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Advances in Microbial Bioremediation of Textile Effluents: Mechanistic Insights and Future Perspectives. A Review

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Abstract: *The textile industry generates large volumes of wastewater containing toxic pollutants that causes serious environmental and health concerns. These pollutants are often chemically stable, resistant to light and oxidation, and difficult to remove using conventional treatment methods. Physical and chemical processes such as adsorption, oxidation, and membrane filtration have been widely used; however, these techniques may involve high operational costs and the formation of secondary pollutants. In recent years, microbial bioremediation has emerged as an effective and eco-friendly alternative for the treatment of textile effluents. Various microorganisms including bacteria, fungi, actinomycetes, and yeasts have demonstrated significant potential in the degradation and decolorization of synthetic dyes and various pollutants Bacterial species such as Pseudomonas aeruginosa, Pseudomonas luteola, and Escherichia coli have been reported to degrade azo dyes other hazardous pollutants through enzymatic reduction mechanisms. Fungal species such as Pleurotus ostreatus and other ligninolytic fungi produce enzymes like laccase and peroxidases that can effectively break down complex dye molecules. In addition, yeasts such as Candida tropicalis and Saccharomyces cerevisiae have shown considerable biosorption and biodegradation abilities toward dye pollutants. This review highlights the potential of different microbial bio remediators for the treatment of textile effluents containing harmful pollutants and discusses their mechanisms, advantages, and environmental significance as sustainable alternatives for wastewater management and detoxification of contaminants.*

Keywords: Textile effluents, Wastewater treatment, Microbial bioremediation Toxic pollutants, Eco- friendly treatment.

I. INTRODUCTION

The textile industry is one of the largest industrial sectors contributing to environmental pollution due to the extensive use of synthetic dyes, and chemicals during textile processing. Large quantities of dye-containing wastewater are generated during dyeing, washing, and finishing operations. These effluents often contain complex organic compounds, heavy metals, and toxic chemicals that are discharged into aquatic ecosystems if not properly treated. The presence of dye pollutants in water bodies reduces light penetration, disturbs photosynthetic activity of aquatic plants, and causes toxic effects on aquatic organisms and microorganisms [1]. Additionally, many textile dyes are highly stable and resistant to degradation because they are designed to withstand exposure to light, temperature, and microbial attack. This persistence makes the treatment of dye-contaminated wastewater a significant environmental challenge.[2]

Among different dye classes, azo dyes represent the most widely used group in textile industries and account for nearly 60–70% of the total dye production worldwide. These dyes contain azo bonds (–N=N–) that contribute to their chemical stability and strong coloration. However, during degradation processes, azo dyes may produce aromatic amines that can be toxic, mutagenic, or carcinogenic to living organisms [3]. Therefore, effective removal of textile dyes from wastewater is necessary to minimize environmental and health risks.

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Heavy metals are one of the most hazardous pollutants present in textile and tannery effluents. These metals originate from dyes, mordants, and various chemical processing steps used in textile manufacturing [4]. Unlike organic pollutants, heavy metals are non-biodegradable, persistent, and capable of accumulating in the environment and food chain, leading to long-term toxic effects [5]. Their presence in wastewater can significantly alter physicochemical properties such as pH, dissolved oxygen, and conductivity [6]. Exposure to heavy metals has been associated with severe health problems including neurological disorders, kidney damage, carcinogenic effects, and genetic mutations [7]Additionally, they pose serious risks to aquatic life by disrupting biological processes and reducing biodiversity .Due to their stability and toxicity, conventional treatment methods are often ineffective in completely removing heavy metals from industrial effluents[8].

Traditional physicochemical treatment methods such as adsorption, coagulation–flocculation, chemical oxidation, and membrane filtration have been widely applied for pollutant removal. Although these techniques can reduce color and pollutant concentrations, they often involve high operational costs, large energy requirements, and the generation of secondary pollutants such as sludge that require further treatment [9]. These limitations have encouraged researchers to explore environmentally sustainable and cost-effective alternatives.

