



REVIEW ARTICLE

Breaking the colour barrier: Role of extremophiles in azo dye degradation

Shivani Mehra¹, Priya Chaudhary², Kartik Uniyal³, Neha¹ & Shikha Thakur^{1*}

¹Department of Biotechnology, School of Applied and Life Sciences, Uttarakhand University, Dehradun 248 007, Uttarakhand, India

²Centre for Herbal Pharmacology and Environmental Sustainability, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam 603 103, Tamil Nadu, India

³Department of Biochemistry and Biotechnology, Sardar Bhagwan Singh University, Dehradun 248 161, Uttarakhand, India

*Correspondence email - patho.shikha@gmail.com

Received: 26 November 2026; Accepted: 25 June 2026; Available online: Version 1.0: 31 July 2026

Cite this article: Shivani M, Priya C, Kartik U, Neha, Shikha T. Breaking the colour barrier: Role of extremophiles in azo dye degradation. Plant Science Today. 2026; 13(sp4): 1-12. <https://doi.org/10.14719/pst.12941>

Abstract

Effluents released from textile industries are a major source of environmental pollution containing largest and most extensively used category of synthetic azo dyes that are widely utilised in multiple industries and have limitations to the conventional physico-chemical treatments. Bioremediation is green remediation approach that involves microorganisms or their enzymes to degrade and detoxify the pollutants from the environment. Extremophiles that thrive at extreme environmental conditions such as hot water springs have the efficiency to decolorise and detoxify the azo dyes textile wastewater. The quantitative analysis show that extremophiles achieve more than 85–95 % decolorisation of different azo dye in a short retention time at high temperature and pH, with higher efficiency and degradation rate than mesophiles. The mechanism includes reductive cleavage of azo bonds, followed by mineralisation and co-metabolism, with the help of extremozymes such as azoreductase, laccase and peroxidase. Enzymes are integrated with nano-materials forming a nano-biocatalytic platform that enhance dye degradation removal efficiency. The current study highlights the potential and application of extremophilic bacteria as a sustainable bioresource in the remediation of azo dyes and places them at the centre of new generation wastewater treatment.

Keywords: biodegradation; bioremediation; extremozymes; nanomaterials; nano-biocatalysis

Introduction

The textile industries are major contributors of the industrial pollution due to the discharge of effluent that contains complex and persistent xenobiotic compounds (1). Since, the textile wastewater contains a higher concentration of organic pollutants, dye pigments, salts, surfactants and heavy metals which eventually leads to a high chemical and biological oxygen demand and overall toxicity (2). Among these, synthetic azo dyes are particularly hazardous due to their structural complexity, stability and high resistance to degradation (3). These synthetic dyes when discharged in the water bodies reduces light penetration, deplete dissolved oxygen and may transform into toxic or carcinogenic aromatic amines, leading to long-term ecological and toxicological impacts (4–6).

Conventional treatment methods such as coagulation, flocculation, adsorption, oxidation and membrane filtration techniques are widely used but most of them are cost-effective, energy demanding and produce toxic sludge and often fail to achieve complete mineralisation leading to secondary pollution (7). Biological strategies have emerged as eco-friendly and low-cost alternatives for treating dye-contaminated effluent due to their ability to degrade under harsh environmental conditions (8). The extreme physico-chemical environment such as high salinity, alkalinity, temperature and presence of some inhibitory

compounds in the textile wastewater restricts the use of mesophilic microorganisms in industrial-scale treatment (9). Whereas extremophilic microorganisms are adapted to survive and grow under extreme harsh environmental conditions such as hot water spring, saline habitats and alkaline ecosystem offering a promising solution. These includes halophiles, acidophiles, alkaliphiles, psychrophiles, thermophiles and radiophiles (10). They produce enzymes such as azoreductase, laccase, lignin peroxidase and manganese peroxidase that transform dyes and metabolise them into less toxic intermediates or completely mineralise them into water (11). They can be used in large bioreactors due to their stability under extreme conditions, solvent and metal-resistant nature (12).

Recent studies have demonstrated that extremophiles have the ability of decolourise the dyes containing wastewater. Thermophilic *Anoxybacillus rupiensis* shows the high efficiency of decolorisation at approximately 60–65 °C (13), while *Geobacillus* spp. and *Thermus thermophilus* produce thermostable enzymes for high-temperature degradation (14). Alkaliphilic bacteria such as *Bacillus alcalophilus* are effective degraders of dyes at pH 9–11 (15,16).

The enhanced activity of extremophiles is attributed to extremozymes with high structural, catalytic and thermal stability facilitating azo bond reduction and subsequent oxidation (5).

Integration with nanomaterials has resulted in the development of nano-biocatalytic systems that enhance the degradation efficiency through high surface area, efficient immobilisation of enzymes and facilitation of electron transfer mechanisms (17).

Methodologically, these studies involve the isolation from extreme environments (hot springs, salt lakes, alkaline environments), enrichment and screening of dye-containing media, spectrophotometric analysis of decolourisation and enzyme assays (18). Advanced approaches include the immobilisation of enzymes, microbial consortia and nano-supported biocatalysts to enhance stability, reusability and scale-up of the decolourisation process (17). This review critically aims to evaluate the role of extremophiles in azo dye biodegradation, focusing on enzymatic mechanisms, nano-biocatalysis and their potential applications in efficient, scalable and sustainable wastewater treatment.

Structure of azo dyes and its effects on degradation

The most common type of synthetic colourant used in the manufacture of textiles, food, leather and cosmetic industries is the azo dyes, which constitute approximately 60–70 % of all the dyes that are produced globally (19). Chemically, they are characterised by the presence one or more azo bonds -N=N- that are connected to the aromatic rings of benzene or naphthalene. These conjugated complexes give azo dyes their vibrant colour and exceptional chemical stability, making them industrially useful. Based on origin, structure and application, there are various dyes such as basic, acidic, reactive, direct, azo, diazo and mordant dyes, as shown in Fig. 1.

The effectiveness of a wide range of enzyme-mediated methods for azo dye degradation primarily relies on the structural properties of dyes. The asymmetric structures or multiple substituents that induce uniformly were reduced with lower reactivity, but the symmetrical electron-distributed azo bonds are better reduced (20). The oxidation of phenolic and aromatic amine intermediates can be catalysed by the laccases and peroxidases, which act in aerobic conditions. The cleavage of the ring structure can, in most cases, yield simple organic acids. In biological treatment systems, the complete mineralisation of the total dye requires the interaction of reductive and oxidative enzymes under various redox conditions.

The relationship between the structure and the mechanism is important not only for optimising the bioremediation strategies but also to understand the design of the dyes that are more environmental friendly. Biodegradability indicators can be correlated to structural parameters such as molecular weight, electron density and the nature of substituents, which provides a predictive framework to evaluate innovative dye formulations. The fact that the electron-withdrawing substituents hinder the biodegradation process implies that the dyes that have a higher number of electron-withdrawing groups can be designed to enhance the microbial breakdown more readily by microorganisms without loss of colour. Moreover, by changing the structure of dyes to increase their accessibility by microbes, such as they host organisms that are capable of surviving in those conditions that were once considered uninhabitable (19).

Ecological and diversity of hot springs extremophiles

Hot springs are dynamic ecological niches with steep

physicochemical gradients such as temperature, pH, salinity and redox potential, which strongly influence microbial diversity and metabolic functions. These parameters not only determine the distribution of the extremophiles, but also directly regulate the enzymatic activity of the extremophiles in the biotechnological application like degradation of azo dyes (21, 22). Thermophiles and hyperthermophiles genera such as *Thermus*, *Geobacillus*, *Anoxybacillus*, *Aquifex* and *Sulfolobus* are highly specialised in their metabolic pathways and have a wide range of applications (23).

