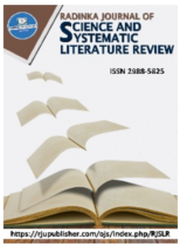

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A Comprehensive Review on Microbial Bioremediation of Industrial Dye

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Abstract

Synthetic dyes, widely utilized across industries such as textiles, cosmetics, and pharmaceuticals, represent a significant environmental hazard due to their persistence, toxicity, and resistance to conventional treatment methods. Current remediation strategies, including coagulation, adsorption, and advanced oxidation processes, are limited by high energy demands, secondary pollutant generation, and inefficiency in degrading recalcitrant dye structures. This review comprehensively evaluates microbial dye remediation as a sustainable alternative, emphasizing the enzymatic potential of bacteria, fungi, algae, and yeasts. Critical findings underscore the efficacy of microbial enzymes, including laccases, azoreductases, and peroxidases, in degrading complex dyes such as azo and anthraquinone derivatives into less toxic or mineralized products. Microbial consortia demonstrate enhanced degradation through metabolic complementarity, while innovative bioreactor systems, such as microbial fuel cells and membrane bioreactors, achieve improved efficiency and energy recovery. Despite these advances, challenges such as the production of toxic intermediates (e.g., aromatic amines), microbial sensitivity to environmental fluctuations, and sludge generation remain obstacles to industrial-scale application. The review highlights the potential of integrating microbial systems with nanotechnology and advanced oxidation processes to address these limitations. Genetic engineering and synthetic biology are proposed as critical tools for enhancing microbial resilience and enzymatic specificity. Future research should focus on hybrid remediation approaches, real-time environmental monitoring, and the development of standardized, scalable protocols. By synthesizing advancements in microbial biotechnology and wastewater management, this review provides a strategic framework for addressing industrial dye pollution, aligning with global sustainability goals and advancing the field of bioremediation.

Keywords: Microbial dye remediation, Enzymatic degradation, Azo dyes, Bioremediation, Sustainable wastewater management

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Introduction

The rapid industrialization of sectors such as textiles, food, cosmetics, and pharmaceuticals has led to the extensive use of synthetic dyes, resulting in significant environmental pollution (Varjani et al., 2020). Globally, over 0.7 million tons of synthetic dyes are produced annually, with azo dyes accounting for approximately 80% of all organic dyes. Their widespread use is attributed to their vibrant colors, cost-effectiveness, and chemical stability (Ajaz et al., 2020). However, these dyes present a dual-edged sword: while they are indispensable for modern industry, their improper disposal has led to severe ecological consequences (Ngo & Tischler, 2022). Dye-laden wastewater not only imparts color to water bodies but also contains toxic, carcinogenic, and mutagenic compounds that disrupt aquatic ecosystems, reduce light penetration, and hinder photosynthesis. These pollutants pose risks to human health, including allergies, tumor development, and genotoxicity, while also threatening biodiversity. Conventional dye remediation methods (Figure 1), including chemical treatments like coagulation and advanced oxidation, and physical methods such as adsorption and membrane filtration, have long been employed to address dye pollution (Bharathi et al., 2022). However, these approaches often fall short of providing sustainable solutions. Their limitations include high operational costs, energy-intensive processes, the generation of secondary pollutants like sludge, and inefficiencies in degrading recalcitrant dyes or their metabolites (Ayub et al., 2025). For instance, advanced oxidation processes, while effective in some cases, produce toxic intermediates that require further treatment. Adsorption techniques are limited by the regeneration capacity of adsorbents, while filtration methods are plagued by issues like membrane fouling. Moreover, the disposal of sludge and other byproducts generated by these methods contributes to secondary environmental pollution (Al-Tohamy et al., 2022). These challenges underscore the urgent need for innovative and sustainable dye remediation strategies.

Bioremediation, leveraging the metabolic capabilities of microorganisms, has emerged as a viable alternative. Microbial systems offer several advantages over traditional methods, including cost-effectiveness, minimal sludge generation, and the potential for complete mineralization of dyes into non-toxic end products (Lin et al., 2023). Microorganisms such as bacteria, fungi, yeasts, and algae have been identified for their ability to degrade a wide range of dyes through enzymatic mechanisms. Enzymes like laccases, peroxidases, azoreductases, and tyrosinases play pivotal roles in breaking down complex dye molecules. Recent advances in bioremediation have focused on the development of novel bioreactor systems, such as microbial fuel cells (MFCs) and membrane bioreactors (MBRs), which offer advantages like energy generation and enhanced pollutant removal efficiency. Additionally, the exploration of genetically engineered microorganisms (GEMs) has opened new avenues for addressing the degradation of complex or recalcitrant dyes.