Microbial bioremediation has emerged as a promising and eco-friendly approach for the treatment of textile effluents. Various microorganisms including bacteria, fungi, yeasts, and algae have demonstrated the ability to degrade or transform complex dye molecules into simpler and less toxic compounds. Bacterial species such as *Bacillus, Pseudomonas,* and *Staphylococcus* have shown high efficiency in dye decolorization through enzymatic systems including azoreductase, laccase, and peroxidase [10]These enzymes catalyze the cleavage of azo bonds and facilitate the breakdown of dye molecules.

Fungi are also considered highly effective in dye degradation due to the production of extracellular ligninolytic enzymes such as laccase, manganese peroxidase, and lignin peroxidase. These enzymes can oxidize a wide variety of aromatic compounds and synthetic dyes, resulting in significant detoxification of wastewater [11]. Furthermore, microbial consortia have shown improved dye degradation efficiency because different microbial species can work synergistically to break down complex dye structures [12]).

Therefore, microbial bioremediation represents a sustainable and efficient strategy for the treatment of textile industry effluents. Understanding the potential microbial bioremediators and their mechanisms of dye degradation is essential for developing effective wastewater treatment technologies.

Types of Textile Dyes and their Environmental Impact

The textile industry uses a wide variety of synthetic dyes to provide color, durability, and aesthetic appeal to fabrics. These dyes are broadly classified based on their chemical structure and application methods. The major types of textile dyes include azo dyes, reactive dyes, anthraquinone dyes, vat dyes, sulfur dyes, and disperse dyes. Although these dyes play an essential role in textile manufacturing, their release into the environment has raised serious environmental concerns due to their persistence, toxicity, and resistance to degradation.

Azo dyes represent the largest class of synthetic dyes used in the textile industry, accounting for approximately 60–70% of total dye production worldwide. These dyes contain one or more azo bonds (–N=N–) that connect aromatic rings and provide intense coloration and chemical stability. However, during degradation processes, azo dyes can form aromatic amines, which are often toxic, mutagenic, and potentially carcinogenic. The presence of azo dyes in wastewater has been reported to cause harmful effects on aquatic ecosystems and may pose risks to human health through contaminated water sources [13].

Reactive dyes are commonly used for dyeing cotton and other cellulose fibers because they form covalent bonds with the fabric, resulting in strong color fastness. Despite their advantages in textile processing, a significant fraction of reactive dyes remains unbound during dyeing and is discharged into wastewater. These dyes are highly water soluble and can significantly increase the chemical oxygen demand (COD) and biological oxygen demand (BOD) of wastewater, thereby affecting the quality of receiving water bodies[14] .

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Anthraquinone dyes are another important class of dyes known for their bright colors and resistance to light and chemical degradation. They are widely used in textile and paper industries. However, their complex aromatic structure makes them highly persistent in the environment, and their accumulation in water bodies can lead to long-term ecological damage[15] .Vat dyes are primarily used for dyeing cotton fabrics due to their excellent resistance to washing, light, and chemical exposure. These dyes are applied in a reduced soluble form and then oxidized to produce insoluble pigments on the fabric. Although vat dyes provide high durability, the chemicals used during their application can contribute to environmental pollution when discharged into wastewater [16].

Disperse dyes are non-ionic dyes mainly used for dyeing synthetic fibers such as polyester, nylon, and acetate. These dyes are applied as dispersions because of their low water solubility. Some disperse dyes have been associated with allergic reactions and toxicity to aquatic organisms when present in high concentrations in water systems [17]

The environmental impacts of textile dyes are significant because many of these compounds are highly stable and resistant to natural degradation processes. When dye-contaminated effluents are released into rivers or lakes, they reduce light penetration, which interferes with photosynthesis in aquatic plants and algae. This disturbance can disrupt aquatic ecosystems and decrease dissolved oxygen levels, affecting aquatic life [18]In addition, certain dye degradation products may accumulate in the food chain and pose long-term environmental and health risks.

Due to these environmental challenges, the treatment of textile dye wastewater has become a critical issue. In recent years, biological treatment methods, particularly microbial bioremediation, have gained increasing attention as environmentally friendly and sustainable approaches for the removal and degradation of textile dyes.

Types of heavy metal an their enviromental impact.