However, the effectiveness of the dye degradation by these extremophiles is regulated by several enhancing and limiting factors (24). The most effective factors that enhance efficiency include the optimal high temperature (50–70 °C) and alkaline or moderately acidic pH (depending on the species), adequate availability of electron donors (e.g., NADH), presence of co-factors and stable enzyme structure such as thermostable laccase and azoreductase. Salinity tolerance and intracellular protective systems (e.g., compatible solutes such as trehalose and ectoine) are also useful in enhancing enzyme stability and extending the catalytic activity of enzymes in industrial environment (25). Also, the factors that reduce efficiency include extreme deviation from optimal pH, temperature and high dye concentration, resulting in substrate inhibition, toxic intermediates formed during azo bond cleavage, lack of sufficient nutrition availability and the presence of inhibitory metal ions or contaminants in industrial effluents. Moreover, the enzymatic activity may be blocked by a lack of oxygen and the existence of harsh redox conditions, especially those that lead to oxidative degradation. Studies from Indian hot springs discussed in Fig. 2 such as Suraj Kund and Manikaran demonstrate that geochemical parameters such as temperature and concentration of sulphate are key drivers of the microbial activity and degradation potential (26). As an example, *Anoxybacillus rupiensis* has shown over 90 % of decolorisation efficiency under the optimised conditions (65 °C, pH 9), highlighting the significance of controlled environmental parameters (27). Likewise, thermal sources of *Geobacillus* sp. and *Bacillus licheniformis* also develop thermostable laccases and azoreductase that can degrade aromatic pollutants at high temperature and salinity (28, 29).

The analyses of the study (Table 1) demonstrate that hot-spring microorganisms possess incredible metabolic and enzymatic abilities and that many of them possess more than one extreme characteristic: heat tolerance, resistance to alkalinity and saline tolerance. Therefore, the general efficiency of the degradation process of azo dyes depends on the interaction between environmental factors and microbial physiology. These influencing factors are important in optimising large scale bioremediation processes using extremophiles.

Enhancing dye degradation through extremozyme properties

The microbial degradation of synthetic dyes and particularly azo dyes, is primarily driven by enzyme-mediated cleavage of chromophore bonds. The enzymes such as azoreductase, laccase and peroxidase are important for initiating and completing decolorisation process. Extremophiles, which are adapted to high temperature, salinity and pH are useful sources of robust and thermostable enzymes that are able to operate under harsh conditions of textile effluents. Development of efficient and

Table 1. Extremophilic sources and biocatalytic potential of extremophilic sources on azo dye degradation

Location	Microorganism	Environmental Conditions	Enzymes mechanisms	Applications	References
Yellowstone National Park, USA	<i>Thermus aquaticus</i> , <i>Synechococcus</i> sp.	70–90 °C, neutral pH	Thermostable oxidoreductases, azoreductase	These thermophilic strains are the first to characterised that can be used as a model to examine thermostability and redox potential of enzymes. <i>T. aquaticus</i> enzymes, like oxidoreductases, are stable at extremes of heat and which has facilitated the use of enzyme engineering in bioremediation.	(21)
Suraj Kund and Manikaran Hot Spring, India	<i>Anoxybacillus</i> sp., <i>Geobacillus</i> sp., <i>Bacillus</i> sp.	60–85 °C, alkaline pH 8–10, abundant in sulphates and carbonates	Laccase, peroxidase, azoreductase	<i>Thermophilic Anoxybacillus</i> and <i>Geobacillus</i> found in Indian geothermal springs have exceptional tolerance to synthetic dyes and high metal concentrations. - Their enzyme complexes indicate more than 90 % decolorisation of reactive dyes under alkali conditions.	(22, 23)
Ethiopian soda lakes (e.g., Lake Shala)	Haloalkaliphilic consortia with <i>Halomonas</i> sp. and <i>Alkalibacillus</i> sp..	55–70 °C, pH 10–11, high salt (up to 25 % NaCl)	Multi-enzyme complex, e.g., azoreductase and oxidases	Ethiopian soda lakes' extremophiles are active in very alkaline, hypersaline environments common in dye effluents.	(30)
Tengchong hot springs, China	<i>herma thermophilus</i> , <i>Thermocrinis ruber</i> ,	80 °C, neutral pH geothermal runoff channels	Azoreductase and thermostable oxidoreductase	- The isolation of <i>T. thermophilus</i> with a high level of azoreductase activity offers a model system of reductive cleavage of complex dye molecules at high temperature. - Enzyme assays reveal that the rate of reduction is increased with cofactor loss, which is encouraging to apply to high temperature bioreactors de-polluting synthetic dye waste water.	(26)
Pamukkale and Central Anatolia Springs, Turkey	<i>Anoxybacillus ayderensis</i> SK3-4	60 °C, pH 9, carbonate -enriched water	Bacterial laccase and peroxidase	<i>A. ayderensis</i> SK3-4 has strong oxidation of anthraquinone and azo dyes by laccase. Its enzyme system is stable during long-term exposure to alkaline pH and high salt, implying its possible application in continuous bioreactors.	(31)
Icelandic geothermal fields	<i>Hermoproteus tenax</i> , <i>Aquifex aeolicus</i>	85–95 °C, microaerophilic pH 6–8	Hydrogenase and oxidoreductase complexes cross-reactively to azo dye intermediates	- Hyperthermophiles degrade aromatic hydrocarbons and similar xenobiotics in an anaerobic environment. - Their high temperature hydrogenase systems aid in the transfer of electrons needed to cleave reductive dyes in reactors forced to limit oxygen.	(29)
Iranian and Central Indian hot springs	<i>Bacillus licheniformis</i> , <i>Anoxybacillus kamchatkensis</i> , mixed consortia	60–75 °C, pH 8–9, silica -rich deposits	Laccase, peroxidase, azoreductase	- The thermophilic consortia area of the geothermal system shows co-metabolism of a range of azo dyes through synergistic enzyme cascades. - Their metabolic pathways guarantee both reduction and oxidation processes taking place at the same time, allowing total mineralisation.	(28, 32)
Yellowstone Alkaline Pools (USA)	<i>Thermus brockianus</i> , <i>Thermus scotoductus</i>	75 °C, pH 9, alkaline siliceous mats	Thermomax oxidoreductases, azoreductases	Their wide specificity in substrate and natural thermostability have seen them used as reference organisms in the design of industrial enzymes.	(33)

