

## REVIEW OPEN ACCESS

# Progress and Prospects of Sustainable Textile Processing Through Immobilized Enzyme Systems

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## ABSTRACT

Enzymes have been increasingly explored as biocatalysts in textile processing due to their potential to reduce energy consumption and chemical usage compared with some conventional processes. Although free enzymes have been extensively studied for textile processes such as desizing, scouring, bleaching, and biopolishing, their widespread industrial implementation is often constrained by limited operational stability and difficulties associated with enzyme recovery and reuse. As a result, enzyme immobilization has gained increasing attention as an approach to improve enzyme robustness and facilitate process integration under industrial conditions. Immobilized enzymes can exhibit enhanced tolerance to variations in pH and temperature, improved mechanical stability, and simpler separation from the reaction medium compared to free enzymes. Ongoing developments in carrier materials, hybrid supports, and functional biopolymer matrices have further broadened the scope of immobilized enzymes for more resource-efficient textile processing applications. Despite these developments, much of the existing literature continues to focus on applications of free enzymes, while comparatively fewer studies provide a systematic analysis of the advances, limitations, and future potential of immobilized enzyme systems specifically for textile processing. This review therefore aims to present a structured overview of recent progress in immobilized enzyme technologies, with particular emphasis on the fundamental principles of enzyme immobilization and the emerging possibilities for incorporating immobilized enzymes into more circular and resource-efficient textile processing frameworks.

## 1 | Introduction

The increasing emphasis on environmentally responsible production has accelerated the shift toward biocatalytic processes in modern industries. Among these, enzymes have emerged as key agents of sustainable transformation due to their capacity to catalyze reactions with high precision under mild physical and chemical conditions [1–4]. Unlike traditional catalysts that often rely on extreme temperatures, pressures, or toxic

reagents, enzymes operate effectively in aqueous and near-neutral environments, thereby minimizing waste generation and energy input [5]. Their exceptional substrate selectivity and catalytic turnover rates make them ideal for industries aiming to reduce dependence on hazardous chemicals and improve overall resource efficiency [6]. Recent advances in enzyme biotechnology, including recombinant production, protein engineering, and immobilization techniques, have expanded the industrial applicability of enzymes far beyond their conventional use in food

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or detergent formulations [7]. They now play a central role in sectors such as textiles [2], leather [8], paper [9], biofuels [10], and pharmaceuticals [11], where they enable cleaner processing routes and contribute to circular economy models. Within global sustainability frameworks and green chemistry principles, enzyme-based technologies are recognized as crucial enablers for reducing the environmental footprint of industrial operations. Their adoption not only enhances process efficiency and product quality but also aligns with the growing regulatory and consumer demand for safer, nontoxic, and low-carbon manufacturing alternatives [12].

The textile industry has long benefited from the catalytic power of enzymes, with early industrial uses traced back to the mid-twentieth century [1, 2, 13]. What began as a niche approach for mild fiber treatment has now evolved into a cornerstone of sustainable textile processing. The growing urgency to mitigate the environmental impact of textile processing driven by pollution control regulations, resource scarcity, and carbon reduction targets has renewed interest in enzyme-assisted operations [1, 4, 14]. Enzymes are increasingly recognized not merely as auxiliary agents but as vital tools for achieving low-impact, high-efficiency textile processing [4]. Over the years, scientific and industrial exploration has identified thousands of enzymes exhibiting desirable environmental and operational traits. Of these, roughly seventy-five have demonstrated sufficient catalytic stability and cost-effectiveness for large-scale textile use [1, 13]. Most commercially adopted enzymes belong to two major functional categories: hydrolases, which catalyze the cleavage of molecular bonds via hydrolysis (e.g., amylases, cellulases, and pectinases), and oxidoreductases, which mediate oxidation–reduction reactions (e.g., laccases and peroxidases) [4, 15]. Together, these biocatalysts support nearly every stage of textile wet processing from raw fiber modification to finishing and surface functionalization [15].

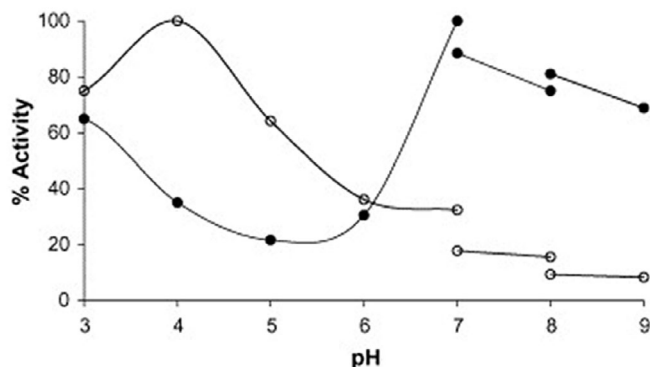
Hydrolases in particular have reshaped fiber preparation and finishing operations [16]. Enzymatic desizing, scouring, bleaching, and polishing have replaced chemical-intensive treatments that previously generated high effluent loads and energy consumption [1]. Amylases remove starch-based sizes from cotton fabrics; pectinases and lipases hydrolyze pectic and waxy impurities during bio-scouring; catalases neutralize residual hydrogen peroxide post-bleaching; and cellulases perform controlled surface abrasion in bio-polishing and denim bio-stoning, improving both fabric aesthetics and hand feel. These transformations not only improve fiber performance but also yield measurable reductions in chemical oxygen demand, water use, and effluent toxicity [17]. While natural fibers such as cotton and wool remain the dominant focus, recent advances have extended enzymatic processing to synthetic and blended materials [18]. Hydrolases such as esterases and cutinase can modify polyester or polyamide surfaces, improving hydrophilicity, antistatic behavior, and dye uptake without harsh etchants [19]. Similarly, protease-based treatments are gaining traction for wool anti-felting [20] and silk degumming [21], providing sustainable alternatives to chlorine-based and alkaline methods. In parallel, enzyme formulations in detergents now combine multiple catalytic species proteases, lipases, amylases, and cellulases to deliver high cleaning performance at reduced washing temperatures and with minimal surfactant or builder content [3, 7, 22].

Traditionally, textile wet processing relies on free enzymes that are introduced into the processing bath at controlled concentrations to catalyze specific reactions. For example, in cotton biopolishing, fabrics are immersed in aqueous cellulase solutions under defined temperature and pH conditions to achieve controlled fiber surface modification [14, 23]. Once the reaction concludes, the enzyme is typically denatured or washed away with the effluent, resulting in a single-use system that limits economic and environmental efficiency [24]. However, this traditional approach poses several technical and sustainability challenges. First, many industrial enzymes are inherently sensitive to harsh processing conditions such as extreme pH, high salt concentration, elevated temperatures, and the presence of surfactants or alkalis [6]. Maintaining enzyme activity often requires adjusting process parameters to milder ranges, which can compromise productivity or fabric quality. Although protein engineering and directed evolution have been employed to enhance enzyme tolerance, these strategies remain costly and time-intensive [25, 26]. Second, current batch processes fail to exploit the renewable catalytic potential of enzymes. Because free enzymes cannot be efficiently recovered, they are discarded after each cycle, leading to unnecessary enzyme consumption and increased production costs [1, 23]. Third, discharging denatured enzymes contributes to the organic load of wastewater streams, raising both environmental and operational burdens associated with effluent treatment. To overcome these constraints, enzyme immobilization has emerged as a transformative approach for integrating biocatalysis into sustainable textile operations [1, 14, 15]. Enzyme immobilization represents a key innovation driving the next generation of eco-efficient textile processing systems [1, 13]. Although enzyme immobilization is an established approach, its relevance has increased significantly in recent years due to advances in carrier materials, immobilization chemistries, reactor configurations, and sustainability-driven processing requirements. Despite these advances, several challenges remain unresolved, including activity losses due to mass-transfer limitations, long-term mechanical and operational stability, enzyme leaching, cost-effective scale-up, and seamless integration into existing industrial workflows [27, 28]. Addressing these limitations is critical for realizing the full potential of immobilized enzymes in the development of more eco-efficient and resource-conscious textile processing systems.

