Transitioning to Green Textile Manufacturing: The Synergistic Role of Microbial Enzymes and Biosurfactants

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Abstract

The textile industry is under severe pressure to replace highly polluting chemical processes with eco-friendly alternatives. While individual applications of microbial enzymes (e.g., cellulases, amylases, pectinases, laccases) and microbially derived biosurfactants (e.g., rhamnolipids, sophorolipids, surfactin) have advanced sustainable textile processing, their combined, synergistic application represents an unmapped frontier. This review comprehensively analyzes the multi-faceted mechanisms driving the synergistic relationship between microbial enzymes and biosurfactants across wet processing operations including desizing, scouring, bleaching, biopolishing, and wastewater remediation. Studyexplores how biosurfactants enhance enzyme performance by reducing interfacial tension, improving fiber wetting, and stabilizing enzymatic tertiary structures against harsh process dynamics. Simultaneously, enzymatic modification of fabric surfaces exposes localized domains, allowing optimal biosurfactant micellization and localized activity. Finally, we address current techno-economic bottlenecks, scale-up barriers, and future multi-omics-driven strategies required to commercialize this binary biomolecular framework for next-generation circular textile manufacturing.

Key words:

Microbial Enzymes; Biosurfactants; Wet Processing; Interfacial Synergy; Bio-scouring; Textile Wastewater Remediation

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1.0 Introduction

The modern textile industry is facing significant challenges due to its heavy dependence on resource-intensive wet processing steps such as desizing, scouring, bleaching, and finishing.

These traditional processes use large amounts of fresh water, energy, and synthetic chemicals. Standard production methods rely on strong oxidizing agents, harsh alkalis, and non-biodegradable surfactants, which result in highly alkaline, colored, and ecotoxic wastewater [1].As global environmental regulations become more stringent and the industry moves towards zero-liquid discharge (ZLD) systems, there is an urgent need to incorporate green chemistry practices into the core operations of the textile sector [2].

Industrial biotechnology presents a promising solution to this environmental shift.

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Specific microbial enzymes function as targeted biocatalysts that can safely replace harmful synthetic additives. At the same time, biosurfactants produced by microorganism's surface-active amphiphilic secondary metabolites grouped into lipopeptides, glycolipids, and polymeric complexes have become a sustainable alternative to surfactants derived from fossil fuels. These bio-based alternatives have excellent biodegradability, low ecological toxicity, and stability under a wide range of temperature and pH conditions [3].

Importantly, using these biological components on their own often causes operational issues in industry.

When used alone, enzymes may require long processing times, high dosages, or fail to fully modify the fabric. Recent developments show that combining microbial enzymes with biosurfactants results in a powerful, multi-step physical and chemical synergy that overcomes the limitations of using them individually, opening up a new area in environmentally friendly textile processing [4].

2.0 Molecular Profiles of the Biomolecular Partners:

2.1 Textile Microbial Enzymes

Microbial enzymes act as precise tools, classified based on their ability to identify and break specific chemical bonds in both natural and synthetic fibers:

Amylases (α-amylases): These biocatalysts quickly break down the internal α-1,4-glucosidic bonds in starch-based sizing agents, transforming insoluble polymer networks into water-soluble sugars that can be easily rinsed away [5].

Pectinases: These enzymes break down the complex pectin matrix within the primary cell wall of raw cotton fibers.

By breaking this structural component, they uncover trapped natural waxes and non-cellulosic impurities for further removal.

Cellulases (Endoglucanases): These agents specifically break the internal β-1,4-glucosidic bonds in the amorphous parts of cellulose.

This controlled breakdown is essential for removing surface fuzz (biopolishing) and achieving the popular look of distressed denim through stonewashing [8].

Laccases and Peroxidases: These multi-copper enzymes use radical-based oxidation pathways to directly oxidize natural pigments during bio-bleaching and break down complex, stable azo-dye chromophores during wastewater treatment.

2.2 Microbially Derived Biosurfactants

Biosurfactants are primarily produced during the stationary phase of microbial fermentation.

They have a unique amphiphilic structure with a hydrophilic (polar) head and a hydrophobic (non-polar) hydrocarbon tail [4].

Glycolipids: This group includes rhamnolipids made by Pseudomonas aeruginosa and sophorolipids produced by Starmerella bombicola.

They are known for very low critical micelle concentrations (CMCs) and strong emulsifying abilities, making them effective mobilizing agents [6].

Lipopeptides: This group includes surfactin and iturin, made by Bacillus subtilis through non-ribosomal peptide synthetases [7].

They have a strong ability to reduce water surface tension and lower the interfacial tension between immiscible substances [8].

3.0 Mechanisms of Interfacial & Catalytic Synergy:

Without Biosurfactants	With Biosurfactants (Sub-CMC)
High Surface Tension	Drastic Surface Tension Drop
Enzymes blocked by wax barrier	Rapid fabric wetting & fiber swelling
Slow, uneven catalytic attack	Enzyme structure stabilized & protected
Reprecipitation of hydrophobic debris	Complete micellar encapsulation of debris

The synergistic interaction between enzymes and biosurfactants results from a mutual physicochemical process occurring at the interface between fiber and water [9].

Natural fibers like unprocessed greige cotton have a natural hydrophobic coating made of resins, fats, and waxes. This organic layer acts as a physical barrier, preventing aqueous enzyme solutions from reaching their intended targets.