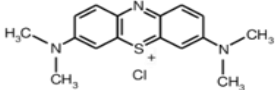
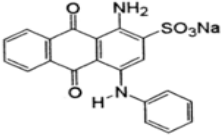
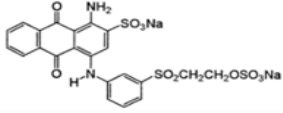
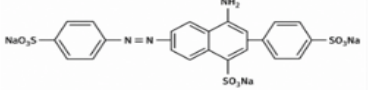
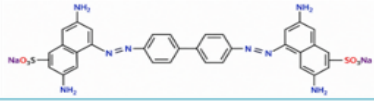
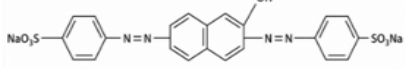
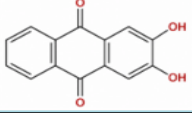
Types of Dye	Structure	Features	Application
1. Basic Dyes (Cationic Dyes) Example: Methylene Blue, Crystal Violet		- Water soluble - Good affinity for negatively charged fibers - Bright, vivid shades	Acrylic fibers, paper, leather, biological staining
2. Acidic Dyes (Anionic Dyes) Example: Acid Blue 25, Acid Red 18		- Water soluble - Good affinity for protein fibers - Leveling dyeing	Wool, silk, nylon, leather, food, paper
3. Reactive Dyes Example: Reactive Blue 19, Reactive Red 195		- Contain reactive groups - Form covalent bond with fiber (cellulose) - Excellent wash fastness - Bright shades	Cotton, viscose, linen, printing, high fastness textiles
4. Direct Dyes Example: Direct Blue 71, Direct Red 81		- Applied directly to cellulose in presence of salt - Easy to use, economical - Moderate fastness	Cotton, viscose, bedsheets, garments, curtains
5. Azo Dyes Example: Congo Red, Orange II		- Contain azo group (-N=N-) - Wide range of colors - Used in many fibers - Good bright shades	Textile printing, paper, leather, color lakes
6. Diazo Dyes Examples: Fast Red B, Fast Scarlet G		- Formed by diazotization of aromatic amines - Good bright shades	Textile printing, paper, leather, color clay
7. Mordant Dyes Example: Alizarin, Madder (purpurin)		- Require mordant (metal salts) to fix on fiber - Excellent light and wash fastness	Wool, silk, cotton historical painting textiles, carpets

Fig. 1. Classification of dyes.

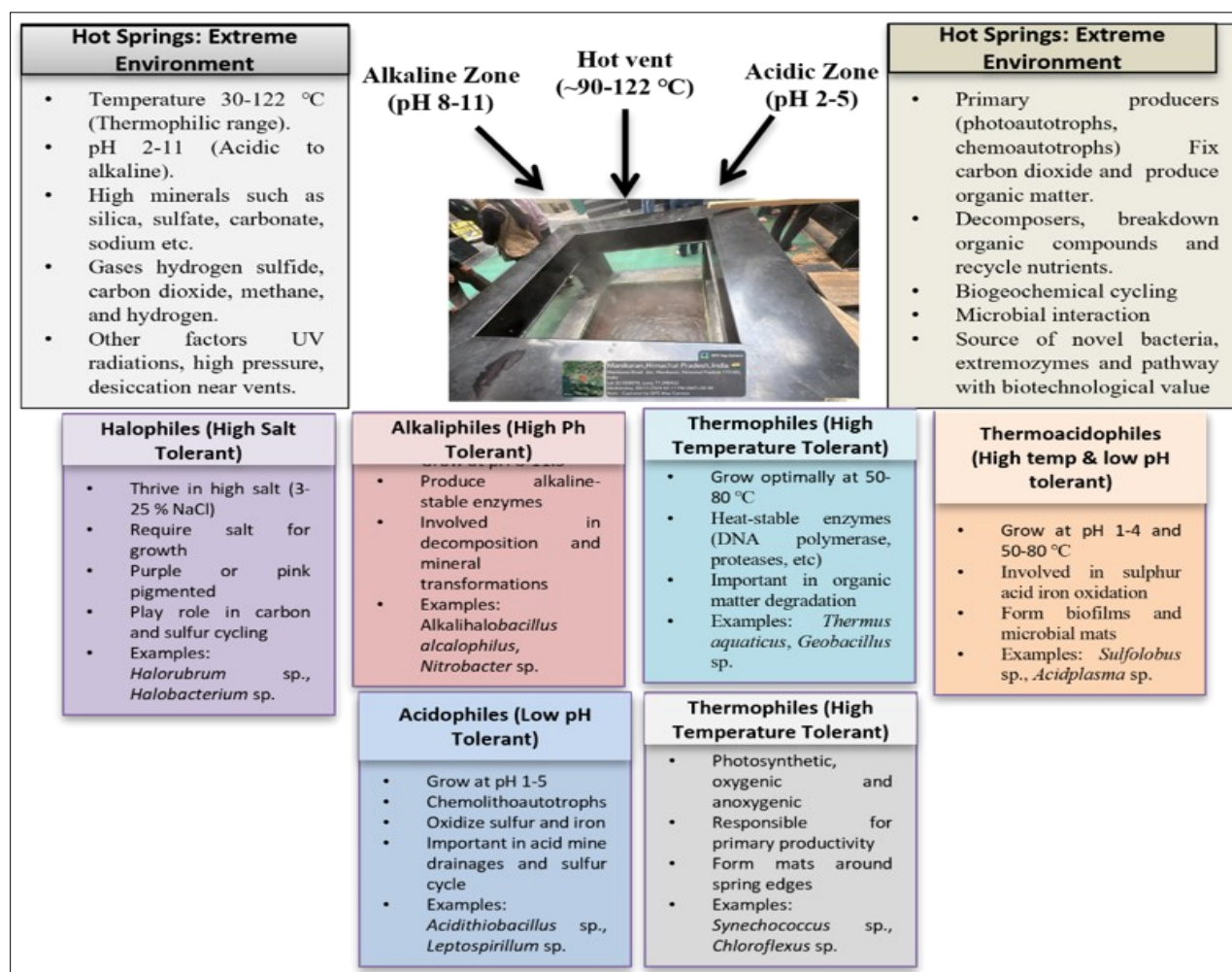


Fig. 2. Diversity of extremophiles in hot spring.