This review will present the recent progress and future prospects of immobilized enzyme in textile processing. Importantly, while numerous reviews address enzyme immobilization from a general biotechnology perspective, this review specifically focuses on textile-related applications, examining textile-specific process conditions, performance requirements, and industrial constraints. By adopting an application-oriented and comparative perspective, the review aims to bridge the gap between general immobilization strategies and their practical relevance for textile processing systems.

## 2 | Principles and Methods of Enzyme Immobilization for Industrial Applications

Enzyme immobilization refers to the confinement or attachment of enzymes onto insoluble carrier materials, allowing them to function as reusable biocatalysts [29]. Although the idea dates

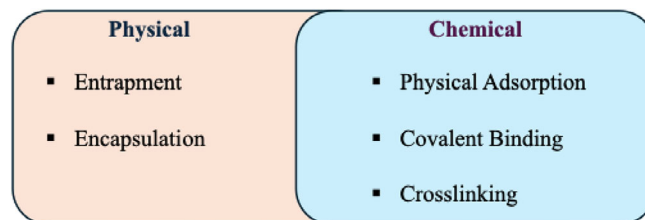


**FIGURE 1** | Optimum pH of free (°) and immobilized cellulase (●) 0.1 M potassium phosphate/citric acid (pH 3.0–7.0); 0.1 M monopotassium dihydrogen phosphate–dipotassium hydrogen phosphate (pH 7.0–8.0); 0.1 M Tris–HCl (pH 8.0–9.0). (Reused with permission from Dinçer, A., & Telefoncu, A. (2007) [36]).

back to the early 20th century, significant technological breakthroughs in the 1950s and 1960s led to a rapid increase in its industrial significance. Chibata and colleagues at Tanabe Seiyaku Company (Japan) reported the first commercial application of immobilized enzymes in 1969. They created an immobilized aminoacylase system for the stereoselective resolution of racemic amino acids, which was a significant advancement in large-scale biocatalysis [29, 30]. Since then, immobilization has become a cornerstone of industrial enzyme technology, including textile applications. Despite its advantages, immobilization presents certain drawbacks, such as the cost of carrier materials and potential structural changes in enzymes that can reduce catalytic activity or lead to detachment from the support. Nevertheless, these challenges are comparable to those encountered in most industrial-scale bioprocesses [31]. The performance of an immobilized enzyme system is generally evaluated through three interrelated parameters: (a) immobilization yield, indicating the proportion of enzyme successfully attached to the carrier; (b) immobilization efficiency, representing the fraction of bound enzyme retaining activity; and (c) activity recovery, which compares the performance of immobilized enzymes with that of their free counterparts [32, 33]. High yield does not always guarantee high efficiency, as harsh immobilization conditions may deactivate enzymes or block active sites, highlighting the need for optimized balance between enzyme loading and retained functionality [32].

Immobilized enzymes offer several advantages over soluble ones. By anchoring enzymes onto solid supports, immobilization can significantly enhance resistance to pH variations, elevated temperatures, and mechanical stresses, thereby extending catalyst lifetime under industrial operating conditions [3, 33, 34]. In our previous study [35], we have demonstrated an increase in improvement of thermal stability of the immobilized glucose oxidase (GOx) enzyme when compared with free GOx enzyme. Dinçer, A., & Telefoncu, A. (2007) [36] reported the shift of pH optimum of cellulase enzyme from 4.0 to 7.0 and the immobilized cellulase beads showed better pH stability than free enzyme at neutral pH range (see Figure 1).

In addition, immobilized systems allow straightforward separation of the biocatalyst from the reaction medium, facilitating



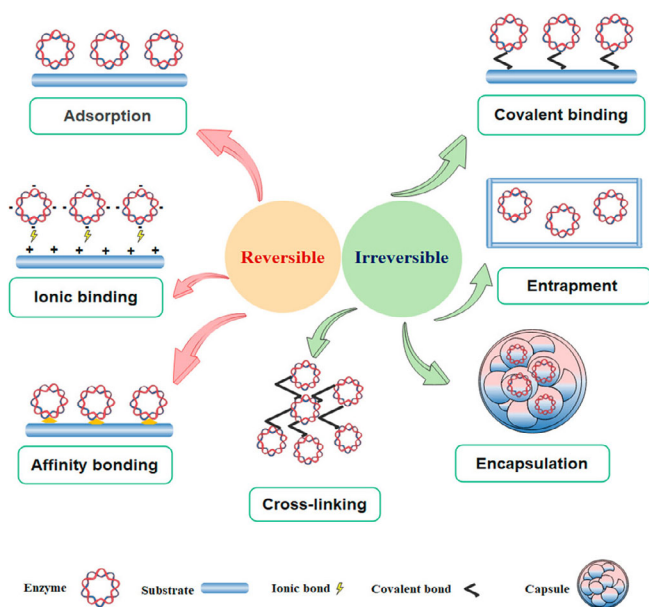
**FIGURE 2** | Enzyme immobilization techniques depending on the nature of interactions between enzymes and supports.

enzyme recovery, reuse, and compatibility with continuous or packed-bed reactors, which can improve process control and reduce catalyst consumption. Immobilization may reduce product contamination by residual enzymes and simplify downstream processing. Additionally, immobilization offers the possibility of developing multi-enzyme systems, in which various enzymes function sequentially in a single reactor to enable intricate cascade reactions [37]. The easy separation of immobilized enzymes from reaction mixtures allows precise control over reaction time and product formation, further simplifying downstream processing [33, 34].

Nevertheless, immobilized enzymes exhibit inherent limitations as well as argued in our previous studies [32, 35]. Immobilization can lead to reduced apparent activity due to diffusional constraints, steric hindrance, or conformational changes induced during enzyme attachment. Furthermore, the cost and complexity associated with support materials, immobilization procedures, and potential enzyme leaching can negatively affect economic feasibility at large scale. Consequently, effective industrial implementation requires careful selection and optimization of immobilization strategies tailored to the target process.

Enzyme immobilization techniques are broadly classified into physical and chemical methods, depending on the nature of interactions between enzymes and supports (see Figure 2). Physical immobilization involves entrapment, and encapsulation generally preserves the enzyme's native structure [38]. Entrapment confines enzymes within porous polymeric matrices (e.g., alginate, chitosan, or polyacrylamide), while encapsulation encloses them within semi-permeable membranes that allow substrate diffusion but prevent enzyme leakage [33, 34]. In contrast, chemical immobilization establishes weak (adsorption) and strong bonds (covalent binding and crosslinking) between functional groups on enzyme surfaces (e.g., amino, carboxyl, or thiol groups) and activated carriers using reagents such as glutaraldehyde or epoxides. This approach enhances enzyme rigidity and stability, though improper orientation can hinder activity [33]. A related strategy, crosslinking, connects enzyme molecules directly or via a bifunctional agent, producing insoluble aggregates. Carrier-free cross-linked enzyme aggregates (CLEAs) offer high catalytic density and are widely applied where volumetric activity is crucial [38].

