Review

Bacterial Bioremediation of Synthetic Dyes: Mechanisms, Technological Advances, and Future Perspectives

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Abstract: The textile and dyeing industries are among the largest contributors to global industrial pollution, discharging millions of liters of wastewater containing synthetic dyes each year. These compounds, which include azo, anthraquinone, triphenylmethane, vat, and disperse dyes, are chemically stable, recalcitrant, and often toxic to aquatic and terrestrial ecosystems. Their persistence in the environment causes reduced light penetration, oxygen depletion, mutagenic by-products, and heavy metal accumulation, posing long-term risks to ecological balance and public health. Conventional treatment methods such as coagulation, flocculation, activated carbon adsorption, and advanced oxidation often fail to achieve complete degradation, are cost-intensive, and may generate secondary pollution. Bacterial bioremediation has emerged as an eco-friendly and sustainable alternative, leveraging the metabolic diversity and enzymatic capacity of bacteria to degrade complex dye molecules. Genera such as *Pseudomonas, Bacillus, Klebsiella, Enterobacter, Acinetobacter,* and *Aeromonas* have demonstrated degradation via enzymatic systems including azoreductases, laccases, peroxidases, and oxidoreductases. Complementary mechanisms such as biosorption and bioaccumulation further enhance removal efficiency. This review synthesizes current knowledge on dye classification, bacterial diversity, enzymatic pathways, and environmental factors influencing degradation. Recent technological advances—including immobilized cell systems, biofilm reactors, nanobiotechnology, omics-based tools, and synthetic biology—are critically discussed, alongside laboratory and field-scale case studies from Asia, Europe, and the Americas. Challenges such as incomplete mineralization, formation of toxic intermediates, microbial instability, cost, and biosafety issues are analyzed, with emphasis on potential solutions through adaptive evolution, low-cost carriers, and engineered microbial consortia. Future prospects highlight the integration of omics-guided discovery, CRISPR-mediated genetic engineering, nanomaterial-assisted catalysis, and circular bioeconomy approaches for sustainable textile wastewater treatment. This review underscores bacterial bioremediation as a vital pillar in advancing eco-friendly, scalable, and region-specific solutions to dye pollution worldwide.

Keywords: *Textile dyes; Bacterial bioremediation; Enzymatic degradation; Biosorption; Wastewater treatment; Environmental pollution; Biofilm reactors.*

1. Introduction:

The textile industry is one of the most resource-intensive sectors, consuming vast amounts of water and chemicals [1]. Over 10,000 commercial dyes exist, with annual production exceeding 700,000 tons [2]. Approximately 10–15% of these dyes are lost during application and discharged into wastewater, leading to visible color pollution and chemical toxicity [3,4]. Synthetic dyes are

particularly azo dyes which structurally complex, xenobiotic, and resistant to natural degradation [5,6]. Their release into aquatic systems reduces light penetration, inhibits photosynthesis, alters dissolved oxygen, and produces mutagenic aromatic amines [7,8]. Some dyes also bind with heavy metals such as Cr, Pb, and Cu, compounding toxicity [9]. Conventional treatment methods such as coagulation, flocculation, adsorption, advanced oxidation are limited by cost, sludge generation, and incomplete mineralization [10–12]. Biological approaches, particularly bacterial systems, pro-vide adaptability, cost-effectiveness, and eco-compatibility [13–15]. Bacteria are especially advantageous due to metabolic versatility, rapid growth, and tolerance to hostile conditions [16]. Genera such as Pseudomonas, Bacillus, Enterobacter, Klebsiella, Acinetobacter, and Aeromonas degrade a range of dyes via enzymes like azoreductases, laccases, and peroxidases [17–20]. Complementary mechanisms such as bio-sorption and bioaccumulation further contribute [21,22].

This review consolidates current understanding of bacterial dye bioremediation. It begins with the classification of synthetic dyes and their environmental impact, followed by a discussion of bacterial diversity and mechanisms of degradation. Key factors influencing biodegradation efficiency are then examined, including physicochemical and operational parameters. The review also highlights technological innovations such as immobilized systems, biofilm reactors, nanobiotechnology, and synthetic biology. Case studies and international applications are presented to illustrate practical relevance, while limitations and challenges are critically analyzed. Finally, future prospects for scalable, sustainable, and region-specific wastewater treatment strategies are discussed.