Heavy metals present in textile effluents include chromium (Cr), lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and nickel (Ni), which originate from dyes, mordants, and various industrial processing chemicals. These metals are non-biodegradable and persist in the environment, leading to long-term ecological risks. Chromium, particularly in its hexavalent form (Cr^{6+}), is highly toxic and carcinogenic, affecting aquatic organisms and human health. Lead interferes with the nervous system and causes developmental disorders, while cadmium accumulates in the kidneys and causes bone damage. Copper and zinc, though essential trace elements, become toxic at higher concentrations and disrupt aquatic life by affecting enzyme activity and metabolic processes. Nickel is known to cause allergic reactions and has carcinogenic potential. The accumulation of these metals in soil and water leads to bioaccumulation and biomagnification in the food chain, ultimately affecting biodiversity and ecosystem stability. Additionally, heavy metals alter physicochemical properties of water such as pH and dissolved oxygen, further harming aquatic organisms. Due to their toxicity and persistence, these pollutants pose serious environmental challenges and require advanced treatment methods for effective removal [19]

Potential Microbial Bioremediators for Textile Pollutant Degradation

The increasing discharge of pollutant -containing wastewater from textile industries has created serious environmental concerns due to the persistence, toxicity, and recalcitrant nature of synthetic dyes. In recent years, microbial bioremediation has gained significant attention as an eco-friendly and cost-effective approach for the removal and degradation of textile dyes. Various microorganisms including bacteria, fungi, yeasts, and algae possess the ability to degrade complex dye molecules through enzymatic reactions and metabolic pathways, transforming them into simpler and less toxic compounds[20]. These microorganisms are therefore considered potential bioremediators for the treatment of textile dye effluents.

Bacterial Bioremediators

Bacteria are among the most extensively studied microorganisms for textile dye degradation because of their rapid growth rate and metabolic versatility. Several bacterial genera such as Pseudomonas, Bacillus, Citrobacter, Staphylococcus, and Alcaligenes have demonstrated high efficiency in the biodegradation of azo and anthraquinone

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dyes [21]These bacteria produce enzymes such as azoreductase, laccase, and peroxidase that break down dye molecules by cleaving azo bonds and degrading aromatic intermediates (Sarkar et al., 2020).

For example, bacterial strains capable of producing azoreductase can reduce azo bonds (–N=N–), leading to the formation of colorless compounds that are further mineralized into harmless products such as carbon dioxide and water [22]Studies have also shown that bacterial strains such as Alcaligenes aquatilis can significantly reduce color intensity and lower biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels in dye-contaminated wastewater [23]

Recent studies also emphasize the use of bacterial consortia rather than individual strains for more efficient dye degradation. Mixed microbial cultures can degrade complex dye molecules more effectively due to synergistic metabolic interactions between different species. For instance, bacterial consortia consisting of Bacillus, Pseudomonas, and Stenotrophomonas species have shown decolorization efficiencies of up to 78–99% for several textile dyes [24]

Fungal Bioremediators

Fungi, particularly white-rot fungi, are considered highly effective microbial bioremediators for textile dye degradation. These organisms produce extracellular ligninolytic enzymes such as laccase, lignin peroxidase (LiP), and manganese peroxidase (MnP), which can oxidize a wide range of aromatic pollutants including synthetic dyes [25]Species such as Trametes versicolor, Pleurotus ostreatus, and Phanerochaete chrysosporium have been widely studied for their ability to degrade various textile dyes. These fungi are capable of breaking down dye molecules through oxidative enzymatic reactions that lead to the cleavage of chromophoric groups and detoxification of dye compounds [26]

Another promising fungal species is Fusarium oxysporum, which has shown the ability to degrade dyes such as Congo red, malachite green, and Remazol Brilliant Blue R with degradation efficiencies exceeding 90% under optimized conditions [27].

Yeast and Algal Bioremediators

Yeasts also play an important role in dye bioremediation due to their capacity for biosorption and enzymatic degradation. Yeast species can adsorb dye molecules onto their cell surfaces and subsequently degrade them through intracellular metabolic processes[28]. These microorganisms are particularly useful in wastewater treatment systems because they tolerate high dye concentrations and harsh environmental conditions.