Immobilization methods can also be distinguished as reversible or irreversible (see Figure 3). Reversible systems, based on noncovalent interactions (adsorption, ionic binding, and affinity binding), allow enzyme recovery and support reuse, while irreversible systems formed by covalent bonding, encapsula-



**FIGURE 3** | Enzyme immobilization techniques based on the strength and nature of enzyme-support interactions. Reversible methods include adsorption, ionic bonding, and affinity bonding. Irreversible methods include covalent binding, entrapment, encapsulation, and cross-linking (reused from Maghraby, Yasmin R., et al. (2023) [3] under CC-BY-NC-ND 4.0).

tion, or entrapment provide long-term stability for continuous processing. The choice of method depends on operational goals: reversible systems suit flexible or small-batch processes, whereas irreversible immobilization supports robust, large-scale industrial operations. Overall, enzyme immobilization has revolutionized biocatalysis, enabling efficient, stable, and sustainable enzyme use across diverse sectors, including textile processing.

In addition, immobilized systems allow straightforward separation of the biocatalyst from the reaction medium, facilitating enzyme recovery, reuse, and compatibility with continuous or packed-bed reactors, which can improve process control and reduce catalyst consumption. Nevertheless, immobilization may reduce product contamination by residual enzymes and simplify downstream processing. Despite these advantages, immobilized enzymes exhibit inherent limitations. Immobilization can lead to reduced apparent activity due to diffusional constraints, steric hindrance, or conformational changes induced during enzyme attachment. Furthermore, the cost and complexity associated with support materials, immobilization procedures, and potential enzyme leaching can negatively affect economic feasibility at large scale. Consequently, effective industrial implementation requires careful selection and optimization of immobilization strategies tailored to the target process.

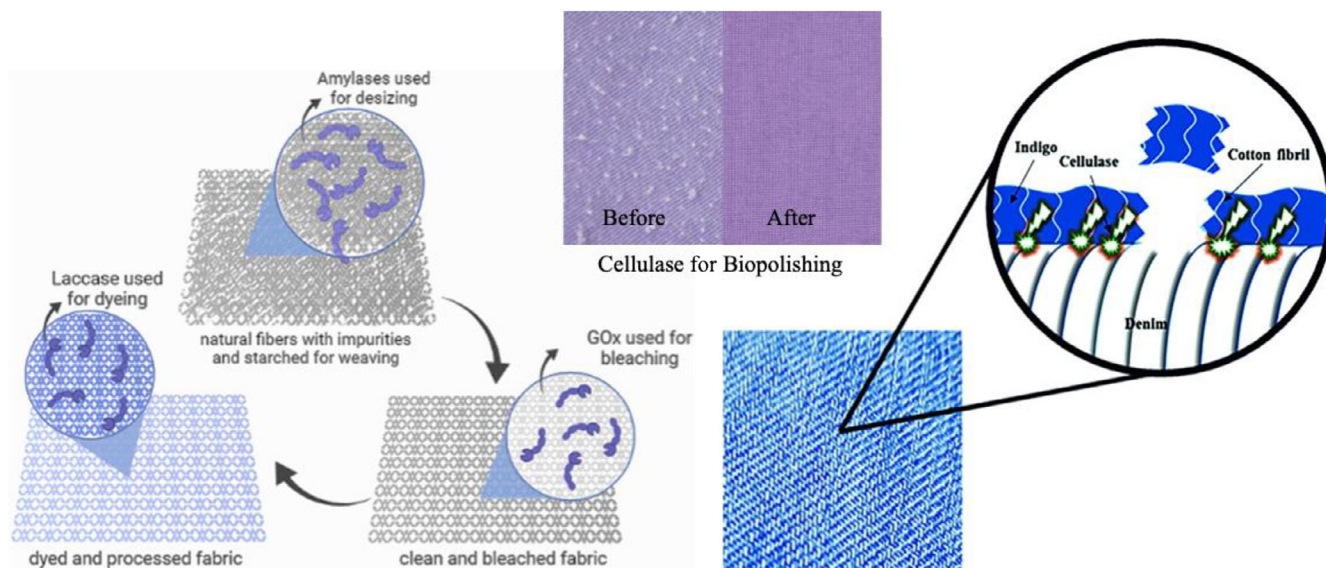
### 3 | Enzymes in Textile Processing: Evolution and Expanding Applications

The integration of enzymes into textile processing has evolved from a niche innovation to a mainstream industrial practice, largely propelled by advances in biotechnology and protein

engineering. Over the past few decades, the ability to design enzymes with enhanced stability, substrate specificity, and tolerance to extreme process conditions such as high temperature, pH, and chemical additives has significantly expanded their application range within textile processing [1]. This progress aligns with the global shift toward greener and more sustainable manufacturing systems, where enzymes are increasingly viewed as environmentally benign catalysts capable of replacing harsh chemicals traditionally used in various textile treatments (see Figure 4) [15, 18].

Historically, the earliest enzymatic applications in the textile sector emerged in processes related to desizing, where enzymes were employed to hydrolyse starch-based sizing agents that protected yarns during weaving [2]. The initial enzymes used for this purpose belonged to the hydrolase class particularly amylases, which catalyze the breakdown of starch into soluble sugars. The pioneering introduction of a microbial amylase derived from *Bacillus subtilis* by Novo Nordisk in the early 1950s marked a critical milestone, demonstrating the commercial viability of enzyme-based textile processing [39]. Following this success, enzyme technology gradually diversified to encompass additional textile operations. During the 1980s, cellulases were introduced for biopolishing and stonewashing, enabling the removal of microfibrils from cotton fibers to achieve a smoother, softer surface and to impart the worn-out appearance desired in denim fabrics [40]. This innovation revolutionized denim finishing by replacing pumice stones in jeans laundering, drastically reducing fabric damage and wastewater pollution. Around the same period, proteases found applications in silk degumming and wool treatment, improving fiber softness and reducing pilling. Similarly, catalases were utilized to decompose residual hydrogen peroxide from bleaching baths into water and oxygen, eliminating the need for intensive rinsing steps and contributing to significant water savings [41]. Today, enzymes from several major classes including hydrolases (amylases, cellulases, proteases, pectinases, and lipases/esterases) and oxidoreductases (laccases, peroxidases, and catalases) play essential roles in textile wet processing [1]. Hydrolases are widely applied in desizing, scouring, and biofinishing operations, while oxidoreductases are emerging as eco-efficient alternatives in dyeing and post-dye bleaching, where they catalyze oxidation or reduction reactions under mild conditions [23, 42]. The dominance of microbial enzymes in the textile sector can be attributed to their high production yield, ease of genetic modification, short cultivation time, and adaptability to industrial fermentation systems. Microorganisms such as *Bacillus*, *Aspergillus*, and *Trichoderma* species are particularly valued for their stability, scalability, and cost-effectiveness [23]. The continuous evolution of recombinant DNA technology and directed evolution has further enhanced the development of enzyme variants tailored to specific textile fibers and process parameters [1, 4, 19, 42].