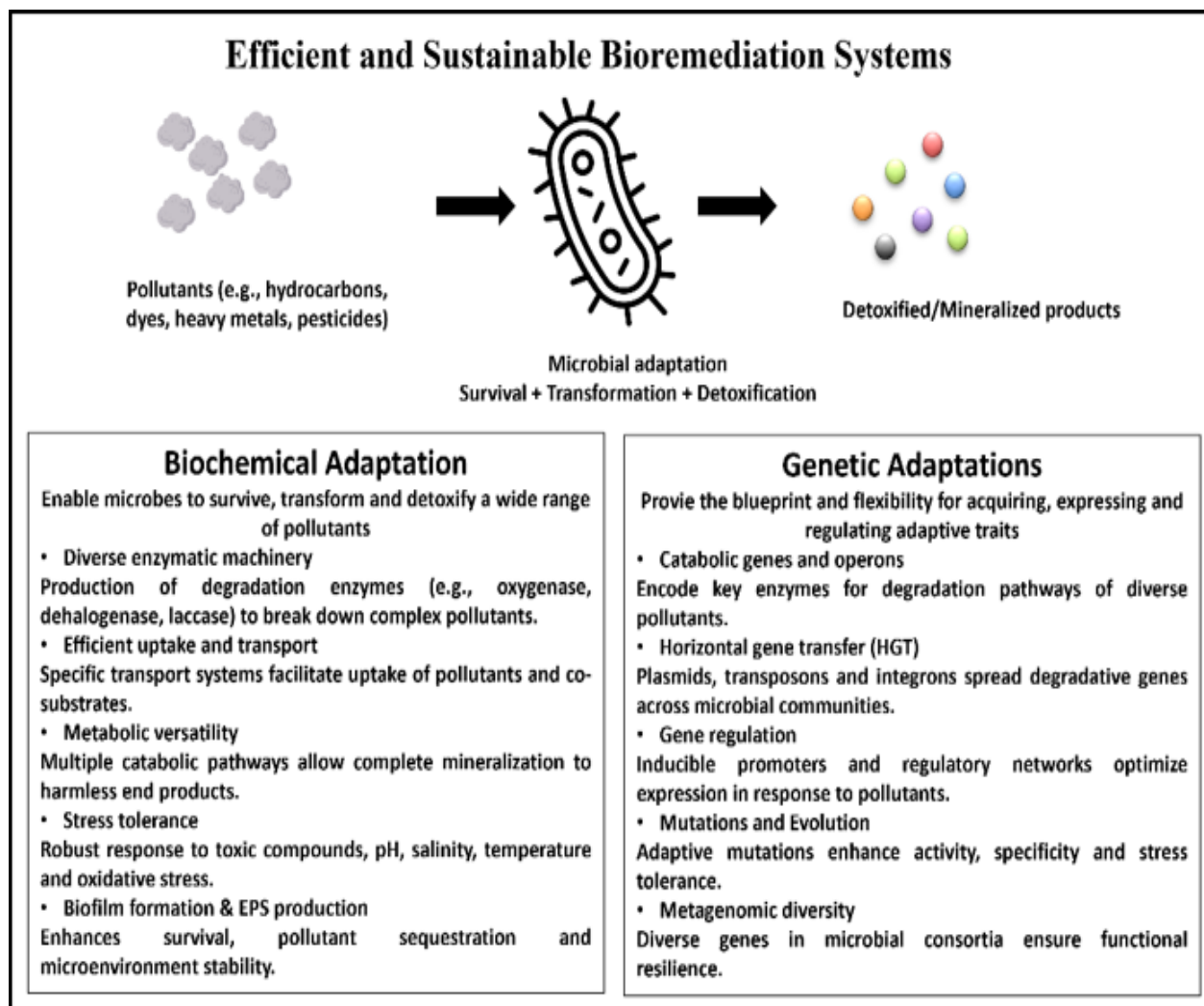


Fig. 3. Biochemical and genetic adaptations driving efficient and sustainable bioremediation.

sustainable bioremediation systems are based on their biochemical and genetic adaptations, as shown in Fig. 3.

Mechanically, azo dye degradation occurs through a coordinated enzymatic pathway. Initially azoreductase (flavin-dependent oxidoreductases) catalyse the reductive cleavage of azo bond (-N=N-) using NADH/NADPH as electron donors and producing colourless aromatic amines. These intermediates are

then oxidised by the laccase and peroxidase into less toxic compounds, which are further mineralised into more simple end products such as CO₂ and H₂O through downstream metabolic pathways (26, 33). This sequential reductive-oxidative mechanism ensures effective decolourisation and detoxication. Extremophilic and engineered enzymes, primarily azoreductase, laccase and peroxidase, highlight their source microorganisms and

Table 2. Extremophilic enzymes used in azo dye biodegradation and their properties

Type of enzyme	Microorganism	Dye type	Activity or stability	References
Azoreductase	<i>Geobacillus sp.</i>	Congo Red, Methyl Orange	•The enzyme shows that it can decolorise more than 85 % in 8 hr and that the enzyme has a long period of catalysis at industrial conditions.	(34)
Laccase	<i>Anoxybacillus ayderensis</i>	Reactive Blue 19, Direct Red 80	•With the capacity to decolorize Reactive Blue 19 in 12 hr, it has great activity even after being exposed to heavy metal ions. •The multi-copper oxidase structure facilitates the electron transfer and its survival under oxidative pressures.	(35)
Peroxidase	<i>Geobacillus stearothermophilus</i>	Direct Black 22, Reactive Red 120	•The enzyme catalyzes oxidative degradation of high molecular weight compounds under thermophilic and slightly alkaline conditions and possibly degradation of toxic compounds towards less harmful compounds.	(36)
Azoreductase	<i>Thermus thermophilus</i>	Methyl Red, Orange II	•The thermophilic enzyme of interest that can be considered an archetype is the azoreductase of <i>T. thermophilus</i>, which can be used at temperatures close to the boiling water. •It's strong hydrophobic interactions and aurotic and compact fluct.h constructions impart an add-on to its amazing resistance to thermal denaturation	(37)
Laccase	<i>Pleurotus nebrodensis</i>	Methylene Blue, Malachite Green	•Targeted protein engineering has enabled a recombinant mutant of <i>P. nebrodensis</i> laccase to have increased redox potential and substrate range.	(38)

exceptional stability and efficiency in degrading various azo and synthetic dyes under harsh industrial conditions, as discussed in Table 2.

The advantages of using extremozymes is higher than that of mesophilic enzymes due to several factors. They are structurally stable, with enhanced ionic interactions and hydrophobic cores which allow them to remain active at high temperature and extreme pH without denaturation. The cofactor efficiency and the redox versatility, such as the high NADH/NADPH dependence in azoreductase and copper-binding domains in laccase allow them to degrade a wide range of structurally different dyes. Also, extremophilic microorganisms such as *Halomonas* and *Anoxybacillus* are tolerant to high salinity, alkalinity and toxic contaminants and continue to maintain their enzymatic activity under the stress conditions of industrial environment. The immobilisation of the enzymes and protein engineering contribute to durability and reusability, which is evidenced by the engineered bacterial and fungal laccases (39, 40).

Genetically, the use of genetic adaptations such as stress-responsive promoters, codons optimisation and regulation operons allow for efficient expression of enzymes under extreme conditions. The genes of azoreductase and laccase are regulated by transcription factors that are activated under the influence of oxidative or thermal distress, which shows an adaptive gene regulation system (41). The high-performance biocatalysts have expanded by advances in metagenomics that have identified a wide range of novel azoreductase from extreme environment (42). The integration of high efficiency, structural robustness and genetic adaptability makes extremophilic enzymes more desirable candidates for the degradation of azo dyes shown in Fig.

4. They can be immobilised and genetically modified into engineered systems and could provide a sustainable and scalable solution for wastewater treatment.

Role of extremophile-biosynthesised nanoparticles and nanomaterials in azo dye biodegradation

The extremophiles show the capability to synthesise functional nanoparticles (NPs) with advanced physico-chemical characteristics that can enhance the catalytic and adsorption-based degradation of azo dyes. The most frequently used nanoparticles are silver, gold and iron oxides, as they possess a high surface area, controlled reactivity and efficient electron transfer properties which make them highly suitable for the treatment of wastewater. The combination with enzymes and microbial consortia enhances the degree of degradation, stability and reusability, which makes hybrid-nano biosystem a sustainable substitute to the conventional process.

The biosynthesis of metallic nanoparticles is the enzymatic or metabolite-mediated reduction of metal ions such as Ag^+ , Au^{3+} , Fe^{3+} into zero-valent or metal oxide to form stable nanoparticles by biomolecular capping of the biomolecules (43, 44). The extremophiles, especially thermophiles and halophiles, are able to produce more uniform and stable nanoparticles as they are adapted to extreme environment (45). The ability of these NPs to degrade azo dyes are through adsorption, catalytic reduction and electron transfer (46, 47). Nanoparticles composed of iron and copper-based adsorb the dyes through either electrostatic or π - π interactions and catalysed the azo bond cleavage into colorless intermediates further broken down by microbes or enzymes (48, 49). These systems enhance co-metabolic degradation and