Microalgae have also been explored as potential bioremediators for textile dye removal. Algal cells possess porous cell walls with functional groups capable of binding dye molecules through biosorption mechanisms. In addition to adsorption, algae can also transform certain dye compounds through enzymatic reactions, thereby reducing the toxicity of dye-contaminated wastewater [29]

Significance of Microbial Bioremediators

The application of microbial bioremediators in textile wastewater treatment offers several advantages over conventional physicochemical methods. Microbial processes are cost-effective, environmentally sustainable, and capable of complete mineralization of dye pollutants. In addition, microorganisms can adapt to different environmental conditions and degrade a wide range of dye structures through diverse enzymatic pathways (Overall, bacteria, fungi, yeasts, and algae represent promising biological agents for the treatment of textile dye effluents. Continued research on microbial metabolism, enzyme engineering, and microbial consortia is expected to improve the efficiency of dye degradation and support the development of sustainable wastewater treatment technologies for the textile industry.

Mechanisms of microbial pollutant degradation.

Microbial degradation of textile pollutant involves several biochemical processes through which microorganisms transform complex pollutant molecules into simpler and less toxic compounds. Microorganisms such as bacteria, fungi, yeast, and algae degrade dyes through mechanisms including enzymatic degradation, biosorption, bioaccumulation, and

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biodegradation. These mechanisms enable microorganisms to remove color and reduce the toxicity of pollutant-contaminated wastewater.

Enzymatic Degradation

Enzymatic degradation is one of the most important mechanisms involved in microbial dye removal. Microorganisms produce various oxidative and reductive enzymes that can break down complex dye molecules. Among these enzymes, azoreductase, laccase, lignin peroxidase (LiP), and manganese peroxidase (MnP) play major roles in dye degradation [30]Azoreductase enzymes are mainly produced by bacteria and are responsible for the cleavage of azo bonds (–N=N–) present in azo dyes. The reduction of these bonds results in the formation of colorless aromatic amines, which can be further degraded into simpler compounds through microbial metabolic pathways[30] Bacterial species such as Pseudomonas, Bacillus, and Escherichia coli have been reported to possess strong azoreductase activity for azo dye degradation [31]Fungal enzymes such as laccase, lignin peroxidase, and manganese peroxidase are also highly effective in dye degradation. These extracellular enzymes are capable of oxidizing a wide range of aromatic compounds including textile dyes. White-rot fungi such as Trametes versicolor and Pleurotus ostreatus produce ligninolytic enzymes that break down dye chromophores and lead to decolorization and detoxification of dye pollutants [32]

Biosorption

Biosorption is another important mechanism through which microorganisms remove dyes from wastewater. In this process, dye molecules are adsorbed onto the surface of microbial cells through physical or chemical interactions. Functional groups such as hydroxyl, carboxyl, amino, and phosphate groups present on microbial cell walls bind dye molecules and remove them from the aqueous phase [33]

Both living and non-living microbial biomass can participate in biosorption. Microorganisms such as bacteria, fungi, and algae possess cell walls that contain polysaccharides, proteins, and lipids that provide binding sites for dye molecules. This mechanism is particularly effective for the removal of reactive and basic dyes from wastewater.

Bioaccumulation

Bioaccumulation involves the uptake and accumulation of dye molecules inside microbial cells. In this mechanism, dyes are transported across the cell membrane and stored within the cell structure. Microorganisms can then metabolize these dye molecules through intracellular enzymatic reactions, resulting in their transformation into less harmful compounds [34] Bioaccumulation is commonly observed in yeast and algal species that have strong metabolic capabilities and high tolerance to toxic compounds. This mechanism contributes significantly to the removal of dyes from contaminated environments.

Biodegradation and Mineralization

Biodegradation is the final stage of microbial dye removal, in which dye molecules are completely broken down into simple inorganic compounds such as carbon dioxide, water, and inorganic salts. During this process, microorganisms use dye molecules as carbon or energy sources for growth and metabolism [35]

Microbial consortia often enhance biodegradation efficiency because different microbial species work together to degrade complex dye molecules. One microorganism may break down the dye into intermediate compounds, which are further degraded by other microorganisms in the consortium. This synergistic interaction improves the overall degradation efficiency and reduces the toxicity of dye pollutants [36].

