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Evolving Biotechnology in Textile Processing

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Abstract:

Biotechnology has become a transformative force in the textile industry, fostering sustainability, innovation, and enhanced functionality throughout the value chain. This review examines the critical role of biotechnology in revolutionizing fiber production, textile processing, dyeing, wastewater treatment, and advanced applications by leveraging biological systems, organisms, and their derivatives. Key advancements include the development of genetically modified fibers like *Bacillus thuringiensis* (Bt) cotton and bioengineered colored cotton, enzymatic processes that replace harmful chemicals, and microbial pigments that offer sustainable alternatives to synthetic dyes. The discussion extends to textile waste valorization, transforming waste into valuable products such as bioethanol and bioplastics, and innovations in wastewater treatment through microbial fuel cells and membrane bioreactors. Additionally, integrating smart and wearable textiles featuring biosensors and adaptive biopolymers highlights the potential of biotechnology to redefine both the functionality and sustainability of textile products. Biotechnology emerges as a cornerstone for the textile industry's sustainable future by tackling environmental challenges and supporting a circular economy.

Keywords: Bio-polymer, Effluent treatment, Enzyme immobilization, Sustainable processing, Wastewater treatment

1. Introduction

The textile industry, a cornerstone of global manufacturing, has long been associated with resource-intensive processes and significant environmental challenges. From the cultivation of natural fibers to the production of synthetic materials, and chemical-intensive dyeing to waste-generating finishing processes, the sector has faced increasing scrutiny over its ecological footprint. In this context, biotechnology has emerged as a transformative force, offering innovative, sustainable, and efficient solutions for the textile value chain [1]. Biotechnology harnesses the power of biological systems, organisms, and their derivatives to address some of the most pressing issues in textile manufacturing. It enables the development of eco-friendly fibers, enzymatic treatments that replace harsh chemicals, and microbial pigments that reduce reliance on synthetic dyes. Furthermore, biotechnological advancements have introduced functionalities such as management and recycling through bioremediation techniques [2].

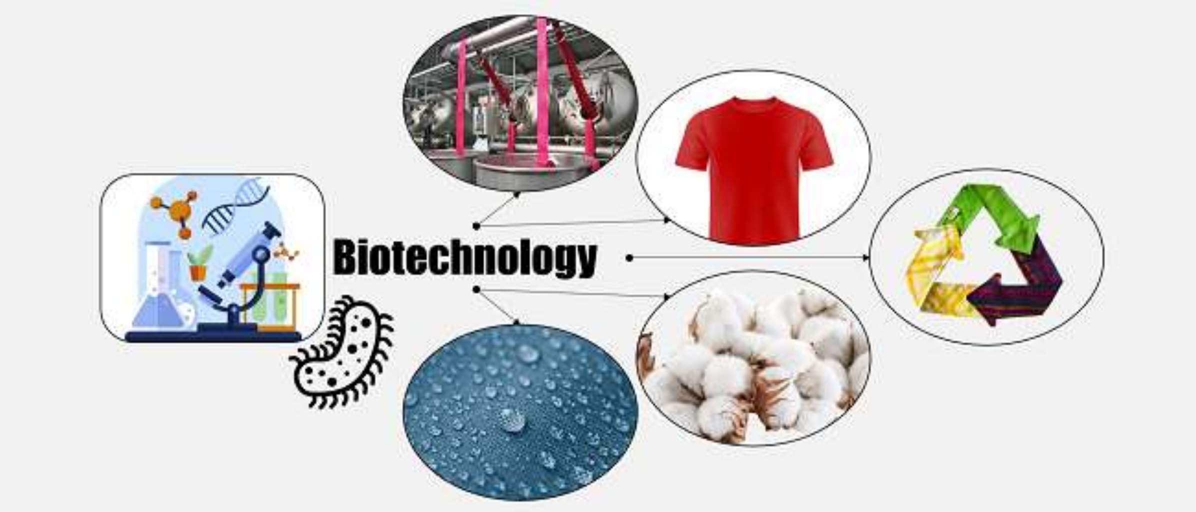


Figure 1: Biotechnology application in textile production and processing

Biotechnology in textiles can be broadly categorized as

- Raw material Development
- Textile Processing
- Dyes and Pigments
- Wastewater treatment
- Advance application

This review explores the diverse applications of biotechnology in textiles, categorizing its contributions to fiber development, processing, dyeing, finishing, and sustainability. By examining recent innovations, challenges, and future directions, this article highlights the pivotal role of biotechnology in steering the textile industry.

2. Raw material development

Biotechnology has significantly advanced this area by enabling the creation of sustainable, high-performance, and eco-friendly materials through genetic engineering, microbial fermentation, and enzymatic processes. Biotechnological interventions have led to innovations in natural fibers, synthetic alternatives, and bio-based polymers, addressing both the environmental concerns and functional demands in the textile sector. By leveraging biotechnological processes, the industry can transform waste into valuable resources, supporting a circular economy.