The incorporation of enzymes in textile processing exemplifies the principles of white (industrial) biotechnology, offering a pathway to achieve cleaner production and higher product quality [42]. Their versatility allows integration across almost all stages of textile processing, from fiber processing and fabric preparation to wet processing, functional finishing, surface modification, and wastewater treatment, as summarized in Table 1. More recently, enzymatic approaches have been explored for recycling and



**FIGURE 4** | Application of enzymes into textile processing (reused from Tochetto, Gabriel A., et al. (2022) [18]; Besegatto, Stefane Vieira, et al. (2018) [15] under CC-BY-NC-ND 4.0).

resource recovery from textile waste, opening new avenues for a circular textile economy [43].

#### 4 | Progress on Immobilized Enzymes in Sustainable Textile Processing and Production

Immobilized enzymes have emerged as a promising approach for enhancing the efficiency and sustainability of textile processing, particularly in operations where free enzymes are already established. Their applications span a wide range of industrial processes, including fiber processing, desizing, scouring, bleaching, biopolishing, denim fading, surface modification, wastewater treatment, and textile waste recycling.

##### 4.1 | Fiber Processing

In textile fiber processing, enzymes play a crucial role in improving fiber quality, facilitating extraction, and enhancing the overall efficiency of preparation processes. A range of enzymes, including cellulases, amylases, proteases, hemicellulase, and xylanases, are commonly employed depending on the type of fiber and desired treatment [14]. Cellulases, for example, catalyze the hydrolysis of cellulose by cleaving  $\beta$ -(1 $\rightarrow$ 4) glycosidic linkages, releasing reducing sugars and softening natural fibers (see Figure 5) [49].

Amylases are widely used to degrade starch-based sizing agents, which aids in their removal and enhances the cleanliness and dyeability of cotton and other plant fibers [51]. Hemicellulases and xylanases are particularly effective in retting bast fibers such as flax, where hemicellulases degrade complex hemicellulose components in the cell wall, facilitating the separation of individual fibers from the matrix and improving extraction efficiency [44, 45]. Proteases are applied mainly to animal fibers such as wool and silk, where they target protein-based impurities. In silk degumming, proteases hydrolyze sericin, the protein binding

silk filaments, resulting in softer, more lustrous fibers suitable for subsequent dyeing and finishing. Similarly, proteases are employed in sand washing of silk to remove residual proteins, enhancing surface texture and quality [46, 47, 48]. Immobilization of fiber-processing enzymes has been extensively investigated to expand their industrial applicability and improve operational performance. Cellulases, for instance, have been immobilized on silica nanocomposites, graphene-based surfaces, polymeric supports, and metal particles, offering higher thermal and operational stability and allowing enzyme reuse [66]. Immobilized  $\alpha$ -amylase on gold nanoparticles demonstrates enhanced stability, prolonged shelf life, improved substrate selectivity, and efficient starch removal without fiber damage, with superior penetration into woven cotton fabrics [67]. In wool shrink-resist finishing, immobilized proteases reduce weight loss and tensile strength degradation due to controlled proteolytic activity limited to the fiber cuticle [68].

Beyond conventional fiber processing, immobilized enzymes are increasingly applied in fiber polymerization and functionalization. *Candida antarctica* lipase B (CALB), often immobilized on silica or polymethyl methacrylate resin (Novozym 435), facilitates reactions such as transesterification and ring-opening polymerization at mild temperatures, enabling the synthesis of polycaprolactone from caprolactam. Similarly, at neutral pH and ambient circumstances, graphite-immobilized glucose oxidase has demonstrated potential for oxidative polymerization of polythiophene, demonstrating the adaptability of immobilized enzymes for both natural and synthetic fiber applications [69].

##### 4.2 | Desizing

$\alpha$ -Amylases have been extensively employed in the textile industry for cotton desizing because of their high specificity and efficiency. These enzymes hydrolyse starch polymers into water-soluble oligosaccharides, such as maltose, dextrins, and glucose, which are easily washed away (see Figure 6) [70]. Industrially,

**TABLE 1** | Summary of application of enzyme in different industrial textile processes.

Enzyme	Textile processing	Application	Reference
Hemicellulase	Fiber preparation	Flax retting	[44]
Xylanase	Fiber preparation	Flax retting	[45]
Protease	Fiber preparation Wet processing-pretreatment Dyeing and Finishing	Degumming of silk, sand washing of silk, Wool finishing	[46, 47] [48]
Cellulase	Fiber preparation Wet processing-pretreatment Dyeing and Finishing Functionalization Waste management	Bio-polishing (depilling), Ageing, denim abrasion and finishing, Cotton softening, Textile recycling,	[49] [50] [49] [36]
Amylases	Wet processing-pretreatment	Desizing	[51]
Pectate lyase	Wet processing-pretreatment	Scouring	[52]
Protease	Wet processing-pretreatment	Scouring	[53]
Lipases	Wet processing-pretreatment Waste management	Scouring, textile recycling, Wastewater treatment	[54]
Pectinase	Wet processing-pretreatment	Scouring, desizing, detergent	[55]
Glucose oxidase	Wet processing-pretreatment Waste management	Bleaching, Wastewater treatment	[56]
Catalase	Wet processing-pretreatment	Post bleaching clean-up	[57]
Laccase	Wet processing-pretreatment Waste management	Excess dye removal, Wastewater treatment	[58]
Peroxidase	Wet processing-pretreatment Waste management	Excess dye removal, Wastewater treatment	[59]
PETase	Waste management	Textile recycling	[60]
Cutinase	Waste management Functionalization	Textile recycling, Surface modification	[61] [62]
Tyrosinase	Functionalization	Surface modification	[63]
XET <sup>a</sup>	Functionalization	Surface modification	[64]
	Functionalization	Surface modification	[65]
Transglutaminases			

<sup>a</sup>Xyloglucan endotransglucosylase.

$\alpha$ -amylases are preferred over  $\beta$ -amylases; the former act endo-wise, cleaving internal  $\alpha$ -1,4 glycosidic bonds within starch chains, while  $\beta$ -amylases function exo-wise, sequentially releasing maltose units from chain termini [39]. Recent research has demonstrated comparable or even superior efficiency of immobilized amylases relative to conventional chemical desizing or free enzyme treatments [71]. For example,  $\alpha$ -amylase immobilized on chitosan or Eudragit matrices not only improved the removal of starch and impurities but also enabled four to six reuse cycles, despite requiring slightly higher initial enzyme concentrations [71]. Similarly, immobilization on acrylate-epoxidized soybean oil resin allowed the enzyme to retain 60% activity over five consecutive cycles while operating under mild conditions (40°C, pH 7.4) within a 15–30-minute reaction window [72].

While free enzymes provide rapid starch degradation, immobilized enzyme systems offer greater sustainability through repeated reuse and retention of functional stability. However, the complexity of immobilization techniques and associated pro-

duction costs remain challenges, limiting widespread industrial adoption. Continued research and development are essential to optimize immobilized enzyme-based desizing processes and expand their practical applicability in the textile sector [71, 73]. The potential for enzyme recovery, reduced contamination, and reusability are the most notable commercial advantages of using immobilized enzymes. Researchers are looking into other ways to improve performance even further.