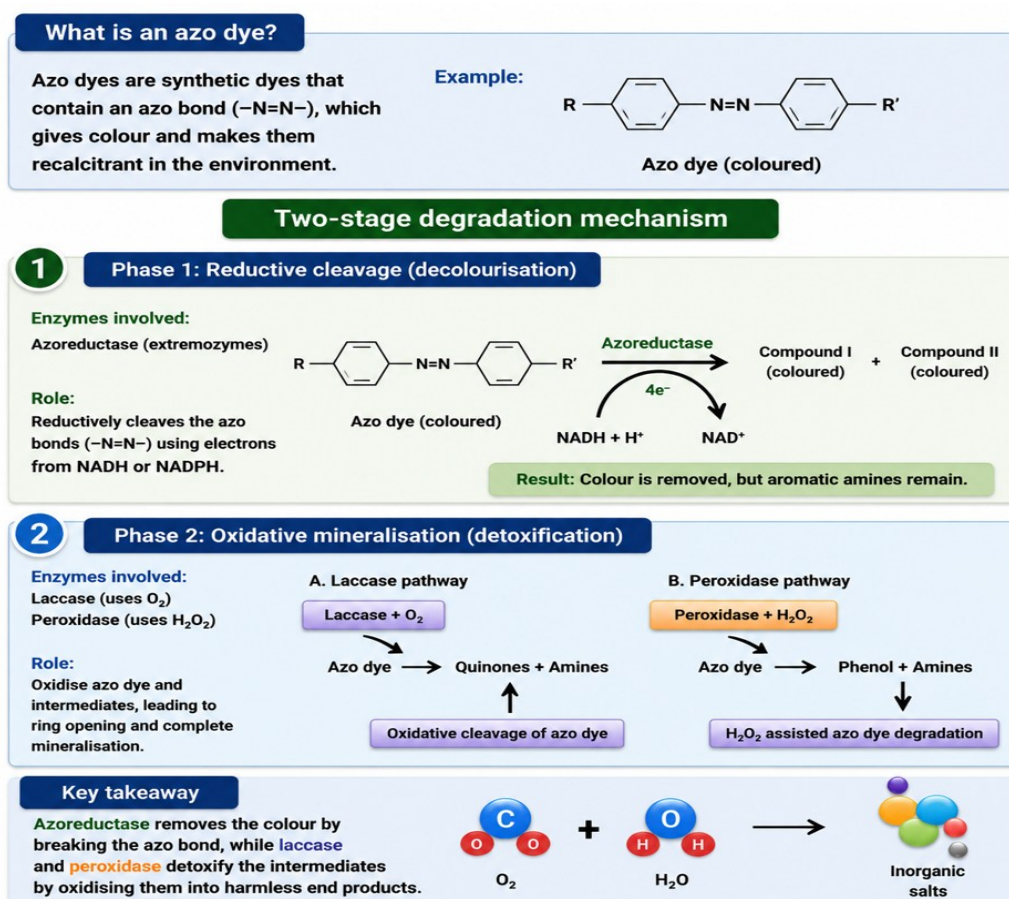


Fig. 4. Mechanism of azo dye degradation by extremozymes.

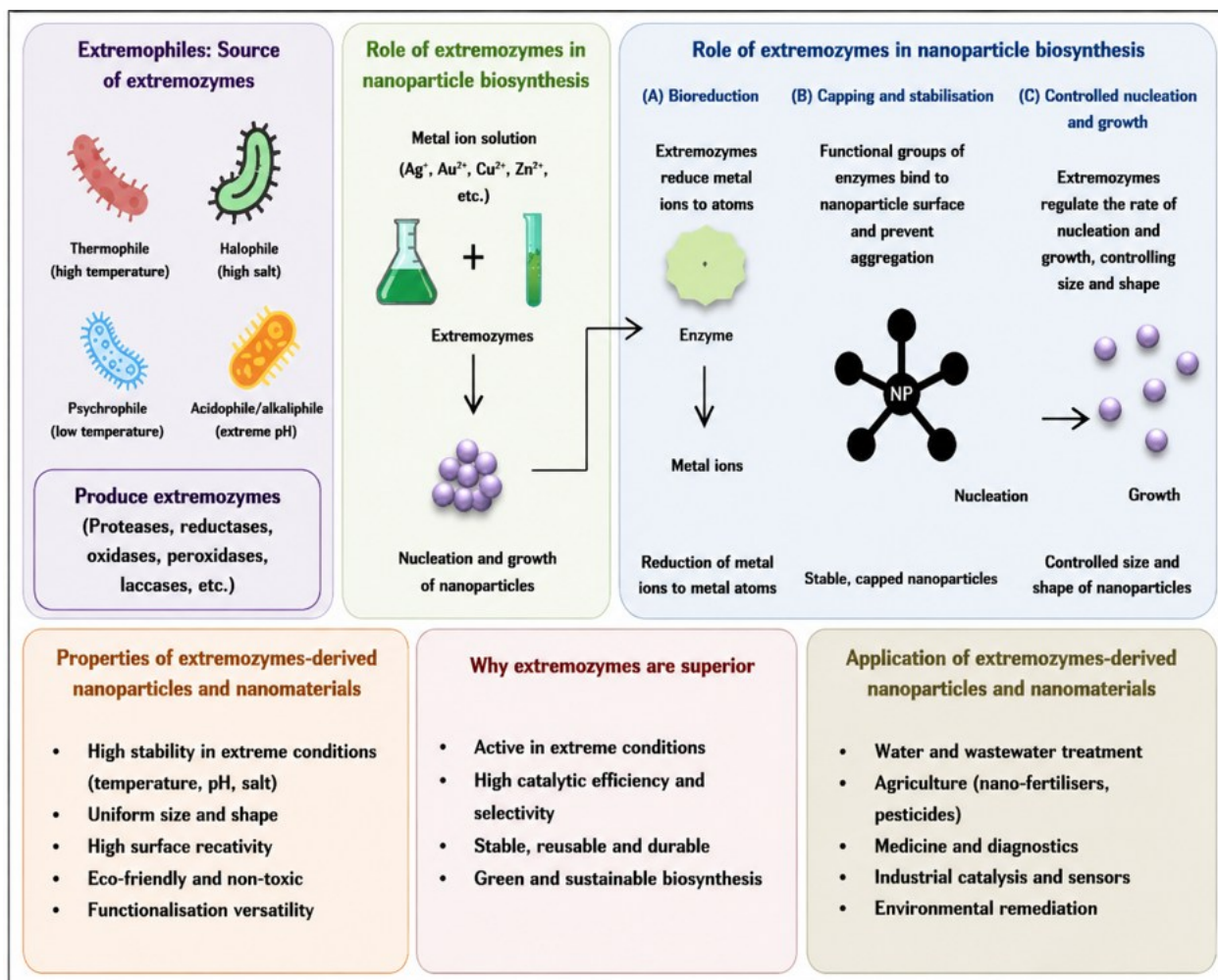


Fig. 5. Mechanistic of the biosynthesis of nanoparticles and nanomaterials under the extreme conditions.

complete mineralisation of dyes and can be scaled and used long-term in industries. The microbial synthesis of bio-nanoparticles and their role in the degradation of azo dyes catalytic reduction, adsorption and nano biocatalysis, is discussed in Fig. 5.

These hybrid systems can allow to reach high degradation rates (> 90 %) and can undergo multiple reuse cycles, which are favourable for industrial applications (50, 51). Compared to the conventional physico-chemical methods the extremophiles-biosynthesized nanoparticles (52, 53) which aligns with green chemistry and the principles of the circular bioeconomy. Biosynthesis of nanoparticles minimises the need of high-energy processes and expensive chemical reducing agents (49, 53). The reusability of immobilised enzymes helps in lowering the operational costs, increasing degradation efficiency, reducing the treatment time and energy input (53). The naturally occurring extremophiles decreases the dependency on expensive synthetic catalysts. The setup costs for the production of nanomaterials can mitigate the long-term advantages such as durability, recyclability and reduced chemical usage which makes the nano-biosystems economical and sustainable.