(i) Cotton - This primarily involves genetically modified (GM) cotton, including insect resistance traits and herbicide tolerance. The two most notable types are *Bacillus thuringiensis* (Bt) Cotton and Herbicide-Tolerant (HT) Cotton [4]**.** Bt cotton is a genetically modified crop designed to resist insect pests, particularly the bollworm. Bt cotton is engineered by incorporating a gene from a bacterium, which produces a protein toxic to specific insect pests This bacterium naturally produces proteins (Cry proteins) that are toxic to specific insect pests, particularly lepidopteran larvae like bollworms while being safe for humans, animals, and beneficial insects. Bt genes are introduced into the cotton plant's genome, enabling the plant to produce Bt proteins in its tissues. When pests, such as the pink bollworm or cotton bollworm, feed on the cotton plant, they ingest the Bt proteins. The proteins bind to receptors in the pest's gut, creating pores that disrupt its digestive system, ultimately leading to the pest's death. The adoption of Bt cotton has resulted in a 30% increase in yield compared to conventional cotton, significantly benefiting farmers' incomes [3-5].

Figure 2: The difference between pest-resistant BT cotton and non-BT cotton.

Another area of research regarding GM cotton is herbicide-resistant HT cotton. HT cotton, developed to withstand specific herbicides, allows for more efficient weed management, Herbicides typically used include glyphosate and glufosinate. HT cotton plants are modified to include genes that make them resistant to particular herbicides. Farmers can apply herbicides to the fields, which kill weeds while leaving the cotton plants unharmed [6].

As the world moves toward pollution-free organic textiles and products, naturally colored cotton will be the next buzzword in the market. Manufacturing colored cotton through biotechnology is an innovative approach that addresses environmental concerns associated with synthetic dyes. This process involves genetic engineering and using natural pigments to produce cotton fibers in various colors, reducing the need for harmful dyeing processes. Researchers have successfully engineered cotton plants to express betalain pigments, resulting in pink fibers without compromising fiber quality. Anthocyanin biosynthetic pathway has been targeted to create colored cotton by manipulating key enzyme genes, leading to the production of fibers with enhanced pigmentation [7-9].

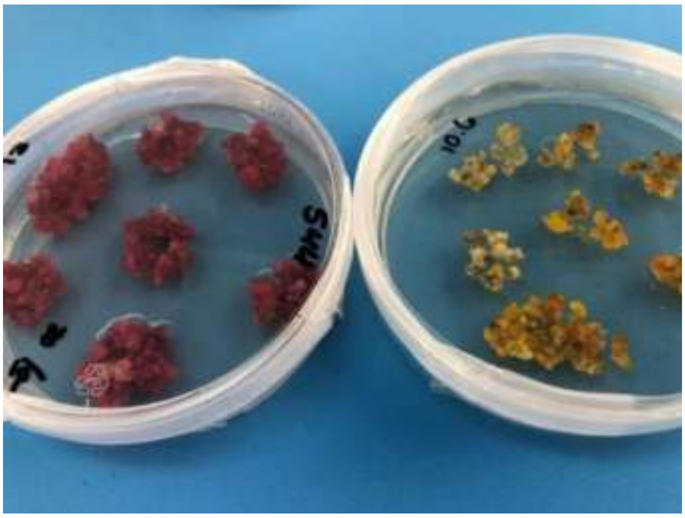


Figure 3: Naturally colored cotton obtained via gene modification

(ii) Jute - Biotechnology offers significant potential for improving the quality and yield of jute fibers, although research in this area is still limited compared to other crops. By leveraging genetic engineering, microbial technologies, and innovative processing methods, the potential for improved jute fiber production is significant. Research has identified key genes involved in lignin biosynthesis, negatively impacting fiber quality. Targeting these genes can lead to developing jute cultivars with improved fiber characteristics [10]. Multi-trait transgenic jute lines have been developed to resist pests and diseases, enhancing overall yield without compromising fiber quality. These lines incorporate genes for insect resistance and herbicide tolerance [11]. Biotechnology is also used for accelerated retting methods, drastically reducing the time required for fiber extraction. Traditional retting can take several days, while accelerated methods can shorten this process significantly, increasing productivity. The Application of enzymatic treatments as part of the accelerated retting process. These treatments help break down the pectin and lignin in the jute stalks more effectively, facilitating easier separation of the fibers from the stalk and improving overall extraction efficiency.