### 4.3 | Scouring

Bioscouring employs specific enzymes to selectively degrade and remove surface impurities without damaging the fiber structure [74]. Compared to conventional alkaline scouring, bioscouring significantly reduces environmental impact, lowering biological oxygen demand and chemical oxygen demand to approximately 20%–45% of alkaline levels, and reducing total dissolved solids to 20%–50% [75, 76]. Additionally, enzymatic scouring produces

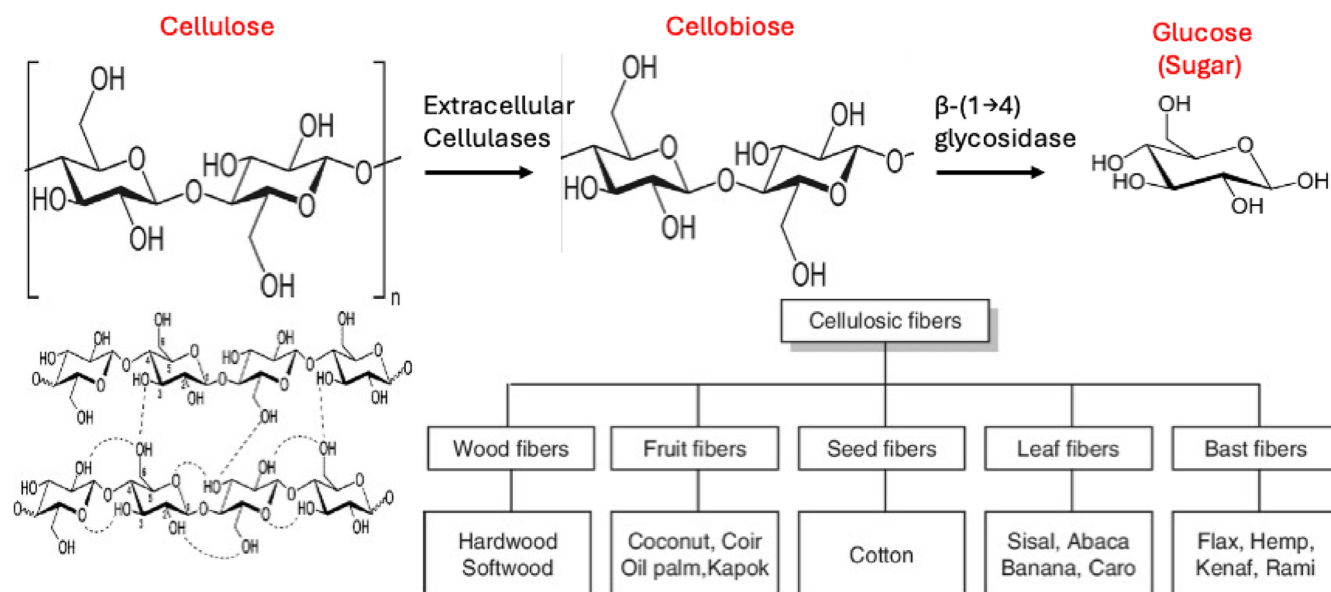


FIGURE 5 | Mechanisms of action of cellulase enzyme against cellulosic fibers.

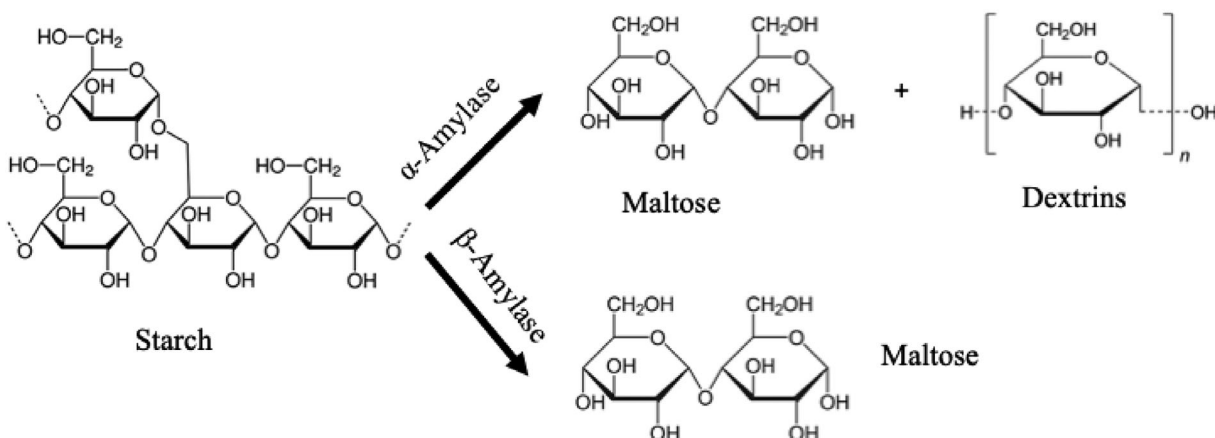


FIGURE 6 | Route for breaking down starch into maltose using  $\alpha$ -Amylase and  $\beta$ -Amylase.

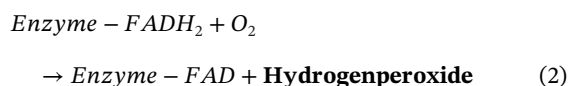
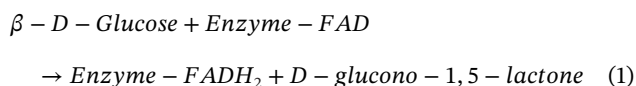
softer fabrics, requires lower energy input, avoids harsh chemicals, and enhances worker safety. A variety of enzymes are employed in bioscouring, depending on the nature of the target impurity. Alkaline or acidic pectinases degrade pectins, cutinases remove waxy cutin, cellulases act on cellulose, amylases remove starch-based gums, proteases target protein impurities, xylanases degrade hemicelluloses, and lipases hydrolyse fats and oils [55]. Often, a cocktail of these enzymes is applied to address multiple impurities simultaneously, improving overall cleaning efficiency. Pectinases are now the most common biocatalysts for cotton bioscouring. By preferentially cleaving methylesterified pectin polymers through demethoxylation, they produce water-soluble pectic acids and methanol as a byproduct. This enzymatic action weakens the cotton cuticle and facilitates the removal of bound waxes under mild conditions, typically at neutral pH and temperatures below 60°C [1, 18, 42].

The immobilization of scouring enzymes has attracted considerable interest to enhance their operational stability, allow for

enzyme recovery, and enable multiple reuse cycles. For instance, Sawada and Ueda (2001) [77] demonstrated that cotton could be effectively scoured using pectinase immobilized in a reverse micellar system. The immobilized enzyme maintained high activity even in organic solvents, performing on par with or better than both conventional alkaline scouring and aqueous bioscouring. Similar to this, thermophilic lipase immobilized on sericin-based discs has been used to scour wool, producing bio-scoured fibers that are more dyeable for specific dyes than wool that has been handled conventionally. Various support materials have been explored for enzyme immobilization, including membranes, resins, silica gels, and magnetic particles. While these immobilized systems are widely applied in industries such as food processing, paper production, and medicine, their potential for textile bioscouring remains significant [1, 3, 78]. Further research and development are needed to optimize immobilized enzyme formulations, tailor them for specific fibers and impurities, and scale them for sustainable industrial applications.