Biodegradation usage: Innovations and problems

Textile dye biodegradation has reached both laboratory and pilot-scale but not to full scale industrial application. Batch reactors are simple and inexpensive to use in laboratory studies yet incapable of processing continuous industrial effluents (9). Continuous bioreactors (packed-bed, membrane UASB) allow long-term removal of dyes with increased microbial activity and reduced downtimes, but have problems with clogging, biofilm instability and

enzyme inactivation (54, 55).

Magnetic nanoparticles, silica gels, polymer beads or carbon nanotubes are used to immobilise the enzyme to enhance stability and recyclability. Repeated cycles of dyes such as Reactive Black 5 and Congo Red using immobilised laccase systems remove > 90 % of the dye (56). However, mass transfer limits, high costs of support material and enzyme leaching still prevail. Continuous reactors (UASB, trickle-bed) are good at 80–90 % COD removal but are subject to biofilm shedding, hydraulic shock and fluctuating quality of influent. Bioaugmentation is enhanced by mixed microbial consortia and genetically engineered strains that have regulatory and societal limitations (57). Recent development involves thermostable laccase and azoreductase through rational design and directed evolution (58), nano-biocatalytic systems (Fe_3O_4 , TiO_2 , graphene oxide) with a combination of adsorption and redox catalysis and microbial electrochemical systems that provide electrons to enhance reductive cleavage (59). Photo-biocatalytic systems provide complete decolorisation as shown in Fig. 6.

Further developments must be focus on intensifying the process, modular design of reactors and superior way of immobilisation. The most promising current method is immobilised enzyme nanocomposites in continuous flow modes that have been shown to be recyclable, energy efficient and produce minimum sludge.

Future prospects and research directions

The future of azo dye biodegradation is of huge potential by incorporating advanced microbial, molecular and engineering

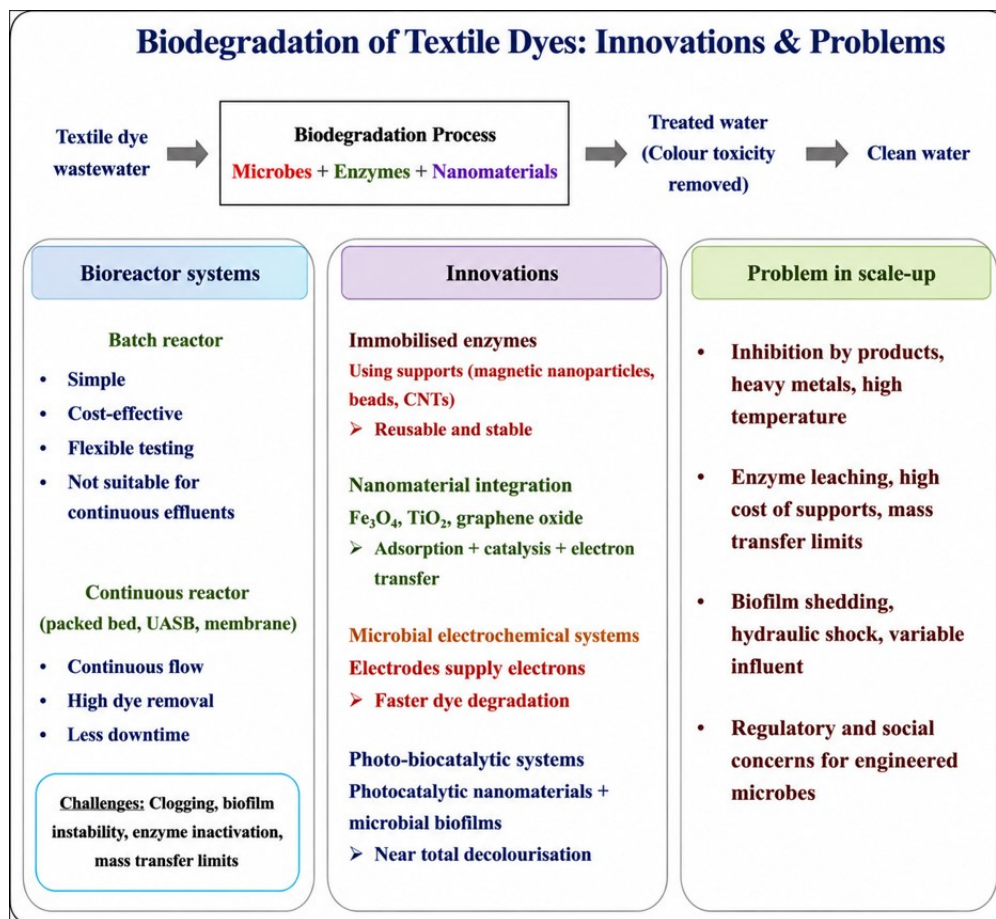


Fig. 6. Biodegradation of textile dyes using microbes, enzymes and nanomaterials.

technologies for the textile wastewater in an efficient, economical and sustainable manner. Although microbial techniques used traditionally have made some gains, they are inconsistent when subjected to diverse industrial conditions and therefore require creative alternatives. Recent studies focus on extremophile biotechnology, omics-driven pathway discovery, bioreactor optimisation, nanoscale analysis and techno-economic evaluation to build next-generation bioengineered systems of treatment (60, 61).

The discovery of extremophilic microorganisms with the potential to operate at high temperature (typically 45–80 °C), salinity and pH (ranging from 4 to 9) provide exclusive enzymatic and metabolic opportunities to dye degradation. Microbial diversity is present as a small proportion of what is recovered in the conventional culturing methods, thus current isolation approaches, which include in situ cultivation chambers, diffusion bioreactors and microfluidic droplet platforms, enable microbes to grow in near natural conditions (61). Millions of simultaneous screenings with small sample volume can now be done on high-throughput microfluidic systems quickly to identify potent dye-degrading strains and test environmental tolerance (62). Automated screening devices also screen microbial behaviour in the industrial environment to the point of improving the identification of effective extremophilic degraders (63).

Omics of degradation can offer molecular information on degradation processes. The presence of gene clusters of multi-heme azoreductase and auxiliary enzymes with high catalytic efficiency has been revealed through genomics, transcriptomics, proteomics and metabolomics (64). Dye-contaminated soil is found to harbour novel oxidoreductases through metagenomic

studies, whereas proteomics and metabolomics follow the detoxification pathways and mineralisation pathways. Such results also inform the enzyme engineering process, now metagenomic data is used to inform the recombinant expression of thermostable laccases and peroxidases and synthetic biology is being used to create optimised electron transfer and cofactor recycling pathways (65, 66). Integration of multi-omics data and machine learning will soon allow prediction of the quantification of the degradation kinetics and microbial consortium design.

Bioreactor configurations should be optimised to be able to translate laboratory success to industry. An MB electrostatic reactor (Anaerobic moving bed biomass reactor) has demonstrated high colour and chemical oxygen demand (COD) removal at stable operation (67) and microbial adaptability to variable dye loads has been demonstrated in long-term upflow anaerobic sludge blanket (UASB) reactors (pilot-scale) (68). Better results are achieved using hybrid reactors, which combine fluidised, packed beds as well as membrane reactors because they follow an anaerobic-aerobic process sequence (69). The hybrid moving bed biofilm reactor-membrane bioreactor (MBBR-MBR) configurations also reduce the amount of fouling and make it possible to recover nutrients (70). For future applications, nanomaterial-based biosensors can be an advantage shown in Fig. 7.

The biosensors and nano-sensors represent a great breakthrough in real-time process monitoring. Biosensors based on optical and electrochemical methods can quickly determine the level of dye and enzyme activity and nanomaterial-based biosensors detect various parameters to control adaptive bioreactors (71, 72). Combining with internet of things (IoT), they offer remote control and safety of operations.