(iii) Flax – a significant commercial crop that provides linseed and bast fibers, utilized in various applications. Advances in molecular biology have enabled the development of transgenic flax varieties with improved resistance to pathogens and enhanced yield. The construction of genetic linkage maps aids in breeding programs to produce high-quality flax with desirable traits. The flax shows excellent regeneration from adventitious shoot (organogenesis) and via embryo (somatic embryogenesis). This ability of flax is also the basis of producing certain advanced fibers. This reflects upon its ability to form tissue cultures at a large scale. A novel process utilizing the pectinolytic strain Geobacillus thermoglucosidasius has been developed, resulting in high-quality flax fibers with improved fineness and resolution suitable for fine linen yarn production while eliminating traditional retting risk [12].

(iv) Hemp- is a fast-growing plant that requires very little water and no herbicides, pesticides, synthetic fertilizers, or genetically modified (GM) seeds. The latest research is to produce new hemp varieties using biotechnology. There are GM variants that are pest-resistant, disease-resistant, and with more enhanced fiber elasticity. Transgenic cultivars of Hemp can be used for the synthesis of PHA and other biopolymers [13].

(v) Wool – harvesting of wool has evolved significantly through biotechnology integration, offering innovative alternatives to traditional shearing methods. Recent research highlights various biotechnological approaches, including biological de-fleecing and enzymatic treatments, which aim to enhance wool harvesting efficiency while minimizing animal stress and labor costs. A method involving intravenous infusion of amino acid mixtures lacking lysine and methionine creates a weakened zone in the wool staple, allowing for painless mechanical harvesting. This technique demonstrated a significant reduction in staple strength, facilitating easier fleece removal without causing distress to the sheep. In bio-clip, a protein-derived chemical is injected into sheep which makes the sheep lose its fleece utilizing epidermal growth factor (EGF) to induce shedding of the fleece. Research indicates that sheep with better nutrition and body condition exhibit improved wool harvestability, emphasizing the importance of pre- and post-injection management [14].

(vi) Synthetic Fibers- The integration of biotechnology in developing novel synthetic fibers has led to significant advancements in textile processing and functionalization. Enzymatic modifications, particularly for polyester fibers like poly(ethylene terephthalate) (PET), enhance properties such as hydrophilicity without compromising the material's bulk characteristics. Enzymes like cutinase can hydrolyze ester bonds in PET, increasing surface hydrophilicity by introducing new carboxyl and hydroxyl groups. This method allows for targeted functionalization, enhancing the textile's usability in various applications without altering its core properties. Advanced techniques for spinning biodegradable fibers from microbial-produced polyesters have been developed, ensuring stable production and desirable filament properties. The depolymerization of synthetic fibers using biotechnology presents a promising avenue for sustainable recycling practices. This approach leverages enzymes and microbial processes to break down synthetic polymers selectively. Enzymatic processes enable selective depolymerization of synthetic fibers, allowing for the recovery of monomers from contaminated blends [15,16].

Biotechnology focuses on enhancing microbial enzymes to depolymerize synthetic polymers, including fibers. Genetic modifications improve enzyme activity, facilitating more efficient biodegradation and recycling processes, although further research is needed to optimize these strategies for various fiber types. Genetic modifications in bacteria have enhanced the hydrolytic activity of enzymes, improving their effectiveness in degrading a wider range of synthetic polymers [17].

(vii) Novel Textile Fibers: this refers to an innovative material that offers unique properties or enhanced performance compared to traditional fibers like cotton, polyester, or wool. These fibers are often designed to meet modern demands for sustainability, functionality, or specialized applications in fashion, industrial, or technical textiles. The development of high-tech textiles relies on enhancements of fiber raw materials and processing techniques. Biopolymers are increasingly utilized in the textile industry due to their eco-friendly properties and versatility. These materials, derived from renewable resources, offer sustainable alternatives to

traditional synthetic fibers. Key biopolymers used in textiles include polylactic acid (PLA), polyhydroxyalkanoates (PHA), Polyhydroxybutyrate (PHB) chitosan, and cellulose [18].
The classification of biopolymers is based on their origin as follows.

(A) Plant-based Biopolymers - these are increasingly gaining traction in the textile industry due to their renewable nature and reduced environmental impact. Biopolymers such as PLA, PHA, and cellulose create biodegradable fibers, which can replace non-biodegradable synthetic fibers [19].