Despite its promise, microbial dye remediation faces several challenges. The scalability of these methods to industrial levels remains a significant hurdle, requiring optimized reactor designs and operational conditions. Furthermore, the specificity of microbial systems to certain dye types and environmental factors such as pH, temperature, and nutrient availability can influence their effectiveness. The formation of byproducts during microbial degradation and the potential environmental impacts of bioremediation processes are areas that require further investigation. Integration with complementary technologies, such as nanotechnology and photolytic systems, is being explored to address these limitations (Kapoor et al., 2021).

Over the past decade, the field of microbial dye remediation has witnessed significant advancements. Improvements in understanding microbial degradation pathways, enzyme systems, and the adaptive mechanisms of microorganisms have laid a strong foundation for developing innovative solutions (Srivastava et al., 2022). Moreover, interdisciplinary approaches combining biotechnology, nanotechnology, and environmental engineering are driving the evolution of this field. As industries grapple with the environmental and regulatory challenges posed by dye pollution, microbial remediation stands out as a sustainable and efficient alternative. By addressing existing limitations and leveraging cutting-edge technologies, microbial bioremediation has the potential to revolutionize wastewater treatment and mitigate the ecological footprint of industrial dye usage.

Previous reviews on microbial dye remediation often fall short in addressing several critical aspects that are essential for advancing the field. Many focus narrowly on individual microbial strains or basic biodegradation mechanisms, offering limited insight into the potential of microbial consortia or the emerging applications of synthetic biology. This review bridges this gap by emphasizing the synergistic interactions within microbial consortia and exploring how synthetic biology can be harnessed to design robust, custom-engineered consortia for tackling complex dye mixtures under industrial conditions. Furthermore, earlier studies frequently overlook the impact of real-world environmental variables such as heavy metals, pH fluctuations, and mixed contaminants on microbial activity, as well as the challenges of scaling up laboratory-optimized systems. This review provides a comprehensive analysis of these environmental and process factors, highlighting practical trade-offs and innovative solutions for enhancing scalability and robustness in industrial applications.

Additionally, while prior works inadequately address microbial remediation in the context of complex wastewater matrices, this review delves into microbial resilience and adaptability to mixed contaminants, focusing on strategies like bioaugmentation and pretreatment. It also incorporates recent advancements in enzymology to present updated insights into novel enzymes and molecular mechanisms that drive dye degradation. Unlike earlier reviews, which often lack connection to industrial applications, this work bridges fundamental microbiology with the challenges of large-scale implementation, considering economic viability and process optimization.

Methodology

This review was developed through a systematic and keyword-driven search strategy using databases such as PubMed, Scopus, Web of Science, and Google Scholar. Boolean operators combined keywords such as "microbial dye degradation," "bioremediation," "enzymes," and "microbial consortia." Queries included combinations like "microbial consortia" AND "dye remediation" and "enzymes" AND "azo dyes" OR "anthraquinone dyes". Inclusion criteria focused on peer-reviewed articles published within the last decade, emphasizing microbial mechanisms and scalability in dye remediation. Exclusion criteria eliminated non-English publications and studies lacking experimental evidence or microbial context. Relevant data, including microbial strains, enzymatic mechanisms, and degradation pathways, were categorized into thematic areas.

Figure 1. Framework of Traditional Dye Remediation Processes. The chemical treatment process is depicting coagulation, flocculation, and oxidation processes and physical treatment process showing adsorption and membrane filtration.

Result and Discussion

Overview of Dye Pollution

Industrial dyes, though integral to numerous industries, pose variable levels of toxicity and environmental threat depending on their chemical compositions. Various sources of dye pollution have been shown in Figure 2. Azo dyes, for instance, dominate the synthetic dye market but harbor significant environmental and health risks. These dyes can degrade into aromatic amines, compounds linked to carcinogenicity and mutagenicity. Additionally, certain dyes contain heavy metals such as chromium, lead, or cadmium, which bioaccumulate in ecosystems and disrupt aquatic and terrestrial life. The chemical complexity of dyes, coupled with the inclusion of non-biodegradable toxic agents like formaldehyde and chlorinated compounds, exacerbates their environmental footprint, compromising water quality and aquatic life sustainability.