## 4.4 | Bleaching

Enzymes such as glucose oxidase and catalase have been effectively applied in immobilized forms to generate or decompose hydrogen peroxide under controlled conditions, providing an eco-friendly alternative to traditional chemical bleaching agents. Glucose oxidase catalyzes the oxidation of glucose to produce hydrogen peroxide in situ, which acts as the primary oxidant for pigment removal [56]. The same principle has also been applied to perform bleaching [17]. Typically, Glucose-1-oxidase (GOx) ( $\beta$ -D-glucose: oxygen-1-oxidoreductase) is a naturally produced redox enzyme that catalyzes the oxidation of  $\beta$ -D-glucose into D-glucono-1,5-lactone or D-glucono- $\delta$ -lactone and hydrogen peroxide by using molecular  $O_2$  as an electron acceptor (see reaction 1–2) [79–81].



Opwis et al. (1999) were the first to demonstrate a glucose oxidase-based bleaching approach for textiles, in which the enzyme was covalently bound to cotton fibers using cyanuric chloride as a coupling agent. This immobilized system effectively generated substantial amounts of hydrogen peroxide in situ, providing the oxidative power required for the bleaching process [82]. In a subsequent investigation, glucose oxidase was covalently attached to alumina and glass supports, resulting in high enzyme loading efficiency and effective bleaching performance. The glass matrix, owing to its higher porosity, facilitated greater protein binding and exhibited an enhanced hydrogen peroxide generation rate of approximately 0.35 g/L. In contrast, the alumina support offered superior operational stability, enabling the immobilized enzyme to retain activity over multiple reaction cycles [2]. Tzanov et al. (2001) [83] reported that enzymatically produced hydrogen peroxide requires comparatively higher concentrations to achieve bleaching efficiencies equivalent to those obtained with conventional chemical peroxide treatments. Building on this, subsequent research investigated the immobilization of glucose oxidase on various inorganic supports, including alumina and glass, to optimize the balance between enzyme loading capacity, hydrogen peroxide generation rate, and operational stability during repeated bleaching cycles [1, 2]. Glass supports, owing to their highly porous structure, facilitated greater enzyme adsorption and enhanced the rate of hydrogen peroxide formation. In contrast, alumina supports exhibited higher mechanical and operational stability, allowing repeated reuse of the immobilized enzyme, thereby rendering them more suitable for continuous or large-scale industrial bleaching processes [56].

To avoid damaging the fiber, leftover hydrogen peroxide must be effectively eliminated after bleaching. Catalase quickly breaks down leftover peroxide into water and oxygen, especially when it is immobilized. This drastically cuts down on processing time, energy use, and freshwater consumption [3]. Alumina-based carriers are preferred for industrial applications due to

their mechanical and chemical stability under alkaline conditions and elevated temperatures. Textile-based carriers have also been investigated, offering operational convenience through simple mechanical recovery and minimal residual protein contamination [84]. The immobilization of enzymes not only enhances their thermal and pH stability but also allows repeated use over multiple cycles, reducing enzyme consumption and process costs. Additionally, immobilized systems provide more controlled enzymatic activity, improving bleaching uniformity while preserving fiber strength and quality [1].

## 4.5 | Bio-Polishing

Bio-polishing is an enzymatic finishing technique designed to improve the surface quality of cellulose-based textiles, particularly cotton [49, 50]. The process primarily targets protruding microfibrils on fiber surfaces, which are responsible for fuzziness and the formation of pills during wear. By removing these microfibrils, bio-polishing enhances fabric appearance, brightness, and hand feel, increases water absorbency, and creates a smoother, more uniform surface structure. The process is driven by cellulase enzymes, which catalyze the hydrolysis of  $\beta$ -(1 $\rightarrow$ 4) glycosidic bonds in cellulose polymers as explained in Figure 5 earlier. The enzymatic action is highly specific, allowing targeted modification of fiber surfaces while preserving the bulk integrity of the textile [76]. While bio-polishing improves fabric aesthetics and functionality, it can inadvertently weaken the textile, as uncontrolled cellulase activity may degrade bulk cellulose, leading to significant tensile strength loss, sometimes up to 36%, with free enzyme systems [49]. To mitigate this effect, immobilized cellulase enzymes have been developed. Immobilization restricts enzyme mobility, limiting hydrolysis primarily to the fiber surface. This approach reduces deep penetration into the cellulose network, thereby preserving tensile strength and fabric weight while still achieving the desired surface refinement [50, 18].

In comparison to traditional free enzyme bio-polishing, Sankarraj and Nallathambi (2018) [49] showed that immobilized cellulase dramatically decreased fiber weight loss and maintained higher tensile strength. According to their research, enzyme immobilization improved optical qualities, such as fabric whiteness, while also reducing structural damage. The mechanism underlying this improvement lies in the reduced diffusion of immobilized cellulase, which prevents excessive interaction with bulk cellulose while maintaining effective activity on protruding microfibrils. Additionally, immobilization facilitates rapid removal of the enzyme from the fabric at the end of the treatment, preventing prolonged exposure and unintended degradation. Kumar et al. (2008) [85] further confirmed that immobilized cellulase retained its bio-polishing efficacy over six consecutive treatment cycles, demonstrating enhanced operational stability and catalytic efficiency compared to free enzyme systems. This reusability contributes to reduced enzyme consumption and overall process cost while maintaining fabric quality. Studies have highlighted the effectiveness of Eudragit L-100-immobilized cellulase in bio-polishing [2]. This smart polymer offers multiple advantages: (a) minimized fiber weight loss while preserving fabric integrity, (b) reduced tensile strength degradation, (c) exceptional reusability across multiple cycles, and (d) pH-responsive behavior that facilitates simple enzyme recovery and reuse. Immobilized cellulase

systems also allow finer control of the bio-polishing process [1, 3, 4]. By restricting enzymatic action to the fiber surface and preventing uncontrolled bulk cellulose degradation, they mitigate the traditional trade-off between surface modification and structural integrity. Moreover, immobilized enzymes can form clusters or aggregates that further limit penetration depth, while their stability under a range of temperatures and pH conditions ensures consistent performance in industrial processing. These characteristics make immobilized cellulases a preferred solution for modern textile finishing, combining improved fabric aesthetics, operational efficiency, and environmental sustainability.

#### 4.6 | Denim Fading

Enzymatic fading has emerged as an eco-friendly and efficient alternative. Key enzymes employed include laccases and cellulases. Laccases catalyze the oxidation of indigo dye into intermediates such as isatin and 2,2'-dihydroxyindigo, facilitating dye degradation and fading [2, 86]. Cellulases, first applied in denim finishing in the late 1980s, hydrolyse cellulose microfibrils in cotton, releasing trapped indigo dye and creating a naturally worn appearance [23, 50, 87]. Additionally, the use of blended enzyme systems—which combine laccase, cellulase, and amylase in a single treatment bath—has been studied. These multi-enzyme techniques have been shown to improve overall process efficiency and resource utilization while reducing energy and water usage. These enzymes are classified according to their pH optima: acid cellulases (pH 4.5–5.5), neutral cellulases (pH 6.6–7), and alkaline cellulases (pH 9–10), which enable selection in accordance with particular textile processing needs. They also show adaptability throughout a wide temperature range (30–60°C) [50]. A major challenge in enzymatic denim fading is back-staining, where indigo particles released by cellulase hydrolysis redeposit on lighter areas or the white weft threads of the fabric. Excessive enzyme concentration, prolonged treatment time, and suboptimal pH or temperature exacerbates this problem by accelerating uncontrolled dye release. Strategies to mitigate back-staining include optimizing wash parameters, using anti-redeposition agents, and, notably, employing immobilized enzymes.