- Polyhydroxyalkanoates (PHAs): are synthesized using waste materials like rice bran, sugarcane molasses, and other agro-industrial by-products. The process involved is microbial fermentation of plant-based oils or sugars using bacteria like Ralstonia eutropha or Cupriavidus necator [20]. PHAs are stored as intracellular granules and extracted for use.PHAs are used in Biodegradable plastics, agricultural films, and medical sutures.
- Xanthan Gum: is a versatile biopolymer produced by the bacterium Xanthomonas campestris, widely recognized for its unique rheological properties and applications across various industries. Its ability to function as a thickening agent, Xanthan gum is produced through fermentation using carbon sources like glucose and sucrose[21]. Recent advancements include a coupled fermentation system that enhances the yield of low-molecular-weight xanthan gum, which exhibits improved bioactivity. These proteins are used in medical applications due to their biocompatibility and wound-healing properties [22].
- Wheat Starch and Arabic Gum: These polysaccharides improve moisture management and comfort in textiles while also serving as eco-friendly finishing agents
- Polylactic acid (PLA): is a biodegradable biopolymer made by fermenting plant starch to produce lactic acid, which is then polymerized to form PLA. The raw material for polylactic acid (PLA) biopolymer is fermented plant starch, such as corn, sugarcane, or sugar beet pulp
- Lignin-based biopolymer: is a versatile biopolymer derived from lignocellulosic biomass, engineered microbes, or enzymes breakdown of lignin into aromatic compounds.Polymerization of these compounds into functional biopolymers. Lignin-based hydrogels exhibit biocompatibility and biodegradability, making them suitable for drug delivery and wound healing [23].

Table 1: Summary of Key Plant-Based Biopolymers

Biopolymer	**Source**	**Applications**
Starch-Based	Corn, potato, cassava	Packaging, films, utensils
Polylactic Acid (PLA)	Corn, sugarcane	Packaging, textiles, 3D printing, medical devices
Cellulose & Derivatives	Wood, cotton, hemp	Textiles, paper, coatings, films

Lignin	Wood pulp	Bioplastics, adhesives, carbon fibers
Pectin	Citrus peels, apple pomace	Food films, medical dressings
Hemicellulose	Plant cell walls	Coatings, films
Natural Rubber	Latex from the rubber tree	Tires, adhesives, elastic materials
Protein-Based Polymers	Soy, wheat gluten, zein	Films, adhesives, packaging
PHAs	Bacteria fed on plant sugars	Packaging, medical applications
Alginates	Seaweed	Films, stabilizers, coatings

(B)Animal Origin Biopolymers – these are derived from various animal sources and have gained attention for their sustainable and biodegradable properties. These biopolymers, including chitosan, gelatin, collagen, keratin, and silk fibroin, are utilized in diverse applications such as food packaging, environmental remediation, and biomedical technologies. Their unique characteristics make them suitable alternatives to conventional plastics and synthetic materials [24-26].

- Chitosan and Chitin: Derived from crustacean shells, they are known for their biodegradability and are used in food packaging and biomedical applications.
- Gelatin: Sourced from collagen, it is widely used in food products and pharmaceuticals due to its gelling properties.
- Collagen: A structural protein crucial in tissue engineering and wound healing.
- Keratin: Found in feathers and hooves, it has potential in environmental applications for its ability to adsorb pollutants.
- Silk Fibroin**:** Known for its strength and biocompatibility, it is used in sutures and drug delivery systems.

Table 2: Summary of Animal-Origin Biopolymers

Biopolymer	**Source**	**Applications**
Collagen	Animal skin, bones, tissues	Wound dressings, tissue engineering, cosmetics
Gelatin	Derived from collagen	Food thickener, capsules, packaging films
Keratin	Wool, feathers, hair	Biomedical materials, cosmetics, fertilizers

Chitin/Chitosan	Crustacean shells, insects	Biomedical, water treatment, food coatings
Hyaluronic Acid	Rooster combs, connective tissue	Medical fillers, cosmetics, eye care
Fibroin	Silk (silkworms, spiders)	Sutures, textiles, tissue engineering
Elastin	Animal connective tissues	Tissue regeneration, skincare
Casein	Cow's milk	Food binding, adhesives, packaging films

3. Textile Processing

Integrating biotechnology in textile processing transforms the industry by promoting sustainability and reducing environmental impact. This approach primarily involves using enzymes and biopolymers, which offer eco-friendly alternatives to traditional chemical processes. The use of enzymes in textile processing represents a significant advancement towards sustainable practices in the industry. Enzymes serve as eco-friendly alternatives to traditional chemical processes, reducing environmental impact while enhancing efficiency. Their application spans various stages of textile processing, including fiber pretreatment, coloration, and finishing, leading to substantial savings in water, energy, and time. Enzymes are biological catalysts (also known as biocatalysts) that speed up biochemical reactions in living organisms. They can be extracted from cells and then used to catalyze a wide range of commercially important processes. Different enzymatic processes, such as chemical substitution, have been developed or developed for various textile wet processes [27]. Enzymes such as cellulases, amylases, pectinase, and laccase replace hazardous chemicals in processes like desizing, bioscouring, and biobleaching [28].