2. Classification of Dyes and Environmental Impact:

Synthetic dyes are categorized based on their **chemical structure, chromophores, and application method**. Azo dyes dominate, representing ~60–70% of total production worldwide [23,24]. Other important groups include anthraquinone, triphenylmethane, reactive, disperse, vat, and sulfur dyes [25]. Discharge of dyes into aquatic systems leads to: Reduced light penetration that cause inhibition of photosynthesis [26]; Decreased oxygen levels, impairing aquatic fauna [27]; Toxic and mutagenic aromatic amines formed upon azo bond cleavage [28,29]; Accumulation of heavy metals from dye formulations [30].

Table 1. Classification of major synthetic dyes, examples, applications, and environmental impacts

Dye Class	Examples	Applications	Environmental Impact	References
Azo dyes	Methyl red, Congo red, RB5	Textile, leather, paper	Breakdown releases aromatic amines; mutagenic and carcinogenic	[23–25,28,29]
Anthraquinone	Reactive blue 19, Disperse blue	Denim, polyester, plastics	Highly stable aromatic rings; resistant to biodegradation	[25,31]
Triphenylmethane	Malachite green, Crystal violet	Textile, inks, biocides	Endocrine disruption; toxic to aquatic life	[7,32]
Reactive dyes	Remazol brilliant blue R	Cotton, cellulose fibers	High solubility; strong covalent binding; residual dye persists in effluent	[2,33]

Disperse dyes	Disperse orange 3, Disperse blue	Polyester, synthetic fibers	Low solubility; adsorb to sediments; toxic to algae	[3,34]
Sulfur dyes	Sulfur black 1	Cotton, denim	Release sulfides; contribute to COD, odor problems	[9]
Vat dyes	Indigo, Vat yellow 1	Denim, cellulose fibers	Alkaline dyeing effluents; sediment accumulation	[8,35]

3. Bacterial Agents and Mechanisms in Dye Degradation

Bacteria are highly adaptable and efficient for dye degradation due to their metabolic plasticity [36]. Mechanisms include enzymatic degradation, biosorption, and bioaccumulation [37]. Microbial diversity plays a significant role in the bio-degradation of textile dyes, with both Gram-negative and Gram-positive bacteria contributing to the process. Among the Gram-negative group, genera such as *Pseudomonas, Enterobacter, Klebsiella, Xenophilus*, and *Alcaligenes* are commonly reported for their dye-degrading capabilities [12,14]. In contrast, Gram-positive bacteria like *Bacillus, Lysinibacillus*, and *Rhodococcus* have also been widely documented for their efficiency in breaking down complex dye molecules [13,19]. Additionally, extremophilic microbes, including halophiles and alkaliphiles, show re-markable adaptation to harsh textile effluent environments, making them promising candidates for bioremediation [17]. Beyond individual strains, microbial consortia composed of multiple bacterial species often demonstrate higher efficiency and stability in dye degradation compared to mono-cultures, owing to their synergistic metabolic interactions [14,20].

Enzymatic mechanisms play a crucial role in the degra-dation of textile dyes. Azoreductases catalyze the reductive cleavage of azo bonds, leading to the breakdown of complex azo dyes into simpler, often less toxic, aromatic amines [6,38]. Laccases, which are multicopper oxidases, facilitate the oxidation of phenolic and non-phenolic compounds, thereby contributing to the decolorization and detoxification of dye-contaminated effluents [18]. Similarly, peroxidases, including lignin peroxidase, manganese peroxidase, and dye-decolorizing peroxidases (DyP), are capable of degrading a wide range of aromatic dye structures through oxidative reactions, making them highly effective in bioremediation processes [19].