Immobilization localizes enzymatic activity to the fiber surface, controlling hydrolysis and minimizing dye dispersion. Several studies have demonstrated the advantages of immobilized cellulase systems. Pazarlioglu et al. (2005) [88] covalently immobilized a commercial cellulase onto ZrOCl<sub>2</sub>-activated particles, resulting in improved denim abrasion and fading performance while markedly reducing back-staining. The immobilized enzyme demonstrated enhanced catalytic efficiency and operational stability, enabling controlled cellulose hydrolysis without excessive release of indigo dye. Similarly, Yu et al. (2013) [89] reported the immobilization of cellulase on Eudragit S-100 carriers, which exhibited excellent reusability and maintained fabric structural integrity. This approach improved process sustainability by enabling enzyme recovery and reuse, addressing the limitations of conventional free cellulase treatments that often compromise denim strength and durability.

In general, immobilized cellulase systems offer numerous industrial benefits, including enhanced catalytic efficiency, operational

stability, and reusability. By restricting enzymatic action to the fiber surface, these systems reduce water, energy, and chemical consumption compared to conventional stone washing, while minimizing back-staining and preserving fabric quality. The adoption of immobilized enzymatic processes for denim fading not only aligns with sustainable manufacturing goals but also provides consistent, reproducible, and high-quality finishing, making it a promising alternative to traditional mechanical and chemical methods.

#### 4.7 | Textile Surface Modification

The functional behavior and aesthetic appeal of textile materials are largely determined by their surface characteristics, whereas their mechanical strength and long-term durability are primarily influenced by the properties of the bulk structure [61, 62]. Typically, the surface layer represents only a small fraction of the total fiber volume approximately 1% of the overall material. For example, in a fiber with a 10 μm diameter, the surface layer extends roughly 0.1 μm [63]. Consequently, modifications confined to this ultrathin layer can be classified as surface modifications [64, 65].

A diverse set of enzymes has been applied for textile surface modification, tailored to fiber type and desired functionality [4]. Cellulases are widely employed on cellulosic substrates such as cotton, Tencel, viscose, and linen. They hydrolyse surface cellulose microfibrils, reducing fuzz and pilling while improving fabric softness, drape, color clarity, and brightness. Unlike conventional chemical softeners, the effects of cellulase treatment are durable and nongreasy [50]. Proteases are used primarily in wool processing, where they hydrolyse protein-based cuticles to produce shrink-resistant fibers with improved whiteness, dyeability, and tactile feel [48]. Tyrosinases are applied to chitosan and protein-based fibers, catalysing the oxidation of phenolic groups to facilitate cross-linking or polymerization reactions. This enzymatic action enhances mechanical strength, water resistance, and can impart antimicrobial activity [63, 90]. For synthetic fibers, particularly polyesters such as polyethylene terephthalate, hydrolase enzymes including cutinases, lipases, and esterases have demonstrated significant potential for surface modification.

Cutinases are highly effective at hydrolyzing surface ester bonds in PET [91], accessing crystalline regions due to their open active sites and flexible lid domains, and generating hydroxyl and carboxyl terminal groups [92]. These modifications improve fiber wettability, compatibility with coatings or composites, and recyclability. Esterases and lipases, although initially considered less efficient due to limited access to crystalline polymer regions, have shown improved performance through enzyme engineering, immobilization, or optimized process conditions [23]. Beyond polyester, enzymatic treatments are increasingly applied to polyamide (e.g., Nylon 66) and polyacrylonitrile (PAN) fibers. Laccase-mediator systems can introduce hydrophilic functional groups onto polyamide surfaces through oxidative modification, thereby improving surface wettability. In contrast, hydrolytic enzymes such as proteases, amidases, and cutinases selectively cleave surface amide bonds, increasing the availability of reactive sites and enhancing dye affinity for acid and reactive dyes, all

while maintaining the tensile integrity of the fibers [1]. Similarly, polyacrylonitrile fibers can be enzymatically modified using nitrilase or esterases, which convert surface nitrile groups into carboxyl groups. This transformation enhances fiber dyeability and reduces static charge accumulation. Overall, these enzymatic functionalization strategies provide high selectivity and precision, while minimizing chemical usage and environmental impact compared to conventional chemical treatments [93].

Recent research highlights immobilized enzyme systems and synergistic multi-enzyme approaches as advanced strategies for textile surface modification. For instance, immobilized proteases applied to wool fiber cuticles achieve anti-felting modifications while minimizing fiber weight loss and strength reduction [94]. Immobilized cellulases on cellulosic fabrics have shown increased operational stability, improved process reproducibility, and enhanced cost-effectiveness, enabling precise surface refinement with minimal structural damage [85]. Enzymes have also been used to impart functional properties, beyond conventional surface modification. Hydrolases like lysozyme exhibit antimicrobial activity by hydrolysing bacterial cell wall polysaccharides and have been immobilized on cotton and wool through carbodiimide-mediated or glutaraldehyde cross-linking, retaining activity after multiple washes [95]. Enzymatic approaches have enabled textile functionalization for wound healing, toxin neutralization, and antimicrobial protection, providing eco-friendly alternatives to chemical biocides. Similarly, enzymes such as laccase and peroxidases are employed for covalent grafting of functional molecules including polyphenols, chitosan, gallic acid, siloxanes, and phosphorus- or nitrogen-based compounds via radical-mediated polymerization, introducing hydrophobicity, antimicrobial properties, or flame retardancy to textile surfaces.

## 5 | Future Prospects of Immobilized Enzyme in Textile Processing

Immobilized enzymes, when applied to support materials rather than directly to textiles, represent a transformative approach in textile processing. These systems provide the enzyme with a stable, reusable platform while allowing the textile substrate to be treated indirectly [1]. This strategy opens several future-oriented applications, including but not limited to (a) **Enhanced Process Sustainability and Reusability**: Immobilizing enzymes on supports such as polymers, nanoparticles, membranes, or textiles allows for repeated use, reducing enzyme consumption, operational costs, and environmental impact. Studies demonstrate that immobilized enzymes maintain high activity and stability over multiple cycles, with minimal leaching and contamination, making them ideal for desizing, scouring, bleaching, and biopolishing [96, 97]. For example, immobilized amylase, pectinase, and glucose oxidase on chitosan and Eudragit S-100 supports enabled effective cotton pre-treatment for at least three cycles, maintaining fabric quality and dyeability [96]. Textile-based supports are particularly attractive due to their low cost, high surface area, and ease of functionalization [13]. Nano-inorganic supports further enhance enzyme stability under harsh industrial conditions, though their environmental impact must be considered. (b) **Integration into Continuous Flow and Reactor-Based Systems**: Supported immobilized enzymes can be incorporated