Table 3: Uses of enzymes in the textile industry

Enzyme	**Use**	**Microorganisms**
Amylase	Desizing-Removal of starch	*Bacillus* sp., *B. licheniformis*
Cellulose	Cotton softening, denim finishing	*Aspergillus niger*, *Penicillium funiculosum*
Catalase	Bleach termination	*Aspergillus* sp.
Laccase	Non-chlorine Bleaching, fabric dyeing	*Bacillus subtilis*
Pectinase	Bioscouring	*Bacillus* sp., *Pseudomonas* sp.
Protease	Removal of wool fiber scales, degumming of silk	*Aspergillus niger*, *B. subtilis*

Lipase	Removal of size lubricants, denim finishing, Gum removal	*Candida Antarctica*
Ligninase	Wool finishing	*Trametes versicolor*, *Phlebia radiata*
Collagenase	Wool finishing	*Clostridium histolyticum*
Cutinase	Cotton scouring, synthetic fiber modification	*Pseudomonas mendocina*, *Fusarium solani pisi*, *Thermomonospora fusca*

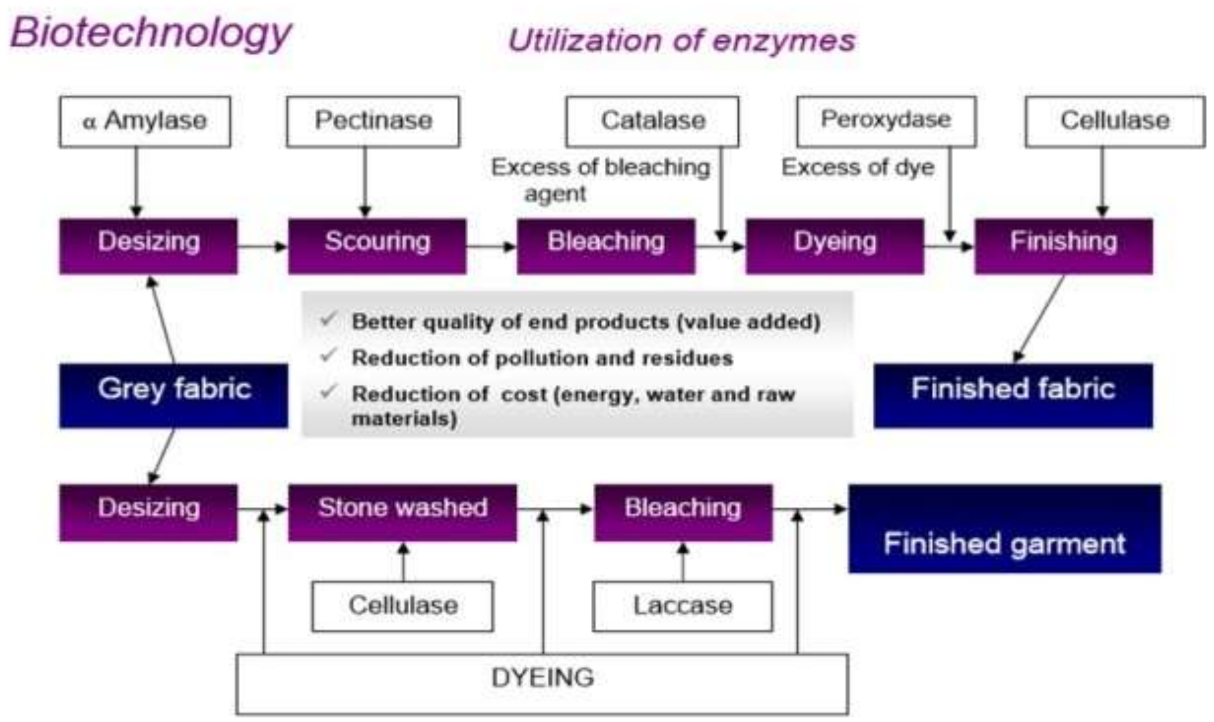


Figure 4 -Biotechnology in Textile Processing

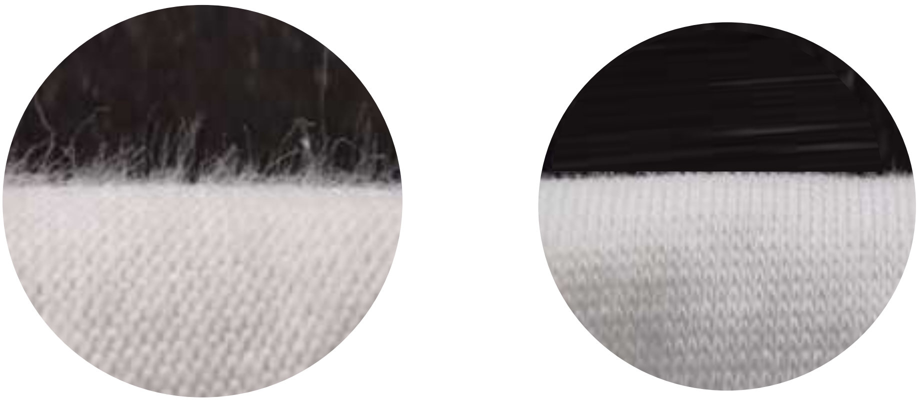
3.1 Enzymes

(i) Amylase: In textile desizing primarily involves using Amylase enzymes, which facilitate the removal of starch-based sizing agents without damaging the fabric. This enzymatic approach is gaining traction due to its eco-friendly nature and efficiency compared to traditional chemical methods. Amylases, specifically α-amylases, are the most commonly used enzymes for desizing, accounting for approximately 25% of the enzyme market in textiles. Enzymes hydrolyze starch, breaking it down into simpler sugars, which can then be easily washed away, preserving the integrity of the fabric. Optimal desizing occurs under specific temperature, pH, and enzyme concentration conditions, with thermostable enzymes available for higher-temperature applications. Enzymatic desizing is more sustainable than chemical methods, as it reduces harmful chemicals and energy consumption. Unlike chemical desizing agents, enzymes do not compromise the strength or quality of the fabric, ensuring a better final product. Research has shown that amylase produced from Bacillus cereus can effectively desize fabrics without degradation, demonstrating the potential of locally sourced biotechnological solutions [29-30].

(ii) Pectinase: The application of biotechnology in cotton bioscouring primarily involves using enzymes to replace traditional chemical methods, enhancing both environmental sustainability and fabric quality. Various studies have demonstrated the effectiveness of different enzyme combinations in improving the scouring process, leading to better fabric properties and reduced environmental impact. A study utilized a combination of pectate lyase, lipase, protease, and xylanase, optimizing their concentrations to significantly remove non-cellulosic impurities while maintaining the structural integrity of cotton fibers.

Another research highlighted the use of glucose oxidase alongside starch-degrading enzymes and pectinases, which not only scoured but also bleached the cotton fabric, showcasing a multifunctional approach. Pectinases derived from Indigenous Penicillium species were shown effective in cotton bioscouring, which degrade pectin in plant tissues, enhancing the removal of impurities from cotton fabrics and reducing fabric weight and improving softness, indicating their potential for enhancing fabric quality [31-32].