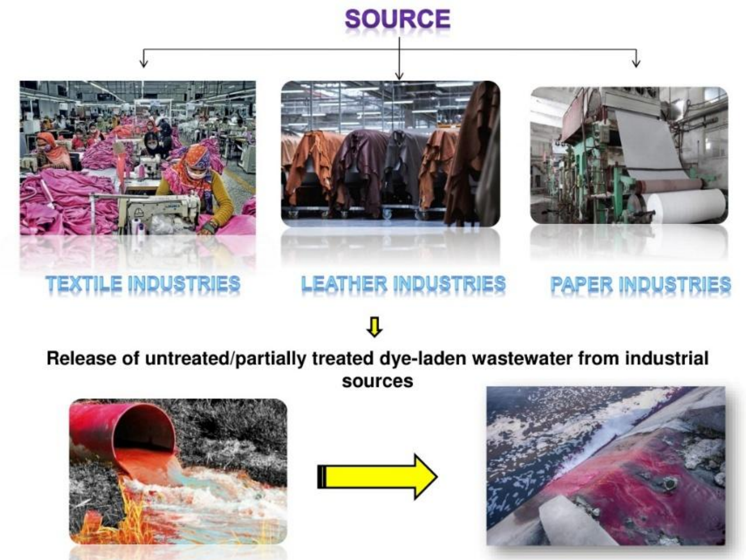

Figure 2. A conceptual diagram highlighting the sources of dye-contamination.

Dye pollutants diminish sunlight penetration in water, reducing photosynthesis and oxygen production, thereby disrupting aquatic ecosystem. Studies have shown that exposure to dye-contaminated water causes oxidative stress and bioaccumulation in fish, leading to severe histopathological damage.

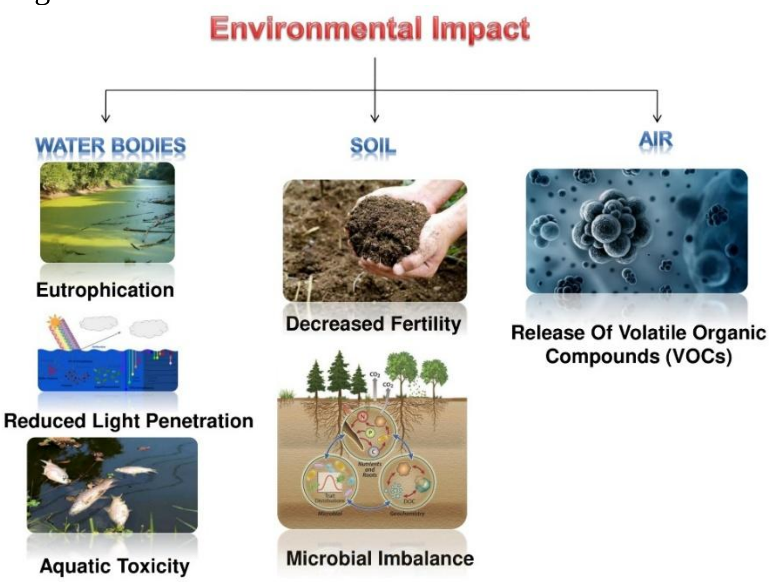

Figure 3. A conceptual diagram highlighting the impacts of dye-contaminated wastewater on the environment.

Beyond ecological impacts, human exposure to these pollutants, particularly through heavy metals and aromatic amines, is associated with increased risks of cancer, genetic mutations, and systemic organ dysfunction (Figure 4).

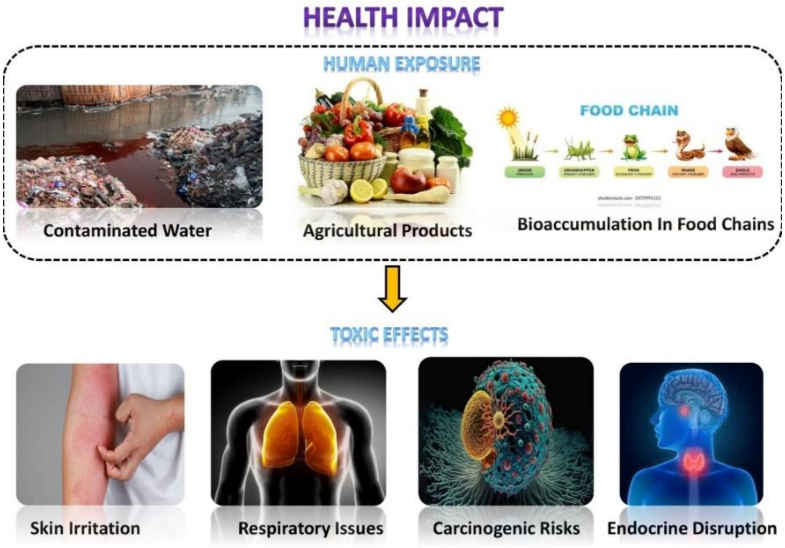

Figure 4. A conceptual diagram highlighting the impacts of dye-contaminated wastewater on human health.