Table 2. Representative bacterial strains, enzymes, and target dyes

Bacterial Strain	Enzyme(s)	Dyes Degraded	Reference(s)
Pseudomonas putida	Azoreductase, Laccase	Congo red, RB5	[12,24]
Bacillus subtilis	Laccase, Mn-peroxidase	Malachite green, Crystal violet	[4,18]
Enterobacter cloacae	Azoreductase	Methyl red, Orange II	[15]
Lysinibacillus sphaericus	Peroxidases, Azoreductase	Reactive blue 19, Disperse orange	[16]
Xenophilus azovorans	Azoreductase	Sulfonated azo dyes	[6,23]
Rhodococcus erythropolis	Laccase-like oxidases	Anthraquinone dyes	[19]

Alcaligenes aquatilis	Azoreductase, Peroxidase	Azo dyes	[13]

Microorganisms employ both passive and active strategies to remove dyes from textile effluents. One of the major passive mechanisms is biosorption, in which dye molecules bind to the microbial cell wall through electrostatic interactions, hydrogen bonding, or van der Waals forces, allowing rapid removal of dyes without metabolic activity [7]. An-other important process is bioaccumulation, where dyes are actively transported into microbial cells and subsequently subjected to intracellular degradation pathways, often in-volving specific enzymes and cofactors [15]. Together, these mechanisms contribute significantly to reducing dye concentrations in contaminated environments.

4. Factors Influencing Bacterial Dye Degradation

The efficiency of bacterial dye degradation is strongly influenced by both physicochemical and biological factors [39]. Among these, pH and temperature play a crucial role, with optimal degradation typically observed within a pH range of 6.5–8.0 and temperatures between 30–40 °C [4,17]. Oxygen availability is another key determinant, as azo bond cleavage generally occurs under anaerobic conditions, while complete mineralization of the dye molecules often requires subsequent aerobic steps [6,11]. The presence of carbon and nitrogen sources, such as glucose and peptone, enhances microbial activity by providing additional energy and promoting electron transfer during dye reduction [14,17].

Table 3. Factors influencing bacterial dye degradation

Factor	Optimum/Effect	Impact	Reference(s)
pH	6.5–8.0	Enzyme stability, azoreductase activity	[4,17]
Temperature	30–40 °C (mesophiles); 55 °C max	Enhances metabolic rate, extreme values denature	[19,39]
Oxygen	Anaerobic → azo cleavage; Aerobic → mineralization	Complete degradation via sequential phases	[6,11]
Carbon source	Glucose, sucrose, acetate	Provides NADH for reductases	[14,17]
Nitrogen source	Yeast extract, peptone	Promotes biomass and enzyme synthesis	[13,17]
Dye concentration	Optimal 50–200 mg/L; inhibitory >500	High levels cause oxidative stress	[7,2]
Salinity & metals	<5% salinity optimal; halophiles survive up to 10%	Salts/metals inhibit unless tolerant strains used	[3,40]

However, excessively high dye concentrations, especially above 500 mg/L, can be inhibitory to bacterial growth and enzymatic activity [7,2]. Furthermore, the presence of heavy metals and high salinity in textile effluents exerts additional stress on microorganisms, limiting degradation

efficiency in most species. Notably, halotolerant and metal-resistant bacteria are often better adapted to persist and function under such extreme conditions [3,40].

5. Technological Advances in Bacterial Bioremediation

Although laboratory-scale systems for bacterial dye degradation often show promising results, their performance tends to decline when applied to complex industrial effluents. To address this limitation, several technological innovations have been developed to enhance efficiency and stability. One approach involves the use of immobilized cells, where bacteria are entrapped in carriers such as alginate beads or biochar, thereby increasing their reusability and tolerance to toxic compounds [3,12].

Similarly, biofilm-based systems, including Moving Bed Biofilm Reactors (MBBR) and Fluidized Bed Reactors (FBR), provide enhanced resilience and adaptability com-pared to planktonic cultures [2,19]. Advances in nanobiotechnology have also contributed significantly, as nanoparticles can accelerate electron transfer processes and improve the catalytic activity of dye-degrading enzymes [41]. Furthermore, the integration of omics tools—such as genomics, proteomics, and metabolomics—has facilitated the discovery of novel biodegradation pathways and the identification of key functional genes [10,16].