(iii) Cellulase: Cotton biopolishing primarily involves the application of cellulase enzymes, which enhance the fabric's aesthetic and tactile properties while promoting eco-friendliness. Biopolishing is an enzymatic treatment process that improves the surface properties of cotton fabrics by removing protruding fibers and microfibrils, leading to smoother fabric with enhanced performance attributes. Cellulase enzymes break down the cellulose molecules in cotton. They specifically hydrolyze the exposed microfibrils on the fabric surface without compromising the structural integrity of the material [33].



Before Bio-polish **After Bio-polish**

Figure 5: Cellulase treatment on cotton hosiery fabric

(iv) Catalase: it is gaining traction due to its eco-friendly properties. Catalase is used in textile applications to remove hydrogen peroxide from fabrics after bleaching processes. Catalase catalyzes the decomposition of hydrogen peroxide into water and oxygen. Catalase is used in textile applications to degrade excess hydrogen peroxide after bleaching, significantly reducing the rinses required. It can be added shortly before chemicals and dyes in the dye bath, enhancing efficiency without affecting other substances [34,35].

(v) Laccase: The use of laccase in denim fading has gained attention due to its environmentally friendly properties. Laccase catalyzes the oxidation of phenolic compounds, which aids in degrading indigo dye in denim fabrics. Laccase is used in denim fading by breaking down dye molecules and enhancing discoloration. Using laccase can achieve up to 96.79% decolorization of indigo dye, demonstrating its effectiveness in treating textile effluents. The enzymatic process significantly reduces chemical oxygen demand (COD) in wastewater, making it a more sustainable alternative to traditional denim washing methods [36-37].

(vi) Protease: these are investigated for applications in textile processing, particularly for fibers like wool and silk. They can enhance processes such as fiber pretreatment and finishing. Proteases are utilized in the textile industry for processes such as biopolishing, which enhances fabric smoothness and appearance, and for removing protein-based stains. Proteases hydrolyze keratins in wool, degrading cuticle scales by reducing disulfide bonds and hydrolyzing peptide bonds. Their application improves fabric quality while being environmentally friendly compared to traditional chemical methods. Proteases are utilized to remove sericin, the gum that coats silk fibers, improving their softness and dyeability [38,39].

3.2 Dyes and Pigments

Bio pigments are natural colorants derived from biological sources such as plants, microbes, algae, and fungi. These bio-dyes are non-toxic, biodegradable, and derived from renewable resources. Microbial pigments can be isolated from various environments, such as soil from organic farms, with specific strains yielding high pigment production [40].