Extremozyme-Integrated Nanomaterial-Based Biosensors For Azo Dye Industries

Advantages

- Enhanced Efficiency
- Improved effectiveness
- Sustainable practices

Components

- Extremozymes
- Nanoparticles

Applications

- Real-time monitoring
- Reduce environmental impact
- Cleaner production methods

Fig. 7. Application of extremozymes-integrated nanomaterial-based biosensors.

Still, economic and environmental impacts are crucial as well. Life-cycle calculations suggest that microbial and nano-based systems are more eco-friendly and energy efficient than other traditional approaches, but might take a longer startup or may be subject to the ecotoxicity of NPs (73). Hybrid microbial-nanomaterial systems have the advantage of a trade-off between strength and selectivity, but they are sustainable to low-cost production and recycling of nanomaterials. The circular economy can be scaled and sustained further by policy support, incentives of the government such as biomass recovery, enzyme reuse etc. (74). The future for the biodegradation of azo dye lies in the interlacing of azo dye discovery with omics, real time monitoring and cost-effective optimisation. Together these innovations will result in smarter, scalable and more eco-friendly treatment systems that will meet the industry needs and ecological priorities.

Conclusion

Extremophiles and their enzymes serve as an efficient and sustainable solution for degradation of azo dyes in harsh industrial conditions. They are able to mineralise the complex dyes efficiently due to their unique mechanisms by azoreductase enzyme which reduces the azo dyes bond and oxidative detoxification. Extremozymes integrated with nanotechnology in the form of nano-biocatalytic systems for enhancing the catalytic efficiency, stability and reusability of extremophiles. These hybrid approaches are cost-effective in the long-term industrial scale as they significantly reduce the toxic environmental impact of azo dyes by using less energy and generating less amount of sludge as compared to conventional methods. Enhancement of the extremophiles-biosynthesised nano particle systems for large scale application are expected with advancements in the omics technology, enzyme engineering and development of bioreactor. Overall, the extremophile-based bio-nanotechnological approaches are a promising pathway towards efficient, scalable and eco-friendly wastewater treatment.

Acknowledgements

The authors express their gratitude for the support and academic environment provided by the Department of Biotechnology, School of Applied and Life Sciences, Uttaranchal University Dehradun Uttarakhand India; the Centre for Herbal Pharmacology and Environmental Sustainability, Chettinad Hospital and

Research Institute, Chettinad Academy of Research and Education Tamil Nadu India; and the Department of Biochemistry and Biotechnology, Sardar Bhagwan Singh University Dehradun Uttarakhand India. Their collective guidance, access to scientific resources and support played a significant role in the planning, writing and completion of this review article.

Authors' contributions

SM, PC, KU, N and ST collectively contributed to the development of this review. SM conceptualised the study and organised the literature. PC assisted in the compilation of scientific data and the editing of the manuscript. KU supported the interpretation of the data and contributed to manuscript editing. N contributed to the critical review of the literature and manuscript revision. ST supervised the overall preparation of the manuscript, critically reviewed the content and ensured the accuracy and coherence of the final version. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

- Khan S, Malik A. Environmental and health effects of textile industry wastewater. In: Environmental Deterioration and Human Health: Natural and Anthropogenic Determinants. Springer; 2013. p. 55–71. https://doi.org/10.1007/978-94-007-7890-0_4
- Tripathi M, Tripathi M, Singh S, Pathak S, Kasaudhan J, Mishra A, Bala S, et al. Recent strategies for the remediation of textile dyes from wastewater: a systematic review. *Toxics*. 2023;11(11):940. <https://doi.org/10.3390/toxics11110940>
- Al-Tohamy R, Ali SS, Li F, Okasha KM, Mahmoud YA-G, Elsamahy T, et al. A critical review on the treatment of dye-containing wastewater: ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. *Ecotoxicol Environ Saf*. 2022;231:113160. <https://doi.org/10.1016/j.ecoenv.2021.113160>
- Alzain H, Kalimugogo V, Hussein K, Karkadan M. A review of environmental impact of azo dyes. *Int J Res Rev*. 2023;10(6):673–89.