II. COMPARATIVE STUDY

Chemical vs Biological Methods for Textile Wastewater Treatment

The treatment of textile effluents has traditionally relied on physical and chemical methods; however, in recent years, biological approaches using microorganisms have gained significant attention due to their sustainability and efficiency.

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A comparative evaluation of these methods based on cost, efficiency, and eco-friendliness is essential to determine the most suitable approach for wastewater treatment.

Chemical methods such as coagulation, flocculation, oxidation, and adsorption are widely used for dye removal. These techniques are effective in reducing color and pollutant load within a short period. For example, adsorption using activated carbon has been reported to achieve high dye removal efficiency. However, these methods often require expensive chemicals, high energy input, and sophisticated equipment, making them economically less feasible for large-scale applications[37]. Additionally, chemical treatments generate large amounts of sludge, which requires further disposal and may cause secondary environmental pollution.

Oxidation processes, including ozonation and advanced oxidation techniques, are capable of breaking down complex dye molecules into simpler compounds. However, these methods are energy-intensive and may not completely mineralize pollutants, resulting in the formation of toxic intermediates[38]. Similarly, coagulation and flocculation processes are effective in removing suspended solids and color but produce chemical sludge that poses disposal challenges [39]

In contrast, biological methods involving microorganisms offer an eco-friendly and cost-effective alternative. Microbial bioremediation utilizes bacteria, fungi, and yeasts to degrade textile dyes into non-toxic or less toxic compounds. Several studies have reported that bacterial species such as Pseudomonas, Bacillus, and Enterobacter can effectively degrade azo dyes through enzymatic mechanisms [40]These microorganisms produce enzymes like azoreductase, laccase, and peroxidase, which break down complex dye structures.

Biological methods are generally less expensive because they require minimal chemical inputs and operate under mild environmental conditions. Moreover, they produce little to no secondary pollution, making them environmentally sustainable[41]). Fungal species such as Pleurotus ostreatus have shown high efficiency in degrading dyes due to their ligninolytic enzyme systems, which can mineralize complex aromatic compounds.

However, biological methods may have some limitations, such as slower degradation rates compared to chemical methods and sensitivity to environmental conditions like pH and temperature. Despite these limitations, optimization of growth conditions and the use of microbial consortia can significantly enhance degradation efficiency [42]Overall, biological methods are considered superior in terms of eco-friendliness and sustainability, while chemical methods offer rapid treatment but at a higher environmental and economic cost. Therefore, integrating biological processes with conventional methods may provide an effective hybrid approach for textile wastewater treatment.

Comparative Study:

Chemical vs Biological Methods for Textile Wastewater Treatment

Parameter	**Chemical Methods**	**Biological Methods**
Principle	Use of chemical reagents (oxidation, coagulation, adsorption)	Use of microorganisms (bacteria, fungi, algae)
Examples	Coagulation–flocculation, ozonation, Fenton reaction, adsorption	Activated sludge, microbial bioremediation, biofilms, algal treatment
Efficiency	Rapid removal of color and COD	Slower but complete degradation
Cost	High	Low
Environmental Impact	Generates toxic sludge	Eco-friendly, minimal sludge
Sludge Production	High	Low
Energy Requirement	High	Low to moderate
Specificity	Non-specific	Highly specific
By-products	May produce toxic intermediates	Less harmful products
Operational Conditions	Less sensitive	Sensitive to pH, temperature
Sustainability	Less sustainable	Highly sustainable

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Time Required	Fast	Slow
Suitability	Primary treatment	Secondary/tertiary treatment
Overall Advantage	Quick treatment	Complete detoxification
Limitation	Expensive, sludge issue	Slow, needs control

III. FUTURE PROSPECTS

One of the major future directions in microbial dye bioremediation is the development of efficient microbial consortia. Mixed microbial cultures can degrade complex dye molecules more effectively than individual microbial strains because different microorganisms possess complementary metabolic pathways. Such synergistic interactions can enhance dye degradation efficiency and improve the stability of biological treatment systems [43]Another promising area is the application of genetic engineering and metabolic engineering techniques to enhance microbial degradation capacity. Advances in biotechnology have made it possible to modify microorganisms to produce higher levels of dye-degrading enzymes such as laccase, azoreductase, and peroxidases. Genetically engineered microorganisms could potentially degrade a wider range of textile dyes more rapidly and efficiently [44]

