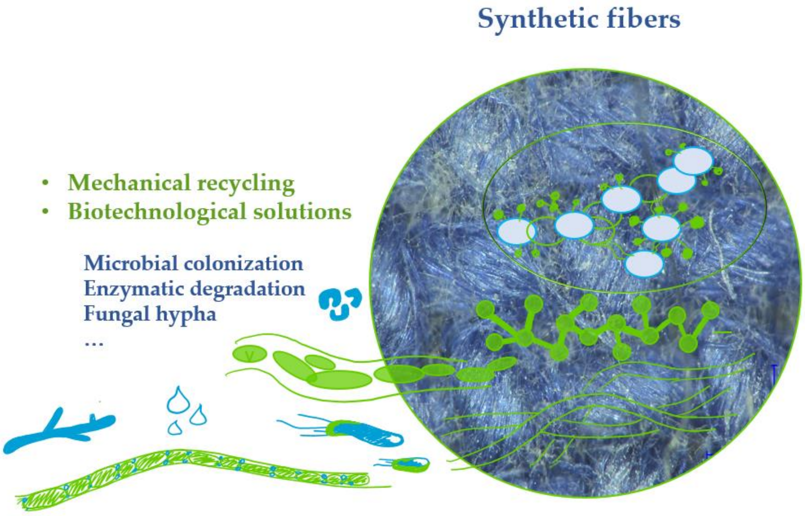
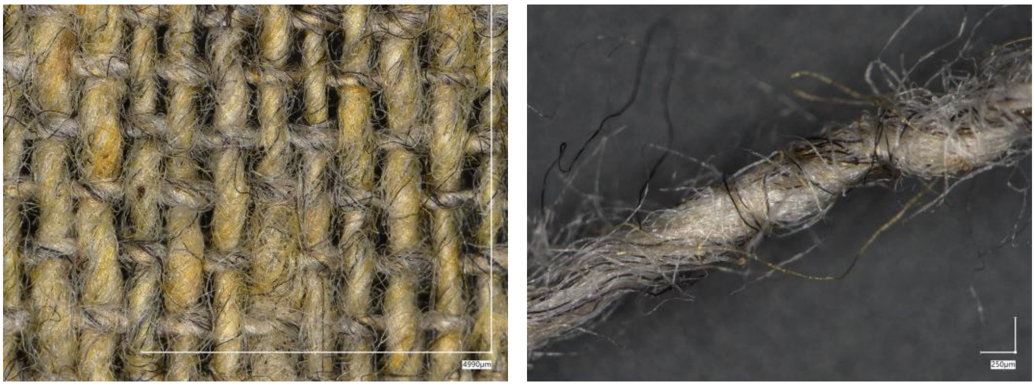


Figure 1. Synthetic fiber recycling options.

For example, Marqués-Calvo et al. described the results of enzymatic and microbial biodegradation of poly(ethylene terephthalate) (PET) and PET copolyester plastics using two commercial fungal lipases and two bacteria from environmental isolates on a laboratory basis [8]. On the other hand, Mohanan et al. described the microbial and enzymatic degradation of synthetic plastics used in the textile industry [9]. Incorporating biotechnological solutions into current recycling approaches that promote environmental conservation and enable the transition to a circular economy and regulatory aspects [10]. This short review explores the potential of biotechnological solutions in synthetic fiber recycling. It addresses the challenges and highlights applications that hold the key to a more sustainable textile economy. It addresses enzymatic degradation, a fundamental facet of biocatalysis, and demonstrates the potential of enzymes for targeted degradation of various synthetic fibers with minimal by-product generation.

2. Mechanical recycling processes and limitations

Mechanical recycling processes such as mechanical sorting, mechanical shredding and melt spinning are central to the sustainable management of man-made fibers and provide cost-effective and widely used approaches to various stages of the recycling process. But these methods of recycling also have limitations. The mechanical recycling of textiles leads to a reduction in quality due to the reduction in fiber length and this is reflected in the limited possibilities of use on the end market. The microscopic image in Fig. 2 shows a textile fabric made from recycled polyester (PES) fibers, presumably mechanically recycled and consisting of 20% polyester and 80% cotton (see Fig. 2a, shopping bag, Comco Plast CCC GmbH, Germany). Images were taken using a digital microscope (Keyence, VHX-970FN, Neu-Isenburg, Germany). The fibers in the warp threads are relatively short and the surface of the yarn is uneven, with individual fibers protruding (see Fig. 2b).



a) b)

Figure 2. Microscopic images of 20% polyester/80% cotton fabric (a) and warp yarn (yellow and black polyester fibers cover the white cotton fibers) (b).