Regional disparities in industrial practices significantly influence the global dye pollution burden. Developed nations typically enforce stringent environmental regulations and employ advanced wastewater treatment technologies to mitigate dye pollution. In contrast, many developing nations, where textile manufacturing is a critical economic sector, face challenges such as weak regulatory frameworks and limited technological infrastructure. In developing regions, untreated wastewater containing dye residues is frequently discharged directly into water bodies, significantly elevating pollution levels. For example, African countries and parts of Asia, home to high concentrations of textile industries, experience acute dye pollution due to excessive water consumption, reliance on synthetic dyes, and inadequate wastewater management systems. Conversely, developed countries often implement efficient dye removal systems, achieving greater control over water contamination. Strengthening regulations and fostering investments in advanced treatment technologies remain critical to bridging these regional gaps. Among the diverse classes of dyes, reactive and vat dyes are notably persistent, presenting significant remediation challenges. Reactive dyes are designed to form covalent bonds with fibers, ensuring their permanence and vibrant hues. Their chemical stability, however, complicates degradation, particularly in conventional treatment systems. Similarly, vat dyes, such as indigo, are insoluble in water but can be solubilized under alkaline conditions for fiber bonding. Their application, particularly in denim production, highlights their durability but also underscores their persistence in wastewater.

Other dye types, including disperse dyes for synthetic fibers and sulfur dyes valued for affordability, also exhibit high resistance to degradation. Their strong bonds with fibers and inherent chemical stability hinder natural breakdown, necessitating advanced and tailored remediation strategies. Mitigating dye pollution requires an integrated approach encompassing stricter environmental regulations, technological advancements, and sustainable industrial practices. Investing in advanced wastewater treatment technologies such as microbial bioreactors, photolytic systems, and nanomaterial-based remediation can enhance dye degradation efficiency. Additionally, promoting the use of eco-friendly dyes and the development of sustainable dyeing techniques could significantly reduce the environmental impact. Strengthened international collaboration and knowledge sharing among industries, governments, and researchers are pivotal in achieving long-term solutions for dye pollution control.

Microbial Mechanisms of Dye Degradation

Microbial degradation of dyes is a multifaceted process that combines universal strategies and dye-specific pathways. The structural complexity of dyes dictates their biodegradation routes, with different microbes employing distinct enzymatic systems to target specific dyes (Figure 5). For instance, azo dyes with nitrogen-nitrogen (-N=N-) double bonds are commonly degraded by microorganisms like *Bacillus pseudomycoides*, which utilize enzymes to cleave these bonds. Similarly, other dyes require alternative enzymatic systems tailored to their molecular structure. However, certain mechanisms, such as biosorption and enzymatic degradation, are broadly applicable. Key enzymes like azo reductase, laccase, lignin peroxidase, and NADH-DCIP reductase play critical roles in transforming complex dyes into simpler, less toxic compounds. Notable microbial examples include *Acinetobacter calcoaceticus*, which efficiently degrades reactive orange II and methyl orange, and *Staphylococcus* species, known for breaking down reactive blue 21 (Kolekar et al., 2012). These examples highlight the adaptability and efficiency of microbial systems, combining universal degradation strategies with dye-specific enzymatic precision. Microbial dye degradation is often more sustainable and cost-effective than abiotic methods, although the latter may provide quicker results. Microbial systems utilize natural enzymatic pathways and metabolic flexibility to degrade dyes effectively, even in toxic or extreme conditions. Their eco-friendly nature minimizes secondary sludge production and reduces environmental impact, making them an attractive solution for large-scale applications. For example, microbial fuel cells (MFCs) not only degrade dyes but also generate electricity, demonstrating a dual-purpose utility. In contrast, abiotic methods like advanced oxidation processes (AOPs), adsorption, and coagulation offer rapid dye removal but at a higher environmental and economic cost. These processes often involve substantial energy consumption and chemical inputs, which can result in toxic byproducts requiring further treatment. Thus, while abiotic methods are suitable for scenarios demanding immediate results, microbial degradation is better suited for sustainable, long-term wastewater treatment solutions.

Despite its advantages, microbial dye degradation can sometimes produce secondary pollutants or other unintended effects. During the degradation process, intermediate compounds may form that are more toxic than the original dye, necessitating additional monitoring and treatment. Microbial activity can also release volatile organic compounds (VOCs) into the environment, contributing to air pollution and posing health risks such as respiratory irritation or carcinogenic effects. Moreover, microbial processes can alter soil and water chemistry, including changes in pH, nutrient levels, and oxygen content, potentially disrupting local ecosystems. There is also a risk of bioaccumulation, where incomplete degradation products persist in organisms and magnify toxicity through the food chain. Additionally, microbial activity may mobilize heavy metals from contaminated sediments, spreading these pollutants to surrounding water bodies and ecosystems. To mitigate these risks, careful monitoring and integration of complementary treatment methods are essential to optimize the benefits of microbial remediation while minimizing potential adverse effects.