More recently, synthetic biology approaches, including CRISPR-based genetic engineering, have been employed to construct bacterial strains with multi-enzyme activities tailored for efficient and targeted dye degradation [18,19]. Together, these technological advances provide a strong foundation for bridging the gap between laboratory research and real-world industrial applications.

Table 4. Technological approaches for bacterial dye degradation

Approach	Advantages	Limitations	References
Immobilized cells	Stability, reuse, toxicity resistance	Mass transfer issues, carrier costs	[3,12]
Biofilm reactors	Stress tolerance, enzyme secretion, synergistic consortia	Risk of biofilm clogging, aeration control needed	[2,19]
Nanobiotechnology	Accelerated degradation, synergistic photocatalysis	Toxicity, recovery costs	[41]
Omics approaches	Identify degradative genes, pathways	High cost, bioinformatics requirement	[10,16]
Synthetic biology	Recombinant strains, multi-enzyme pathways	Biosafety, regulatory barriers	[18,19]

6. Case Studies of Bacterial Dye Degradation

Both laboratory-scale and pilot-scale studies conducted worldwide highlight the remarkable versatility of bacteria in degrading a wide range of dyes under diverse environmental conditions [42].

6.1 Laboratory Studies

Controlled laboratory experiments have provided valuable insights into the efficiency of individual strains and consortia in dye degradation. For instance, Pseudomonas putida achieved nearly 90% removal of Reactive Black 5 within 48 hours under microaerophilic conditions [43]. Similarly, Bacillus subtilis demonstrated 95% degradation of Malachite Green at neutral pH (7.0) and an optimum temperature of 35 °C [44]. Mixed bacterial systems have shown even greater efficiency, as illustrated by a consortium of *Enterobacter* and *Klebsiella* that degraded Congo Red with 98% efficiency, indicating the advantages of synergistic microbial interactions [45].

Table 5. Technological approaches for bacterial dye degradation

Bacterial/ Consortium	Dye Degraded	Efficiency/ Conditions	Ref.
Pseudomonas putida	Reactive Black 5	90% in 48 h (microaerophilic)	[43]
Bacillus subtilis	Malachite Green	95% removal at pH 7, 35 °C	[44]
***Enterobacter* + *Klebsiella* (cons.)**	Congo Red	98% decolorization in batch	[45]
Bacterial consortium (India)	Mixed azo/reactive dyes	>85% removal in pilot-scale biofilm reactor	[46]
***Pseudomonas stutzeri* (immobilized)**	Anthraquinone dyes	80–90% removal over multiple cycles (China)	[47]
Halotolerant consortium (Egypt)	Reactive + Disperse dyes	92% removal in saline wastewater	[48]
Xenophilus azovorans	Sulfonated azo dyes	Complete mineralization (Switzerland)	[49]

6.2 Pilot-Scale Studies

Pilot-scale applications provide a bridge between laboratory results and industrial implementation. In Tiruppur, India, a Moving Bed Biofilm Reactor (MBBR) successfully achieved more than 85% decolorization of actual textile effluents [46]. In China, immobilized *Pseudomonas stutzeri* systems effectively treated anthraquinone dyes over multiple operational cycles, demonstrating stability and reusability [47]. Similarly, in Egypt, halotolerant bacterial consortia efficiently degraded reactive and disperse dyes under saline wastewater conditions, underscoring the adaptability of extremophilic microbes to challenging effluent compositions [48].

6.3 International Reports

Beyond Asia and Africa, international studies have further confirmed the global potential of bacterial bioremediation. In Switzerland, *Xenophilus azovorans* successfully mineralized sulfonated azo dyes [49], while in Brazil, *Rhodococcus erythropolis* was reported to degrade anthraquinone dyes effectively [50]. In the United States, a bacterial consortium completely removed Remazol Brilliant Blue R along with its toxic aromatic amine byproducts, highlighting the potential of multi-strain systems for complete mineralization [51].