Mechanical sorting is an important method that uses equipment such as conveyors and air sifters to efficiently separate synthetic fibers from other materials based on physical characteristics such as size, density, or shape. It excels with large materials, but can be limited when dealing with similar properties, potentially leading to contamination. Mechanical shredding, on the other hand, plays a key role in reducing material size and preparing it for further processing, making it more manageable and compatible with subsequent recycling steps [11-13]. Mechanical sorting struggles with similar materials and risks contamination; sorting accuracy is critical. Mechanical shredding raises concerns about fiber damage and energy consumption, requiring improvements in sustainability. Melt spinning is energy intensive and suitable for specific synthetic fibers, limiting its broader applicability [14].

3. Biotechnological Perspectives for Synthetic Fiber Recycling

Biotechnological implementations offer a range of innovative solutions to improve synthetic fiber recycling. These approaches use the natural capabilities of microorganisms and enzymes to degrade fibers, generate valuable products and contribute to a more sustainable and circular textile industry. Ongoing research and development in this area has the potential to revolutionize the management of synthetic fiber waste and promote environmental protection [15].

3.1. Enzymatic degradation

Enzymatic degradation of synthetic fibers occurs through the directed action of enzymes that target specific molecular bonds within the polymer structure [16]. Enzymes such as proteases, lipases, and cellulases have substrate specificity that enables them to cleave peptide, ester, and glycoside bonds, respectively. Esterases, for example, have been successful in degrading polyester-based synthetic fibers, while other enzymes target different types of synthetic fibers. Enzymatic hydrolysis disrupts the molecular structure of the fiber, leading to the formation of shorter oligomers and eventually monomers that can be assimilated by microorganisms or used as starting material for biochemical processes [17,18]. Enzymatic degradation of synthetic fibers not only helps in waste management, but also opens up opportunities for circular economy. The resulting degradation products, such as monomers and oligomers, can serve as feedstocks for biopolymers, biofuels and other value-added products, reducing dependence on fossil resources. In addition, enzymatic degradation helps reduce the environmental impact associated with the accumulation of synthetic fiber waste [19-21]. Bei et al. investigated the enzymatic degradability of the three polyester types using cutinase and found that the biological degradability depends on the spacing of the ester groups and the crystallinity. In addition, the ratio of hydrophilicity/hydrophobicity of the polyester surface is crucial for the enzymatic degradability.

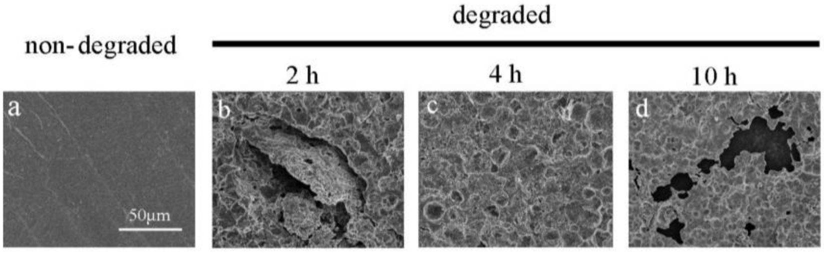


Figure 3. Scanning electron microscope images of poly(ethylene succinate) (PES) polyester films degraded for 2, 4, and 10 hours. Adapted from Ref. [22], originally published under a CC-BY license.

Navone et al. studied the selective digestion of fiber composites of wool-polyester blends using an enzymatic approach by applying a keratinase in a two-step process with the addition of a reducing agent, and the undigested polyester fibers were recovered. Spectroscopic and mechanical analysis of the recovered synthetic fibers confirmed that the enzymatic treatment had no significant effect on the properties of the polyester compared to untreated samples [23]. Egan et al. report on enzymatic textile fiber separation for sustainable waste processing [24]. Tiso et al. investigate the sequential conversion of polyethylene terephthalate (PET) into two types of bioplastics, a medium chain length polyhydroxyalkanoate (PHA) and a novel bio-based poly(amideurethane) (Bio-PU), using a terephthalate-degrading *Pseudomonas umsongensis* GO16 [25]. Limitations of this enzymatic recycling method for synthetic fibers may include the specificity of enzymes, making them less effective on certain types of synthetic fibers. Additionally, the efficiency of enzymatic degradation could depend on the specific synthetic fiber and process conditions, potentially limiting its applicability.