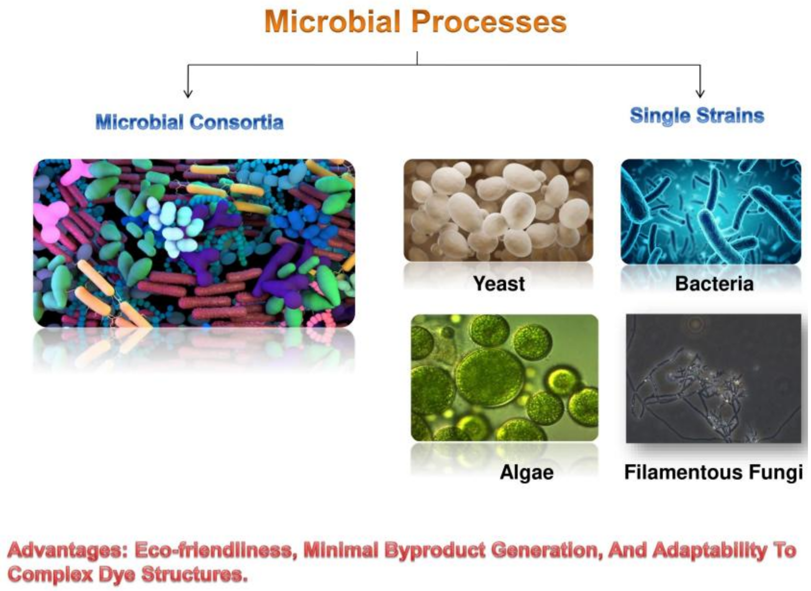

Figure 5. Framework of microbial dye remediation processes depicting microbial consortia, single strains-driven dye degradation pathways and highlighting eco-friendliness, minimal byproduct generation, and adaptability to complex dye structures.

Microorganisms are ubiquitous, thriving even in harsh and polluted environments, which positions them as a rich reservoir of enzymes and metabolites with potential applications in addressing environmental challenges. The utilization of microorganisms in place of conventional physicochemical methods for pollutant removal is termed bioremediation. This approach has garnered significant attention over the past decades, with microorganisms being extensively studied for their ability to degrade polyaromatic hydrocarbons, transform heavy metals into less harmful or immobilized forms, break down pesticides, and mineralize or reduce azo dyes. In the context of dye degradation, microorganisms offer distinct advantages, including cost efficiency, reduced water consumption, and minimal sludge generation. They decolorize dyes by reducing azo bonds to aromatic amines and degrade them into smaller molecules, ultimately yielding H_2O, CO_2, and other mineral by-products. Microbial dye removal mechanisms include adsorption, enzymatic degradation, or a combination of both. Adsorption involves ion exchange facilitated by hydroxy and carboxy groups present on the microbial cell wall, which bind to dye molecules. This process can occur with both live and dead biomass but has limitations, as adsorbed dyes remain in a toxic form, posing disposal challenges similar to traditional physical methods (Dhankhar et al., 2020). In contrast, enzymatic degradation offers a sustainable solution by breaking down dyes into non-toxic compounds. Microorganisms such as filamentous fungi, yeasts, algae, and bacteria have demonstrated the ability to decolorize and degrade azo dyes, making them promising candidates for environmentally friendly and efficient bioremediation strategies.

Microbial Treatment of Dyes Using Filamentous Fungi

Filamentous fungi are highly adaptable microorganisms capable of degrading various xenobiotics through intracellular and extracellular enzymatic activity (Al-Tohamy et al., 2022). These fungi are ubiquitous, thriving in diverse environments such as soil and organic waste. The degradation of azo dyes by filamentous fungi is a synergistic process involving biosorption and enzymatic actions (Fu & Viraraghavan, 2000). Both living and dead fungal biomass have been explored for treating dye-laden effluents, with dead biomass often exhibiting higher dye uptake due to its reliance on physicochemical mechanisms like adsorption, deposition, and ion exchange (Ghodake et al., 2009). Functional groups in fungal cell wall components such as chitin, chitosan, and glucan facilitate dye binding. For example, *Aspergillus niger* has shown efficacy in adsorbing dyes such as Basic Blue 9 and Reactive Brilliant Red, though cell wall integrity significantly affects adsorption efficiency.

Enzymes such as laccases, lignin peroxidases, and manganese peroxidases contribute to dye degradation by converting complex dye molecules into simpler forms. Comparisons of living and dead fungal biomass reveal both approaches as effective for dye color removal, with studies highlighting the superior decolorization rates of dead biomass for dyes like Reactive Black 5. Despite these advantages, living cells require precise optimization of conditions such as pH and nutrient levels, while the disposal of dye-laden dead biomass poses environmental challenges due to potential dye leaching.