The use of immobilized microbial cells and enzymes is also gaining attention as an effective strategy for improving bioremediation efficiency. Immobilization techniques enhance the stability, reusability, and operational lifespan of microbial cells and enzymes in wastewater treatment systems. These approaches may help overcome some limitations associated with free microbial cells in large-scale applications [45]

In addition, integration of microbial treatment with advanced technologies such as membrane filtration, advanced oxidation processes, and nanotechnology could significantly improve dye removal efficiency. Hybrid treatment systems combining biological and physicochemical processes have the potential to achieve complete mineralization of dye pollutants while minimizing secondary waste generation.

Challenges in microbial pollutant bioremediation

Despite its advantages, microbial pollutant bioremediation faces several challenges that limit its large-scale implementation. One major challenge is the complex composition of textile wastewater, which often contains a mixture of dyes, heavy metals, salts, and other toxic chemicals. These compounds may inhibit microbial growth and reduce the efficiency of biodegradation processes [13]

Another challenge is the variability in environmental conditions, such as fluctuations in pH, temperature, and dye concentration in industrial effluents. These variations can affect microbial activity and enzyme stability, leading to inconsistent treatment performance.

The slow rate of microbial degradation compared to some physicochemical methods is another limitation. Although microorganisms can effectively degrade dyes, the process may require longer treatment times, which can be a disadvantage in large-scale industrial applications.

Furthermore, there are challenges related to maintaining stable microbial populations in bioreactors. Competition between microbial species and contamination by unwanted microorganisms can reduce the efficiency of microbial treatment systems.

IV. CONCLUSION OF THE SECTION

Although several challenges remain, microbial pollutant bioremediation continues to be a promising strategy for sustainable wastewater treatment. Advances in biotechnology, microbial ecology, and environmental engineering are expected to improve the efficiency and applicability of microbial processes in textile wastewater treatment. Continued research and development will play a crucial role in overcoming existing limitations and enabling the successful implementation of microbial bioremediation technologies in the textile industry.

V. SUMMARY

The textile industry is one of the major contributors to industrial water pollution due to the discharge of pollutant-containing wastewater. Synthetic dyes such as azo, reactive, anthraquinone, vat, and disperse dyes heavy metals are widely used in textile processing, and many of these compounds are highly stable and resistant to natural degradation. Their presence in aquatic ecosystems can reduce light penetration, disrupt photosynthesis, and produce toxic effects on aquatic organisms. Conventional treatment methods including adsorption, coagulation, and chemical oxidation are commonly used but often involve high operational costs and secondary pollution. Microbial bioremediation has emerged as a promising alternative for the treatment of textile polluted effluents. Various microorganisms including bacteria, fungi, yeasts, and algae have demonstrated the ability to degrade dye molecules through enzymatic reactions such as azoreductase, laccase, and peroxidase activity. These biological processes enable the transformation of complex dye compounds into simpler and less toxic substances. Recent advances in microbial consortia, enzyme technology, and genetic engineering offer new opportunities for improving dye degradation efficiency. Therefore, microbial bioremediation represents a sustainable and environmentally friendly approach for the treatment of textile wastewater.

VI. OVERALL SIGNIFICANCE

The mechanisms of microbial pollutant degradation involve a combination of enzymatic reactions, biosorption, bioaccumulation, and biodegradation processes. These mechanisms allow microorganisms to efficiently remove dye pollutants from wastewater and reduce their environmental impact. Understanding these mechanisms is essential for developing efficient bioremediation technologies for the treatment of textile industry effluents.

Future Prospects and Challenges in Microbial pollutant Bioremediation

Microbial bioremediation has emerged as a promising and environmentally sustainable approach for the treatment of textile dye effluents. With increasing environmental regulations and the need for sustainable wastewater management, research on microbial degradation of textile dyes has expanded significantly in recent years. Despite the encouraging progress, several challenges remain in the practical application of microbial technologies at an industrial scale.

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