Table 4: Notable Microbial Pigments and Their Producers

Pigment	Color	Source Microorganism	Applications
Carotenoids	Yellow, orange, red	*Rhodotorula* spp., *Phaffia rhodozyma*, *Blakeslea trispora*	Textile dyeing, cosmetics, antioxidants
Violacein	Violet	*Chromobacterium violaceum*, *Janthinobacterium lividum*	Textile dyeing, antimicrobial fabrics
Prodigiosin	Red	*Serratia marcescens*, *Vibrio* spp.	Textile dyeing, bio-based paints, biomedical uses

Monascins	Red, yellow	*Monascus purpureus* (red mold)	Food and textile dyeing, fermentations
Violacein	Violet	*Chromobacterium violaceum*, *Janthinobacterium lividum*	Textile dyeing, antimicrobial fabrics
Phycocyanin	Blue	Cyanobacteria (*Spirulina platensis*, *Anabaena* spp.)	Natural textile dyes, cosmetics, functional textiles
Melanin	Black, brown	*Aspergillus niger*, *Bacillus subtilis*, *Streptomyces* spp.	Textile printing, UV-protective coatings
Fungal Azaphilones	Yellow, red, orange	*Monascus*, *Penicillium*, *Talaromyces* spp.	Textile dyeing, food additives, cosmetics
Anthraquinones	Red, yellow	*Aspergillus nidulans*, *Fusarium* spp.	Textiles, bio-based paints, anti-fungal coatings
Pyocyanin	Blue-green	*Pseudomonas aeruginosa*	Potential in specialty textiles (limited due to toxicity)
Canthaxanthin	Orange	*Phaffia rhodozyma*, *Brevibacterium* spp.	Dyes for high-performance textiles

Biopigments and dyes offer a compelling alternative to synthetic dyes, aligning with the textile industry's shift toward sustainability and eco-friendliness.

4. Waste Water Treatment

Biotechnology offers innovative solutions for removing pollutants and contaminants from wastewater, leveraging biological processes to enhance treatment efficiency and sustainability. The use of enzymes for waste management is extensive and several enzymes are involved in degrading toxic pollutants. Industrial effluents and domestic waste contain many chemical commodities, that are hazardous or toxic to living beings and the

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ecosystem. Microbial enzyme(s), alone or in combinations, are used to treat industrial effluents containing phenols, aromatic amines, nitriles, etc., by degradation or bioconversion of toxic chemical compound(s) to innocuous products [41].

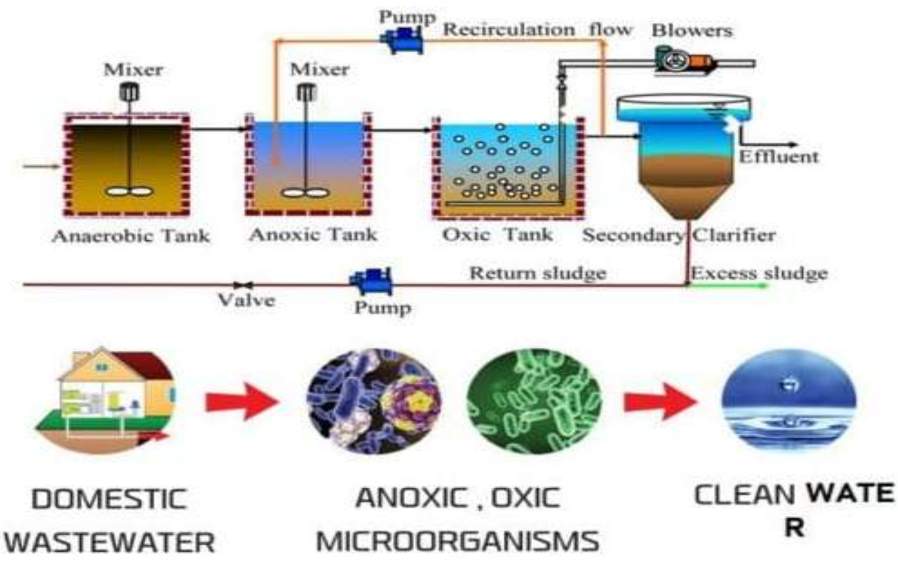

Figure 6: Wastewater treatment plant

(i) **Microbial Biotechnology**- leverages the natural metabolic capabilities of microorganisms to treat wastewater. Advanced processes like microbial fuel cells (MFCs), anaerobic digestion, and membrane bioreactors demonstrate significant potential in addressing water pollution while promoting sustainability. Microbial fuel cells utilize the ability of certain microorganisms to transfer electrons to an electrode during the breakdown of organic matter.