Microbial Treatment of Dyes Using Yeasts

Although less studied than bacteria and filamentous fungi, yeasts hold promise for dye remediation due to their rapid growth and resilience in harsh environments. Yeasts predominantly remove dyes through biosorption, where functional groups on their cell surface facilitate dye adhesion via electrostatic interactions, ion exchange, or chelation. For instance, *Saccharomyces cerevisiae* and related species have demonstrated biosorption capabilities for dyes like Reactive Brilliant Red K-2BP (Wang & Hu, 2008). The enzymatic degradation potential of yeasts is not well-characterized, but preliminary evidence suggests they may produce oxidative enzymes akin to those in filamentous fungi. For example, ligninolytic enzymes have been detected in *Pyricularia oryzae*, and *Saccharomyces cerevisiae* has shown lignin peroxidase activity during the decolorization of Methyl Red. These findings suggest unexplored potential for yeast-mediated dye degradation.

Microbial Treatment of Dyes Using Algae

Algae, ubiquitous in aquatic ecosystems, also demonstrate dye degradation capabilities. Their cell walls contain functional groups such as carboxyl, hydroxyl, and phosphoryl groups, which facilitate biosorption and subsequent enzymatic degradation. Some algae, like *Chlorella vulgaris* and *Oscillatoria* species, can metabolize azo dyes into simpler organic compounds. These organisms not only degrade dyes but also generate biomass, offering dual benefits for wastewater treatment. Algal isolates such as *Chlorella* and *Anabaena oryzae* have shown efficacy in degrading dyes like Orange G, highlighting their potential for treating dye-laden aquatic effluents.

Microbial Treatment of Dyes Using Bacteria

Bacteria are extensively studied for dye remediation due to their rapid growth, diverse enzymatic repertoire, and ability to degrade a wide array of dyes . Compared to fungi, bacteria offer operational advantages, including simpler cultivation and faster dye degradation. Enzymes like azoreductases play a central role in breaking down azo bonds, while bacterial pathways further degrade resulting aromatic amines under aerobic or anaerobic conditions. Studies on pure and mixed bacterial cultures reveal complementary strengths. Pure cultures, such as those of *Dermacoccus abyssi* MT1.1T, enable detailed mechanistic insights, while mixed cultures leverage synergistic interactions to enhance dye degradation (Lang et al., 2014). For example, *Dermacoccus abyssi* degrades Brilliant Black through sequential cleavage of azo bonds, generating intermediates that are further metabolized. Mixed cultures expand the range of degradative pathways, but their optimization requires careful selection of compatible bacterial strains. While bacterial systems are environmentally friendly and generate minimal sludge, understanding their degradation mechanisms is critical for scaling up their application in wastewater treatment.

Microbial Treatment of Dyes Using Microbial Consortia

Microbial consortia, comprising multiple interacting strains, offer distinct advantages and challenges for azo dye degradation. The interactions within consortia can either synergize or impede the bioremediation process, depending on the compatibility and metabolic interplay among constituent microorganisms. The enhanced efficiency of microbial consortia stems from complementary enzymatic and metabolic capabilities distributed among different strains. This metabolic complementarity enables sequential or simultaneous degradation of complex dye structures, which often contain diverse functional groups resistant to single-strain degradation. Specialized enzymes from distinct microbes target various molecular moieties, facilitating a more thorough breakdown. Microbial communities—comprising bacteria, fungi, and algae—exhibit considerable resilience in degrading high concentrations of industrial dyes and co-contaminants. Enzymatic mechanisms enable the stepwise breakdown of complex dye molecules, often facilitated by mixed consortia where metabolic diversity enhances pollutant transformation. Certain extremophiles, such as alkaliphilic microbes, are naturally adapted to the elevated pH, salinity, and heavy metal concentrations typical of textile wastewater, making them particularly effective for bioremediation in such environments. The synergistic activity of mixed microbial populations enhances degradation efficiency beyond that achievable by single strains, enabling comprehensive remediation of heterogeneous pollutant mixtures.

However, biodegradation efficacy depends strongly on factors including dye chemistry, contaminant load, and microbial community composition. Cross-feeding mechanisms, where metabolic intermediates produced by one strain serve as substrates or stimulants for others, further stabilize and sustain the consortium's activity. Such interactions foster resilience, allowing consortia to adapt dynamically to environmental fluctuations and maintain robust degradation performance under diverse and challenging conditions. Consequently, consortia frequently outperform monocultures, achieving higher degradation rates and more complete mineralization of toxic dye components. Conversely, interactions within consortia can also pose barriers. Competition for limited nutrients and cofactors may restrict microbial growth or enzymatic activity, slowing degradation kinetic. Enzymatic incompatibilities, including the production of inhibitory compounds or antagonistic metabolites by certain strains, may disrupt degradation pathways. Additionally, environmental perturbations—such as shifts in dye concentration, pH, or temperature—can destabilize the metabolic balance and community structure, diminishing consortium efficiency. Synthetic consortia, designed by strategically combining well-characterized strains with complementary functions, offer enhanced control over degradation pathways and community dynamics, potentially surpassing natural consortia in efficiency and predictability. However, natural consortia benefit from inherent ecological adaptation and complex interspecies signaling that confer resilience in fluctuating environments. The stability of both synthetic and natural consortia depends on maintaining metabolic harmony and environmental conditions conducive to cooperative interactions