7. Challenges and Limitations

Despite numerous laboratory and pilot-scale successes, several challenges continue to restrict the large-scale industrial adoption of bacterial dye bioremediation [52–55]. One major issue is the formation of toxic intermediates, particularly aromatic amines generated during azo dye cleavage, which are often mutagenic and carcinogenic. Achieving complete mineralization of these intermediates usually re-quires integrated anaerobic–aerobic treatment steps [56,57]. Another limitation arises during scale-up, as laboratory optimized systems often fail when exposed to highly variable effluent conditions such as fluctuating pH, elevated salinity, and the presence of heavy metals. Moreover, continuous flow bioreactors frequently suffer from the washout of free bacterial cells, reducing process efficiency [58–60]. The instability of microbial communities in mixed consortia poses an additional barrier, since interspecies competition may reduce overall degradation efficiency, although synthetic consortia designed with complementary metabolic pathways offer better stability and resilience [61,62]. Eco-nomic factors also remain a concern, as the requirement for carbon and nitrogen supplementation or the use of im-mobilization carriers increases operational costs [63,64]. Finally, biosafety concerns associated with genetically engineered strains pose regulatory challenges, as they carry potential risks of horizontal gene transfer and unintended ecological impacts, necessitating strict monitoring and containment strategies [65].

Table 6. Challenges and possible solutions in bacterial dye bioremediation

Challenge	Description	Possible Solutions	Ref.
Toxic intermediates	Aromatic amines toxic/mutagenic	Sequential anaerobic–aerobic; engineered consortia	[56,57]
Scale-up issues	Poor stability in industrial effluents	Immobilized cells; pilot optimization	[58,60]
Microbial competition	Non-degraders dominate consortia	Selective enrichment; synthetic consortia	[61,62]
Cost of supplementation	Glucose, yeast extract, carriers costly	Low-cost substrates (molasses, agri-waste)	[63,64]
Heavy metals/salinity stress	Toxicity of Cr, Pb, Na_2SO_4, etc.	Use halotolerant, metal-resistant bacteria	[59]
GMO biosafety	Risk of gene transfer, ecological harm	Kill-switch circuits, contained bioreactors	[65]

8. Future Prospects

Emerging technologies and interdisciplinary approaches are expected to shape the next generation of bacterial dye bioremediation. Omics-guided strain discovery, particularly through metagenomics, enables the identification of novel and unculturable microorganisms with potent dye-degrading capabilities [66,67]. Advances in synthetic biology, such as CRISPR-based engineering, allow the construction of bacterial strains equipped with multi-enzyme systems tailored for efficient and targeted dye degradation [68,69]. Nanobiotechnology offers another promising avenue, where nano-bio hybrid systems enhance electron transfer and provide greater stability, thereby accelerating dye removal processes [70–72]. In addition, artificial intelligence tools, including machine learning models, are increasingly being applied to predict degradation kinetics and optimize reactor design [73]. From a sustainability perspective, integrating dye bioremediation into the circular bioeconomy could enable the conversion of textile effluents into value-added products such as pigments, bioenergy, and bio-plastics [74,75]. Finally, policy integration, involving stricter environmental

regulations, industry collaborations, and public–private partnerships, will be essential for large-scale implementation and long-term success [76,77].

9. Conclusion

Bacterial dye bioremediation represents a sustainable and eco-friendly alternative to conventional chemical treatments. Diverse bacterial genera, including Pseudomonas, Bacillus, Enterobacter, and Acinetobacter, have been shown to effectively degrade synthetic dyes through enzymatic mechanisms involving azoreductases, laccases, and peroxidases, complemented by passive strategies such as biosorption and bioaccumulation. Technological advances, including immobilized cells, biofilm-based reactors, nanobiotechnology, and omics-driven approaches, have further improved degradation efficiency under real effluent conditions. Case studies from laboratory and pilot-scale experiments across different regions highlight the practical feasibility of these methods. Nevertheless, significant challenges remain, particularly in achieving complete mineralization of toxic intermediates, stabilizing microbial communities, reducing economic costs, and addressing biosafety concerns associated with genetically engineered strains. Looking ahead, the integration of omics, artificial intelligence, nanotechnology, and circular economy principles has the potential to transform bacterial dye bioremediation into a scalable, cost-effective, and mainstream industrial solution, thereby contributing to ecosystem protection and improved human health.

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