3.2. *Microbial biodegradation*

Microbial biodegradation uses the natural ability of microorganisms such as bacteria and fungi to break down complex synthetic polymers into simpler compounds. Several microorganisms have been identified that possess enzymes that can degrade synthetic fibers. For example, certain bacteria can produce enzymes such as esterases and lipases that target the ester bonds present in polyester fibers. Researchers have also explored the potential of bioaugmentation and biostimulation techniques. Bioaugmentation involves the introduction of specific microorganisms into the environment, while biostimulation aims to increase the activity of existing microorganisms by providing nutrients or other growth-promoting factors. These approaches aim to accelerate the degradation process and increase the efficiency of fiber degradation [26-28]. Wei and Zimmermann focused on microbial biocatalysts involved in the degradation of the synthetic plastics polyethylene, polystyrene, polyurethane, and polyethylene terephthalate (PET) [29]. Advances in genetic engineering allow the modification of microorganisms to enhance their ability to degrade synthetic fibers. By introducing specific genes or pathways, scientists can tailor microorganisms to efficiently break down complex fiber structures and produce valuable end products. Schiros et al. reported on the genetic engineering of microorganisms for bio-fabrication, green chemical processing of raw materials, and green manufacturing processes for the textile industry. They provided an overview of future perspectives for sustainable bio-textile production, focusing on the use of waste streams to improve both recyclability and process economics [30]. Zimmermann reviewed the biocatalytic recycling of polyethylene terephthalate plastic [31]. Yoshida et al. showed that the new species *Ideonella sakaiensis* degrades plastic using two enzymes to hydrolyze poly(ethylene terephthalate) PET. Bacteria isolated outside of a bottle recycling facility to degrade and metabolize plastic [32]. Conventional synthetic fibers such as polyester, nylon and acrylic are derived from petroleum-based resources and end up in landfills or the environment, where they can persist for years and contribute to environmental pollution [33,34]. Biochemical recycling uses biological processes to break down synthetic fibers into their individual molecules, which can then be used to make new fibers or other materials. The conversion of depolymerized synthetic fiber monomers into valuable chemicals and materials can be facilitated by biotechnological processes. These monomers can be used as feedstocks to make new polymers, reducing the need for virgin resources. This approach can help close the loop in synthetic fiber production and minimize waste generation [35,36]. The limitations of microbial biodegradation and enzymatic methods for synthetic fiber recycling include potential specificity of microorganisms and enzymes, as they may not be equally effective on all types of synthetic fibers. Additionally, the efficiency of the degradation process is depending on the specific fiber and process conditions.

4. Current Challenges and Limitations

While biotechnological solutions are promising, several challenges remain. Identifying suitable enzymes or microbial strains for the wide range of synthetic fibers remains a daunting task. Optimizing degradation rates, as well as understanding potential by-products and their environmental impact, requires careful research. In addition, the scalability of biotechnological processes to meet industrial demands requires careful consideration [37,38]. This field is still in its infancy and faces several challenges. Enzymatic degradation of synthetic fibers can be slow and may not result in a sufficient amount of high-quality building blocks for the production of new fibers. Synthetic fibers come in different formulations, and developing enzymes that can effectively degrade all types of synthetic fibers is challenging because of the different chemical structures. Degradation can produce contaminants or fragments that are difficult to separate from the degraded building blocks, compromising the quality of the recycled material. While laboratory-scale trials are promising, scaling up enzymatic processes to an industrial scale can be complex and costly [39-41]. The increasing use of synthetic fibers in textiles has led to serious environmental concerns because they are not biodegradable. Conventional recycling methods based on mechanical and chemical processes are inadequate for the increasing amount of synthetic fiber waste. Biotechnological approaches have emerged as a promising solution for sustainable and effective recycling.

5. Conclusions

This short review discusses recent biotechnological advances in the treatment of synthetic fiber waste and the potential and limitations of mechanical and biotechnological solutions. Biodegradation is emphasized, highlighting the potential of enzymes for targeted degradation of synthetic fibers with minimal by-product formation. The integration of microbial consortia and genetically modified microorganisms offers innovative strategies to convert recalcitrant synthetic fibers into valuable resources. The use of fiber-degrading microorganisms in bioreactors enables large-scale recycling. Incorporating biotechnology into recycling concepts requires a holistic assessment that considers environmental protection and regulatory compliance. The potential of biotechnology is one of the most promising solutions for recycling synthetic fibers, supporting environmental sustainability and the transition to a circular economy.

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