Enzymatic Degradation of Azo Dyes

A range of enzymes are implicated in the reduction and degradation of azo dyes, notably manganese peroxidases, lignin peroxidases, laccases, dye-decolorizing peroxidases (DyPs), and azoreductases. Manganese peroxidases (MnPs) are oxidative enzymes that catalyze the oxidation of Mn(II) to Mn(III), generating active oxidants stabilized by organic acids such as oxalate. While primarily known for lignin degradation, MnPs effectively decolorize azo and phthalocyanine dyes, including the recalcitrant polymeric dye Poly R-478. Originally characterized in the white rot fungus *Phanerochaete chrysosporium*, MnPs have also been identified in bacteria such as *Serratia marcescens*, where they contribute to decolorization of azo and anthraquinone dyes. Lignin peroxidases (LiPs) similarly oxidize phenolic substrates, initiating dye degradation by producing phenoxy radicals that lead to azo bond cleavage and nitrogen release. Though predominantly fungal, lignin peroxidase activity has been reported in bacteria including *Bacillus* sp. and *Acinetobacter calcoaceticus*. The cooperative action of LiPs with other enzymes like laccases and tyrosinases has been documented in strains such as *Pseudomonas desmolyticum* for dye degradation. Dye-decolorizing peroxidases (DyPs) represent a distinct class of heme peroxidases, structurally divergent from classical peroxidases, and are classified into four types (A–D). Types A–C are widespread in bacteria, while type D is fungal. DyPs target azo and anthraquinone dyes and possess conserved motifs essential for catalytic function and heme binding. Laccases are multicopper oxidases that catalyze the oxidation of diverse aromatic substrates through electron transfer involving four copper ions, ultimately reducing molecular oxygen to water. The resulting substrate radicals spontaneously degrade into simpler compounds. Redox mediators such as ABTS enhance laccase-mediated dye decolorization. Although laccases are chiefly fungal, bacterial phenol oxidase activity has also been reported in some strains like *Pseudomonas desmolyticum*. In contrast to these oxidative enzymes, azoreductasescatalyze reductive cleavage of azo bonds and have been extensively studied for their central role in azo dye decolorization and degradation, warranting detailed discussion in subsequent sections.

Environmental and Process Factors Influencing Microbial Dye Degradation

Scaling microbial dye degradation from laboratory to industrial scale involves complex trade-offs between maximizing microbial activity and ensuring system robustness and feasibility. Laboratory optimization typically requires tightly controlled parameters—such as pH, temperature, nutrient supply, and aeration—to achieve peak enzymatic activity. However, replicating these ideal conditions at industrial scale, with large volumes of heterogeneous wastewater and fluctuating environmental variables, often proves impractical and costly, leading to diminished microbial efficacy. Microbial strains are usually selected or engineered under controlled conditions to target specific dyes with high efficiency. Yet, genetically modified strains may lack the resilience and adaptability necessary for industrial environments characterized by variable dye concentrations and the presence of mixed contaminants. Consequently, industrially viable strains must balance high degradation capacity with ecological robustness to sustain activity in less predictable settings. The operational robustness of microbial consortia in industrial applications is critical, given environmental stressors such as pH shifts, temperature fluctuations, and the presence of competing pollutants. While lab-optimized consortia demonstrate stability under controlled conditions, maintaining this stability at scale requires strains that tolerate environmental variability without compromising degradation performance. Cost and process complexity also constrain the deployment of highly engineered or precisely controlled systems, mandating economically viable and scalable bioremediation strategies. Microbial populations in laboratory studies often exhibit prolonged stability and persistence due to optimal growth conditions. In contrast, industrial wastewater environments impose stressors that can reduce microbial viability and activity over time (Ntung Nseabasi-Maina et al., 2021). Thus, the design of microbial systems for industrial use must prioritize resilience and sustained function under dynamic and often harsh conditions. Heavy metals and other industrial effluents present significant challenges by inhibiting microbial activity and disrupting biodegradation pathways. Toxic metals such as cadmium, chromium, and lead impair microbial growth and enzymatic function, leading to reduced dye degradation rates. Additionally, these pollutants can alter nutrient availability and environmental parameters such as pH and redox potential, further compromising microbial metabolism. Heavy metals may also induce shifts in microbial community structure, favoring resistant but less efficient degraders. The combined presence of multiple pollutants can exert synergistic inhibitory effects, exacerbating the reduction in biodegradation efficiency. Pre-treatment methods to remove or reduce heavy metals enhance subsequent microbial remediation. The use of metal-tolerant or genetically engineered strains, along with bioaugmentation approaches introducing beneficial microbes, can improve system resilience. Optimization of environmental conditions—including pH, temperature, and nutrient supplementation—further supports microbial performance in contaminated wastewater treatment.