To counter this, biosurfactants quickly arrange themselves at liquid-gas and liquid-solid interfaces, reducing water surface tension from about 72 mN/m to below 30 mN/m [8, 9].

This significant decrease allows the processing liquid to quickly wet and penetrate the fabric, improving the physical movement and attachment of large enzyme molecules onto the fiber surface [9].

When added at concentrations below their critical micelle concentration (sub-CMC), monomeric biosurfactants act as structural helpers for the enzymes.

The hydrophobic parts of these single monomers connect gently with the non-polar areas on the enzyme's surface, while their hydrophilic parts face outward into the water [10].

This specific organization helps preserve the enzyme's fragile three-dimensional structure, stopping it from unfolding or losing its shape in harsh, hot environments used in textile processing. Also, these specific connections can help the enzyme stay in a flexible and active shape, directly increasing its ability to perform its function [10].

During processes like enzymatic desizing or scouring, leftover material from degradation (such as broken-down waxes, fatty acids, and short-chain dextrins) often sticks back to the clean fabric due to strong hydrophobic forces [11].

Biosurfactants help with this problem. As their amount increases, they form spherical structures called micelles that trap these hydrophobic materials inside their centers, stopping them from returning to the fabric [11].

Textile Process	Target Impurity	Primary Enzyme(s)	Biosurfactant Class	Synergistic Outcome
Desizing	Starch sizes, lubricants	alpha-Amylase	Lipopeptides (Surfactin)	Accelerated size hydration; 30% reduction in processing time.
Scouring	Cuticular waxes, pectins	Pectinase, Lipase	Glycolipids (Rhamnolipids)	Rapid wax emulsification; uniform absorbency at low temperatures.
Biopolishing	Surface micro-fibrils	Endoglucanase	Sophorolipids	Controlled surface shaving; prevents excess strength loss.
Effluent Treatment	Azo & anthraquinone dyes	Laccase, Azoreductase	Polymeric/ Glycolipids	Enhanced dye bioavailability; rapid breakdown of aromatic rings.

4.0. Industrial Applications in Textile Wet Processing:

Using pectinases and amylases together with surfactin or rhamnolipids lets textile mills combine several steps into a single, efficient pre-treatment process.

In this method, the biosurfactants quickly loosen and mix the outer cuticular waxes, giving pectinases direct access to break down the pectin layer beneath.

Similarly, adding glycolipids or sophorolipids during laccase-based bleaching and cellulase-mediated biopolishing reduces the loss of strength in the yarn.

By guiding how the enzyme attaches to the fiber, the biosurfactant prevents it from deeply affecting the strong cellulose core, ensuring it only removes the unwanted surface fuzz [12].

5.0 Biodegradation and Effluent Treatment:

Cleaning up wastewater from textile plants is very hard because of high levels of chemical oxygen demand (COD), strong color, and the presence of harmful aromatic amines from broken-down azo dyes [13].

Hydrophobic dyes tend to stick together in water, forming clumps that block enzymes like laccases from reaching the dye molecules.

Adding biosurfactants breaks these clumps apart and traps individual dye molecules inside micelles.

This increases the dye's surface area, making it easier for enzymes to break it down [13]. Importantly, this method avoids creating toxic chemical sludge that traditional methods leave behind, providing a cleaner and more eco-friendly solution [14].

Key Benefits of Using Biosurfactants:

- Increased Bioavailability: Micelles break up dense dye clusters, making more of the dye available for enzymes [13].
- Faster Reaction Rates: Enzymes can break down isolated dye molecules at a much quicker pace [13].
- No Extra Waste: This process avoids the heavy, harmful sludge that comes from standard chemical treatments [14].

6.0 Current Challenges and Future Outlook:

Even though this approach has great environmental benefits, high production costs and the risk of enzyme damage are holding back its wide use.

Low production levels for biosurfactants make them more expensive than cheaper, petroleum-based alternatives [4]. Also, mixing these systems needs exact control; high doses of ionic biosurfactants can disturb the enzymes' internal structure, causing them to unfold and stop working [10].

To make this technology work for industry, future research must focus on three areas:

- Using Synthetic Biology for Strain Development: Creating advanced microbial factories that can produce and release both enzymes and biosurfactants in the same liquid during fermentation.
- Using Advanced Molecular Modeling: Using detailed computer simulations to study how biosurfactants and enzymes interact, helping predict the best mix without testing all options.
- Using Biomolecular Immobilization: Attaching both enzymes and biosurfactants to strong, reusable solid materials or magnetic nanoparticles to make them last longer and easier to recover from the processing water [15].

7.0 Conclusion:

The collaboration between microbial enzymes and biosurfactants marks a significant advancement in the development of sustainable textile manufacturing.

Together, they enhance fabric wetting, support protein structure stability, speed up catalytic processes, and help break down difficult processing byproducts.This combined system provides a strong alternative to harmful chemical treatments. Adopting this integrated biological approach is essential in guiding the global fashion and textile industries away from traditional, fossil-fuel-based methods and towards a cleaner, circular bio-based economy.

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11.0 Conflict of Interest:

The author declares no conflict of interest.

12.0 Data availability statement:

Data sharing is not applicable to this article.

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