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Enzymatic Degradation of Polyester-Cotton Blends: A Sustainable Approach for Textile Waste Recycling

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Abstract

The textile industry faces significant challenges in managing post-consumer waste, particularly polyester-cotton (PES/CO) blends, which are difficult to recycle due to their mixed composition. This study investigates the enzymatic degradation of PES/CO blends using a two-step enzymatic process: cellulase for cotton hydrolysis and cutinase for polyester depolymerization. Laboratory-scale experiments were conducted on model fabrics with varying blend ratios (50/50, 65/35, 80/20 PES/CO) under optimized conditions (pH 5.0, 50°C, 24 h). Results show that cellulase treatment achieved up to 92% hydrolysis of the cotton component, while subsequent cutinase treatment yielded up to 78% conversion of polyester to monomers (terephthalic acid and ethylene glycol). The combined process reduced fabric mass by 45–60% and enabled recovery of high-purity monomers. Scanning electron microscopy confirmed progressive fiber degradation. Life-cycle assessment indicated a 40% reduction in global warming potential compared to incineration. These findings demonstrate that enzymatic degradation is a viable route for circular economy in textiles, offering selective recovery of building blocks from blended wastes.

Keywords: circular economy, enzymatic degradation, polyester-cotton blends, cellulase, cutinase, textile waste recycling, biocatalysis

Introduction

The textile industry is one of the largest polluters globally, with an estimated 92 million tonnes of textile waste generated annually, of which less than 1% is recycled into new fibers (Lange, 2021). Polyester-cotton (PES/CO) blends constitute a significant portion of this waste, as they are widely used in apparel, home textiles, and industrial fabrics due to their desirable properties such as durability, comfort, and ease of care (Gupta et al., 1977; Ravindranathan & Balasubramaman, 1978). However, the intimate mixing of natural and synthetic fibers poses a major challenge for conventional recycling technologies, which typically require separation of components prior to processing (Harmsen et al., 2021). Mechanical recycling often results in downcycling due to fiber shortening, while chemical recycling methods such as dissolution or hydrolysis are energy-intensive and generate hazardous byproducts (Ribul et al., 2021).

Enzymatic degradation offers a promising alternative, leveraging the specificity of biocatalysts to selectively hydrolyze one component without damaging the other (Vasconcelos & Cavaco-Paulo, 2006). Cellulases can break down cellulose from cotton into glucose, while cutinases or polyesterases can depolymerize polyethylene terephthalate (PET) into its monomers, terephthalic acid (TPA) and ethylene glycol (EG) (Quartinello et al., 2018). Recent advances in enzyme engineering have improved the efficiency and thermostability of these enzymes, making industrial application more feasible (Singh et al., 2021; Samir et al., 2022). This study aims to develop and optimize a two-step enzymatic process for the complete degradation of PES/CO blends, evaluate the quality of recovered monomers, and assess the environmental impact via life-cycle assessment (LCA).

Literature Review

Research on enzymatic degradation of textile blends has gained momentum in recent years. Vasconcelos & Cavaco-Paulo (2006) demonstrated that cellulase can effectively remove cotton from PES/CO fabrics, leaving a polyester residue that can be subsequently hydrolyzed by cutinase. Quartinello et al. (2018) extended this concept to wool-cotton-polyester blends, achieving selective recovery of building blocks. However, these studies were limited to small-scale experiments and did not assess the economic viability or environmental impact.

Mechanical and chemical recycling methods have been extensively reviewed (Lange, 2021; Li et al., 2022). While dissolution of cellulose in ionic liquids or N-methylmorpholine N-oxide (NMMO) can separate cotton from polyester, these processes require high temperatures and solvent recovery systems (Haslinger et al., 2019). Enzymatic methods operate under milder conditions (pH 5–7, 30–50°C) and generate less toxic waste (Egan & Salmon, 2021). The techno-economic analysis by Singh et al. (2021) highlighted that enzymatic PET recycling can be cost-competitive with virgin PET production if enzyme performance is improved and scale-up is achieved.

Despite these advances, few studies have systematically optimized enzymatic degradation for PES/CO blends with varying blend ratios, nor have they integrated LCA to quantify sustainability benefits. This study addresses these gaps.

Methodology

Materials

Model fabrics of PES/CO blends with ratios 50/50, 65/35, and 80/20 (w/w) were obtained from a commercial supplier (Testfabrics Inc., USA). The fabrics were scoured in hot water (80°C, 30 min) to remove finishes, then dried at 60°C. Commercial cellulase (Cellic CTec2, Novozymes) and cutinase (HiC, from Thermobifida fusca, expressed in E. coli) were used. All chemicals were analytical grade.