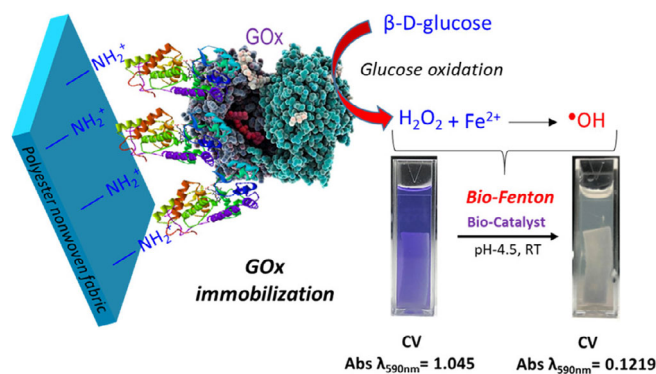
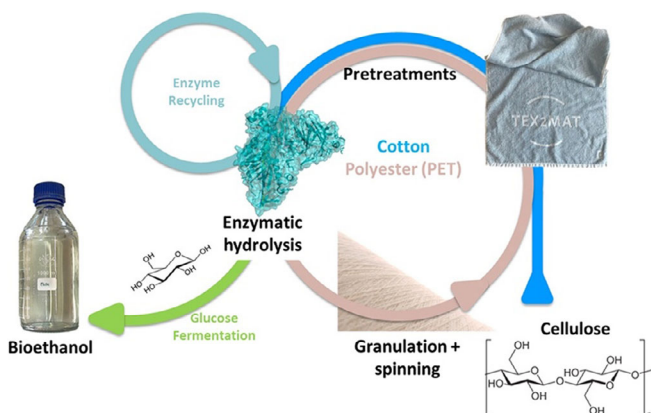


FIGURE 7 | Illustration of immobilized glucose oxidase on functionalized polyester for environmental remediation (reused from Morshed, M.N. et al. (2021) [32] under CC-BY-NC-ND 4.0).

into fixed-bed or fluidized-bed reactors, enabling continuous, high-throughput, and energy-efficient textile processing. These systems offer precise control over reaction parameters (time, temperature, pH) and facilitate industrial scale-up, potentially replacing traditional batch treatments. For instance, immobilized glucose oxidase on functionalized polyester nonwovens demonstrated high loading, stability, and recyclability, supporting robust pollutant removal in bio-Fenton systems (see Figure 7) [32].

(c) **Multifunctional and Modular Support Designs**: Advanced supports such as magnetic nanoparticles, mesoporous silica, or functionalized textiles enable rapid separation, recycling, and even multi-enzyme cascade reactions. Modular enzyme cartridges and co-immobilization strategies allow for flexible, multi-stage treatments, improving efficiency and reducing downtime [97]. Multi-enzyme immobilization on nanostructured or biopolymer supports can enhance substrate channeling, stability, and process efficiency, supporting complex textile treatments like denim fading, color adjustment, and biopolishing in a single step. (d) **Textile Waste Recycling and Circular Economy**: Immobilized enzymes on robust supports are well-suited for enzymatic recycling of textile waste, catalyzing depolymerization of cotton, wool, polyester, or blended fabrics into monomers while being easily recovered for repeated use. The use of agro-industrial residues as supports not only reduces waste but also supports circular economy principles. Enzyme-based recycling and resource recovery processes can significantly reduce the environmental footprint of textile processing and waste management (See Figure 8) [43, 98]. (e) **Digital Integration and Smart Processing**: Immobilized enzyme systems are compatible with sensor-based monitoring and digital process control, enabling real-time optimization for reproducibility, quality, and sustainability. Smart supports and reactors can communicate with production management software, allowing for dynamic adjustment of process parameters and further reducing resource consumption [1, 38]. (f) **Environmental and Industrial Impact**: Immobilized enzymes offer higher resistance to environmental changes, can be recovered and recycled, and are more robust under industrial conditions compared to free enzymes [3]. They reduce the need for harsh chemicals, lower water and energy consumption, and minimize effluent toxicity, supporting greener and more sustainable textile processing [1, 24]. However, the choice of



**FIGURE 8** | Schematic presentation of enzyme-based recycling and resource recovery processes (Reused from Gritsch, Sebastian M., et al. (2023) [98] under CC-BY-NC-ND 4.0).

support material and immobilization method is critical for optimizing enzyme activity, stability, and process economics. (g) **Hybrid and Cascade Reactions:** Immobilized enzymes on supports allow for multi-enzyme cascade reactions where different enzymes act sequentially on a substrate. For example, supported cellulase, laccase, and protease systems could be used for denim fading, color adjustment, and bio-polishing in one integrated step. In the future, textile processing could leverage support-based enzyme arrays for highly efficient multi-stage treatments with minimal waste and energy usage [23].

In essence, immobilized enzymes on support materials shift textile processing from enzyme-intensive, single-use treatments to reusable, controlled, and scalable biocatalytic platforms. They enable sustainable processing, continuous operation, textile recycling, and advanced surface functionalization while reducing chemical inputs, energy consumption, and environmental impact. This approach is expected to be a central pillar in the next generation of industrial textile bioprocessing, combining operational efficiency, circularity, and environmental sustainability.

## 6 | Conclusion

Enzyme-based technologies have long played an important role in textile processing as environmentally compatible alternatives to conventional chemical treatments, aligning with broader sustainability and green manufacturing objectives outlined in the Introduction. Within this context, enzyme immobilization which is an established but continuously evolving strategy has gained renewed relevance to address persistent limitations associated with free enzyme systems, including restricted operational stability, lack of reusability, and limited process control. The ability to anchor enzymes onto solid supports enables enhanced catalyst retention, improved tolerance to process stresses, and the potential integration of biocatalysis into more controlled and resource-efficient textile operations.

This review has shown that immobilized enzymes have been successfully explored across a wide range of textile applications, including fiber preparation, desizing, scouring, bleaching, bio-polishing, denim finishing, surface modification, and

wastewater treatment. These systems offer clear environmental advantages through reduced chemical consumption, lower water and energy usage, and improved effluent quality, while also supporting emerging circular economy concepts such as enzyme-assisted recycling and waste valorization. However, consistent with the challenges identified in the Introduction, the transition from laboratory-scale demonstrations to broader industrial adoption remains constrained by several unresolved issues.

Key technical challenges include mass-transfer limitations that hinder enzyme–substrate interactions in dense textile structures, activity losses or altered kinetics induced by immobilization, and reduced long-term stability under harsh chemical and thermal processing conditions. From an industrial perspective, the cost, durability, and scalability of support materials, as well as the complexity of immobilization and reactor integration, present significant barriers. Importantly, this review highlights that environmental benefits alone are insufficient to ensure industrial uptake; sustainable textile processing must also satisfy economic and operational performance criteria. Trade-offs between catalytic efficiency, process complexity, material costs, and environmental gains remain insufficiently addressed in the current literature.

In response to these challenges, future research directions should focus on advanced immobilization materials including nanostructured supports, smart polymers, and hybrid composites to improve enzyme accessibility and durability. The development of immobilized multi-enzyme systems and enzyme cascades may enable process intensification and multifunctional treatments within single processing steps. At the same time, integrating immobilized enzymes into continuous reactors, automated process lines, and hybrid physico-chemical systems is essential for industrial relevance. Enzyme engineering strategies, such as site-directed mutagenesis and protein modification, further offer opportunities to tailor enzymes for improved performance in immobilized states under realistic textile processing conditions.

Overall, the purpose of this review is not merely to summarize reported progress but to systematically analyze the technical, industrial, and scalability challenges that continue to limit the broader implementation of immobilized enzyme systems in textile processing. The review adopts an analytical framework that integrates mechanistic understanding, comparative evaluation of free and immobilized enzymes, and process-level considerations of sustainability and economic feasibility. By identifying unresolved gaps and critical trade-offs, this work aims to support informed research strategies and industrial decision-making. With continued advances in materials science, biotechnology, and process engineering, immobilized enzymes are well positioned to contribute to textile processing systems that are both environmentally responsible and industrially viable.

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## Declaration Of Generative AI And AI-Assisted Technologies In The Writing Process

During the preparation of this work the author(s) used AI for language improvement of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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