(ii) **Microbial fuel cell**: it enhances the performance and scalability of microbial fuel cells (MFCs) for waste treatment by optimizing microbial communities, substrate utilization, and reactor design. Integrating specific microorganisms and innovative materials can significantly improve energy generation and pollutant removal efficiency in MFCs. Adding specific bacteria, such as Stenotrophomonas acidaminiphila, has been shown to enhance the degradation of complex organic compounds, leading to improved chemical oxygen demand (COD) removal and power density in MFCs [42]. Using waste-derived substrates, like sugarcane extract, has effectively boosted electron generation and facilitated metal ion removal, achieving significant efficiencies for lead and mercury [43].

(iii) **Anaerobic Digestion**: Anaerobic digestion involves decomposing organic matter without oxygen, facilitated by consortia of bacteria and archaea. The process generates biogas (a mixture of methane and carbon dioxide) as a byproduct. Biogas can be used as a renewable energy source for heating or electricity [44].

(iv) *Membrane Bioreactors (MBRs*): Membrane bioreactors combine biological treatment with membrane filtration to separate treated water from solids. Microorganisms in the reactor degrade pollutants, while the membrane provides a physical barrier. Produces water suitable for reuse in industrial or agricultural applications. The membrane filtration process effectively removes solids and pathogens, producing high-quality effluent suitable for reuse [45].

MBRs can also reduce emerging contaminants, enhancing the safety of treated water for agricultural and industrial applications. MBRs effectively remove pathogens and emerging contaminants, enhancing water quality for reuse [46]. MBRs are a game-changer in waste management, especially in regions facing water scarcity and stringent environmental regulations. Their ability to deliver high-quality treated water aligns with global sustainability goals.

5. Advanced Biotechnology Applications

Integrating advanced biotechnology in the textile industry has opened new frontiers in sustainability, functionality, and innovation. These applications aim to address environmental pollution, resource consumption, and the need for functional textiles.

(i) Waste Valorisation: The valorization of textile waste through biotechnology presents a promising avenue for sustainability in the textile industry, particularly in addressing the challenges posed by fast fashion and wastewater management. Using biotechnological processes, textile waste can be transformed into valuable raw materials, promoting a circular economy. Enzymatic hydrolysis is crucial for breaking down complex textile waste, particularly cotton and polyester blends, into simpler compounds that can be further processed into platform chemicals [47]. Breaking down cotton into glucose, which can be fermented to produce bioethanol. Enzymes break down synthetic fibers (e.g. PET) into monomers for reuse. PET is degraded by microbial enzymes (e.g., PETase) into terephthalic acid and ethylene glycol for reuse in new polymers. *Ideonella sakaiensis* is a bacterium capable of breaking down PET [48]. Pseudomonas umsongensis utilizes PET as a carbon source- growth substrate highlights the secretion of the PET hydrolase PHL7, demonstrating direct microbial consumption of PET, which could enhance sustainable upcycling strategies [49].

(ii) Smart and Wearable Textiles: combine advanced materials with biotechnology to create fabrics that can sense, respond, and adapt to environmental conditions or user needs. Biotechnological advancements enable the integration of biological components such as enzymes, microorganisms, or biomolecules into textiles, adding functionality while maintaining Biosensors integrated into textiles represent a significant advancement in wearable technology, offering non-invasive health monitoring capabilities. Smart clothing integrates biotechnology through the use of biosensors and modern textile fibers, enabling health monitoring and communication. This combination enhances personal health care using advanced materials and microelectronics to create responsive and interactive wearable technology [50]. Incorporating enzymes like glucose oxidase into fabrics for monitoring glucose levels in sweat is beneficial for diabetic patients [51]. Keratin proteins are crucial for skin tissue development and wound healing, promoting the activation of keratinocytes and increasing collagen production, which is essential for tissue repair and managing skin disorders incorporating biomolecules like chitosan and antimicrobial peptides (AMPs) presents a promising strategy to combat bacterial and fungal growth. Chitosan, a biopolymer derived from chitin, exhibits inherent antimicrobial properties, while AMPs are known for their ability to disrupt microbial membranes [52].

Summary

The article comprehensively reviews how biotechnology is revolutionizing the textile industry by promoting sustainability, innovation, and functionality. It categorizes the applications of biotechnology into several key areas and highlights specific advancements and challenges in each. This article addresses the environmental challenges of the textile industry by providing sustainable alternatives in fiber production, processing, and waste management. It focuses on Innovations such as microbial dyes, enzymatic treatments, and functional textiles to enhance the eco-friendliness and functionality of textile products. Information. Waste valorization and advanced biotechnological applications promote a circular economy in textiles, reducing resource consumption and environmental pollution. In the future, genetic engineering, enzyme technology, and bio-sourcing may be combined to create a more standard, cleaner, and more efficient textile processing process. It is extremely important now to move towards a clean future and biotech provides us an opportunity to do the same.

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