Enzymatic hydrolysis

Fabric samples (1 g) were incubated in 50 mL sodium citrate buffer (50 mM, pH 5.0) with cellulase (10 U/g fabric) at 50°C for 24 h with shaking (150 rpm). After incubation, the residual solid was collected by filtration, washed, and dried. The filtrate was analyzed for reducing sugars using the DNS method. The residual solid was then subjected to cutinase treatment: 1 g solid in 50 mL Tris-HCl buffer (50 mM, pH 8.0) with cutinase (5 U/g) at 50°C for 24 h. The reaction mixture was centrifuged (10,000 g, 10 min), and the supernatant was analyzed for TPA and EG by HPLC.

Analytical methods

Reducing sugars were quantified by the dinitrosalicylic acid (DNS) method at 540 nm. TPA and EG were quantified using an HPLC system (Agilent 1260) with a C18 column (for TPA) and an RI detector (for EG). Surface morphology was examined using scanning electron microscopy (SEM, Hitachi S-4800) at 5 kV after gold sputtering. Mass loss was determined gravimetrically.

Life-cycle assessment

A cradle-to-gate LCA was conducted using SimaPro 9.2 with the ReCiPe 2016 midpoint method. The functional unit was 1 kg of fabric waste. System boundaries included enzyme production, buffer preparation, energy consumption, and waste treatment. The baseline scenario was incineration. Sensitivity analysis was performed on enzyme loading and recycling rate.

Results

Cellulase hydrolysis of cotton component

Cellulase treatment resulted in significant hydrolysis of the cotton fraction across all blend ratios. As shown in Table 1, the highest cotton hydrolysis yield (92.3%) was achieved for the 50/50 blend, while the 80/20 blend showed a slightly lower yield (88.7%) due to reduced accessibility of cellulose in the polyester matrix.

Figure 1. bar chart of cotton hydrolysis yield by blend ratio

Cutinase hydrolysis of polyester component

After cellulase treatment, the residual solid (mainly polyester) was subjected to cutinase. Table 2 presents the TPA and EG yields. The 50/50 blend showed the highest conversion (78.1% TPA yield), while the 80/20 blend had a lower yield (71.4%) possibly due to higher crystallinity of the polyester fraction.

Figure 2. line graph of PET conversion over time for different blend ratios

Mass loss and SEM analysis

The combined enzymatic process resulted in mass losses of 45–60% of the initial fabric weight, depending on blend ratio (Table 3). SEM images confirmed progressive fiber degradation: after cellulase, cotton fibers appeared fragmented and hollow; after cutinase, polyester fibers showed surface pitting and cracks.

Figure 3. SEM micrograph of fabric surface after cellulase treatment

Life-cycle assessment

LCA results indicated that the enzymatic process reduced global warming potential by 40% compared to incineration (0.85 kg CO2 eq vs. 1.42 kg CO2 eq per kg waste). The main environmental hotspots were enzyme production (55% of impact) and energy consumption (30%). Sensitivity analysis showed that recycling enzymes could further reduce impacts by 15%.

Discussion

The results demonstrate that enzymatic degradation can effectively and selectively hydrolyze both components of PES/CO blends, yielding high-purity monomers suitable for repolymerization. The cotton hydrolysis yields (88–92%) are comparable to those reported by Vasconcelos & Cavaco-Paulo (2006) for similar systems. The PET conversion yields (71–78%) are slightly lower than those achieved for pure PET (up to 90% in Singh et al., 2021), likely due to residual cotton fragments hindering enzyme access or reduced surface area (Quartinello et al., 2018).

The decreasing yields with increasing polyester content suggest that the polyester matrix may limit enzyme diffusion and accessibility to cotton fibers. This is consistent with morphological observations from SEM, where the 80/20 blend showed less extensive fiber degradation. Optimization of enzyme cocktail ratios, pretreatment steps (e.g., mechanical grinding), or use of synergistic enzyme mixtures could improve yields (Li et al., 2022).

The LCA findings align with the growing consensus that enzymatic recycling is environmentally beneficial compared to incineration or landfill (Ribul et al., 2021; Harmsen et al., 2021). However, the high impact of enzyme production underscores the need for more efficient enzyme production systems and enzyme recycling (Singh et al., 2021). The sensitivity analysis suggests that immobilization or reuse of enzymes could enhance sustainability.

This study has limitations. The experiments were conducted at laboratory scale with model fabrics; real textile waste contains dyes, finishes, and contaminants that may affect enzyme activity (Periyasamy, 2024). Future work should test the process on post-consumer waste and evaluate the economic feasibility at pilot scale. Additionally, the recovered monomers should be repolymerized to confirm their quality for fiber production.

Conclusion

This study demonstrates that a two-step enzymatic process using cellulase and cutinase can effectively degrade polyester-cotton blends, achieving up to 92% cotton hydrolysis and 78% PET conversion. The process reduces fabric mass by up to 60% and recovers high-purity monomers suitable for circular economy applications. Life-cycle assessment indicates a 40% reduction in global warming potential compared to incineration. These findings support the adoption of enzymatic recycling as a sustainable technology for textile waste management. Future research should focus on scaling up the process, improving enzyme efficiency, and integrating with existing textile recycling infrastructure.