Challenges and Future Directions in Microbial Dye Remediation

Microbial dye remediation faces significant barriers that must be overcome to enable large-scale industrial applications. A critical challenge is the toxicity of intermediate products such as aromatic amines, which are mutagenic or carcinogenic. These intermediates highlight the inefficiency of microbial systems in achieving complete mineralization, often necessitating secondary treatments. Microbial systems also face inherent biological limitations, including slow growth rates (e.g., in white-rot fungi) and sensitivity to environmental factors like pH, temperature, and inhibitory substances such as heavy metals. These limitations often require finely tuned bioreactor conditions, which increase operational complexity and costs. Furthermore, the generation of sludge by some microbes introduces the need for additional disposal measures, potentially causing secondary pollution. To overcome these challenges, future research must adopt a mechanistic approach to optimize microbial dye remediation: *(i) Genetic and Metabolic Engineering:* Engineering microbes with enhanced metabolic pathways can enable complete mineralization, minimizing toxic intermediates. CRISPR and synthetic biology tools can create microbes resistant to harsh wastewater conditions (e.g., high salinity or pH extremes). Introducing pathways for co-metabolism, where microbes simultaneously degrade dyes and other carbon sources, may improve efficiency. *(ii) Advanced Bioreactor Configurations:* Development of multi-stage bioreactors combining aerobic and anaerobic zones can facilitate sequential degradation of dyes and intermediates. Integration with photocatalysis: Using light-driven catalysts alongside microbes can degrade persistent compounds more effectively. Hybrid systems coupling microbial fuel cells and nanomaterials can simultaneously treat wastewater and recover energy. *(iii) Enzyme Immobilization and Delivery:* Immobilized enzymes derived from microbes can provide consistent degradation activity while avoiding sludge formation. Microbial encapsulation in hydrogel or polymer matrices can shield microbes from inhibitory substances and improve their resilience (Zafar et al., 2022); (Bhoi et al., 2024). *(iv) Microbial Consortia Optimization:* Designing synthetic consortia with complementary metabolic capabilities can address the degradation of diverse dye classes. Elucidating interspecies communication via quorum sensing can help stabilize microbial consortia and enhance their functionality (Patel et al., 2022); (Shi et al., 2021) *(v) Pretreatment and Auxiliary Techniques:* Combining microbial remediation with advanced oxidation processes (AOPs) can break down complex dyes into simpler, bioavailable forms. Electrochemical systems can be integrated to precondition wastewater and reduce the inhibitory load on microbial systems.

Conclusion

This review highlights the potential of microbial systems as a sustainable solution for dye remediation, emphasizing their enzymatic versatility, eco-friendliness, and capacity for complete mineralization. It underscores the advantages of microbial fuel cells, synthetic consortia, and genetically engineered strains for enhancing dye degradation efficiency. However, challenges like intermediate toxicity, sensitivity to environmental fluctuations, and sludge generation remain critical barriers to scalability. While previous studies primarily focused on isolated strains or single enzymes, this review expands the scope by integrating microbial consortia and exploring the potential of hybrid systems. Notably, it aligns with earlier findings on the challenges posed by azo dyes and mixed wastewater matrices but differs by emphasizing the emerging role of synthetic biology and nanotechnology. Disparities in results across studies can be attributed to variations in dye composition, operational conditions, and microbial adaptability. The findings underscore the transformative potential of microbial remediation in addressing global dye pollution, aligning with sustainable development goals by reducing reliance on energy-intensive chemical methods. Furthermore, advancements in bioreactor design and enzyme immobilization can catalyze industrial adoption, offering eco-friendly alternatives to conventional wastewater treatments. This review acknowledges limitations in the scalability of microbial systems and the lack of standardization in protocols. Additionally, the environmental impacts of intermediate byproducts and sludge generation require further exploration. The analysis may also be constrained by the variability in experimental conditions reported in the literature. Future research should focus on integrating microbial technologies with pre-treatment methods like advanced oxidation processes to enhance degradation efficiency. Genetic engineering can address microbial sensitivity to harsh environments, while computational tools can optimize bioreactor designs. Exploring the interplay between microbial consortia and nanomaterials, alongside real-time environmental monitoring, could pave the way for robust, scalable solutions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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