- <https://doi.org/10.52403/ijrr.20230682>
5. Gayathri K, Saranraj P, Nayak AK, Kesavardhini K, Lokeshwari B, Cardoso AM. Microbial innovations for sustainable wastewater management: a comprehensive review of azo dye bioremediation. *Sustainability*. 2026;18(6):3041. <https://doi.org/10.3390/su18063041>
 6. Bora N, Joshi DP, Sharma R. Contamination toxicity and remediation of stable dyes and oils in aquatic wastewater systems. *Discov Environ*. 2026;4(1):166. <https://doi.org/10.1007/s44274-026-00680-w>
 7. Kathing C, Saini G. A review of various treatment methods for the removal of dyes from textile effluent. *Recent Prog Mater*. 2022;4(4):1–15. <https://doi.org/10.21926/rpm.2204028>
 8. Jamee R, Siddique R. Biodegradation of synthetic dyes of textile effluent by microorganisms: an environmentally and economically sustainable approach. *Eur J Microbiol Immunol*. 2019;9(4):114–18. <https://doi.org/10.1556/1886.2019.00018>
 9. Rane A, Joshi SJ. Biodecolorization and biodegradation of dyes: a review. *Open Biotechnol J*. 2021;15(1):97–109. <https://doi.org/10.2174/1874070702115010097>
 10. Tekere M, Kalu CM. Extremophiles of polluted environments: mechanisms of surviving extreme pollution settings. *Int J Agric Biosci*. 2026;15(4):1618–31.
 11. Afoma UM, Malik J, Singh S, Mishra AK, Naushad Z, Tomar A, et al. Sustainable solutions for textile dye based water pollution: a comprehensive review of degradation methods and enzymatic mechanisms. *Biomass Convers Biorefin*. 2026;16(4):147. <https://doi.org/10.1007/s13399-025-06984-w>
 12. Mesbah NM. Industrial biotechnology based on enzymes from extreme environments. *Front Bioeng Biotechnol*. 2022;10:870083. <https://doi.org/10.3389/fbioe.2022.870083>
 13. da Rosa DF, Macedo AJ. The genus *Anoxybacillus*: an emerging and versatile source of valuable biotechnological products. *Extremophiles*. 2023;27(3):22. <https://doi.org/10.1007/s00792-023-01305-3>
 14. Guo G, Liu C, Hao J, Tian F, Ding K, Zhang C, et al. Development and characterization of a halo-thermophilic bacterial consortium for decolorization of azo dye. *Chemosphere*. 2021;272:129916. <https://doi.org/10.1016/j.chemosphere.2021.129916>
 15. Sharma J. Decolourization of dyes by *Alcaligenes faecalis* and *Bacillus flexus* isolated from textile effluent [thesis]. 2018.
 16. Sarethy IP, Saxena Y, Kapoor A, Sharma M, Sharma SK, Gupta V, et al. Alkaliphilic bacteria: applications in industrial biotechnology. *J Ind Microbiol Biotechnol*. 2011;38(7):769. <https://doi.org/10.1007/s10295-011-0968-x>
 17. Tadesse M, Liu Y. Recent advances in enzyme immobilization: the role of artificial intelligence, novel nanomaterials and dynamic carrier systems. *Catalysts*. 2025;15(6):571. <https://doi.org/10.3390/catal15060571>
 18. Aneja K, Purohit A, Yadav SK. Metal-resistant mesophilic laccase from *Achromobacter* species: identification, physical characterisation and dye bioremediation. *Appl Biochem Biotechnol*. 2026;1–19. <https://doi.org/10.1007/s12010-025-05495-8>
 19. Pinheiro LRS, Gradissimo DG, Xavier LP, Santos AV. Degradation of azo dyes: bacterial potential for bioremediation. *Sustainability*. 2022;14(3):1510. <https://doi.org/10.3390/su14031510>
 20. Ding J, Huang Z, Zhang D, Qu Y, Zhang S, Zhang C, et al. Rational structural design of aromatic azo photoactive small molecules for biomedical applications. *Chem Soc Rev*. 2025;54(22):10363–96. <https://doi.org/10.1039/D5CS00334B>
 21. Ward DM, Ferris MJ, Nold SC, Bateson MM. A natural view of microbial biodiversity within hot spring cyanobacterial mat communities. *Microbiol Mol Biol Rev*. 1998;62(4):1353–70. <https://doi.org/10.1128/MMBR.62.4.1353-1370.1998>
 22. Soy S, Lakra U, Prakash P, Suravajhala P, Nigam VK, Sharma SR, et al. Exploring microbial diversity in hot springs of Surajkund, India through 16S rRNA analysis and thermozyme characterization from endogenous isolates. *Sci Rep*. 2023;13(1):14221. <https://doi.org/10.1038/s41598-023-41515-5>
 23. Narsing Rao MP, Dong ZY, Luo ZH, Li MM, Liu BB, Guo SX, et al. Physicochemical and microbial diversity analyses of Indian hot springs. *Front Microbiol*. 2021;12:627200. <https://doi.org/10.3389/fmicb.2021.627200>
 24. Puente-Sanchez F, Chavarria M. Diversity of extremophiles in time and space. *Microorganisms*. 2021;9(12):2472. <https://doi.org/10.3390/microorganisms9122472>
 25. Ditiawati P, Yohandini H, Madayanti F. Microbial diversity of acidic hot spring (Kawah Hujan B) in geothermal field of Kamojang area, West Java, Indonesia. *Open Microbiol J*. 2009;3:58. <https://doi.org/10.2174/1874285800903010058>
 26. Qiu H, Shen F, Yin A, Liu J, Wu B, Li Y, et al. Biodegradation and detoxification of azo dyes by halophilic/halotolerant microflora isolated from the salt fields of Tibet Autonomous Region, China. *Front Microbiol*. 2022;13:877151. <https://doi.org/10.3389/fmicb.2022.877151>
 27. Gursahani Y, Gupta S. Decolourization of textile effluent by a thermophilic bacterium *Anoxybacillus rupiensis*. *J Pet Environ Biotechnol*. 2011;2:1–4.
 28. Sharma N, Leung IK. Novel thermophilic bacterial laccase for the degradation of aromatic organic pollutants. *Front Chem*. 2021;9:711345. <https://doi.org/10.3389/fchem.2021.711345>
 29. Gallo G, Aulitto M. Advances in extremophile research: biotechnological applications through isolation and identification techniques. *Life*. 2024;14(9):1205. <https://doi.org/10.3390/life14091205>
 30. Srinivasan S, Bankole PO, Sadasivam SK. Biodecolorization and degradation of textile azo dyes using *Lysinibacillus sphaericus* MTCC 9523. *Front Environ Sci*. 2022;10:990855. <https://doi.org/10.3389/fenvs.2022.990855>
 31. Wang J, Zhang X, Li Y, Wang H, Liu Z, Chen Q, et al. Bacterial laccase of *Anoxybacillus ayderensis* SK3-4 from hot springs showing potential for industrial dye decolorization. *Ann Microbiol*. 2020;70(1):51. <https://doi.org/10.1186/s13213-020-01593-6>
 32. Mohammad BT, Al Daghistani HI, Jaouani A, Abdel-Latif S, Kennes C. Isolation and characterization of thermophilic bacteria from Jordanian hot springs: *Bacillus licheniformis* and *Thermomonas hydrothermalis* isolates as potential producers of thermostable enzymes. *Int J Microbiol*. 2017;2017(1):6943952. <https://doi.org/10.1155/2017/6943952>
 33. Opperman DJ, Sewell BT, Litthauer D, Isupov MN, Littlechild JA, van Heerden E. Crystal structure of a thermostable old yellow enzyme from *Thermus scotoductus* SA-01. *Biochem Biophys Res Commun*. 2010;393(3):426–31. <https://doi.org/10.1016/j.bbrc.2010.02.011>
 34. Ngo ACR, Tischler D. Microbial degradation of azo dyes: approaches and prospects for a hazard-free conversion by microorganisms. *Int J Environ Res Public Health*. 2022;19(8):4740. <https://doi.org/10.3390/ijerph19084740>
 35. Champagne PP, Ramsay J. Reactive blue 19 decolouration by laccase immobilized on silica beads. *Appl Microbiol Biotechnol*. 2007;77(4):819–23. <https://doi.org/10.1007/s00253-007-1208-1>
 36. Aragaw TA, Bogale FM, Gessesse A. Adaptive response of thermophiles to redox stress and their role in the process of dye degradation from textile industry wastewater. *Front Physiol*. 2022;13:908370. <https://doi.org/10.3389/fphys.2022.908370>
 37. Matsumoto KI, Mukai Y, Ogata D, Shozui F, Nduko JM, Taguchi S, et al. Characterization of thermostable FMN-dependent NADH azoreductase from the moderate thermophile *Geobacillus stearothermophilus*. *Appl Microbiol Biotechnol*. 2010;86(5):1431–8.

- <https://doi.org/10.1007/s00253-009-2351-7>
38. Guan G, Li B, Xu L, Qian J, Zou B, Huo S, Ding Z, et al. Improving the properties of laccase through heterologous expression and protein engineering. *Microorganisms*. 2025;13(6):1422. <https://doi.org/10.3390/microorganisms13061422>
 39. Yuan X, Tian G, Zhao Y, Zhao L, Wang H, Ng TB. Degradation of dyes using crude extract and a thermostable and pH-stable laccase isolated from *Pleurotus nebrodensis*. *Biosci Rep*. 2016;36(4):e00365. <https://doi.org/10.1042/BSR20160163>
 40. Rodríguez-Escribano D, Pliego-Magán R, de Salas F, Aza P, Gentili P, Ihalainen P, et al. Tailor-made alkaliphilic and thermostable fungal laccases for industrial wood processing. *Biotechnol Biofuels*. 2022;15(1):149. <https://doi.org/10.1186/s13068-022-02247-2>
 41. Salem MA, Nour El-Din HT, Hashem AM, Aziz RK. Genome-scale investigation of the regulation of azoR expression in *Escherichia coli* using computational analysis and transposon mutagenesis. *Microb Ecol*. 2024;87(1):63. <https://doi.org/10.1007/s00248-024-02380-5>
 42. Zhuang M, Sanganyado E, Xu L, Zhu J, Li P, Liu W. High throughput sediment DNA sequencing reveals azo dye degrading bacteria inhabit nearshore sediments. *Microorganisms*. 2020;8(2):233. <https://doi.org/10.3390/microorganisms8020233>
 43. Koul B, Poonia AK, Yadav D, Jin JO. Microbe-mediated biosynthesis of nanoparticles: Applications and future prospects. *Biomolecules*. 2021;11(6):886. <https://doi.org/10.3390/biom11060886>
 44. Siddiqi KS, Husen A, Rao RA. A review on biosynthesis of silver nanoparticles and their biocidal properties. *J Nanobiotechnology*. 2018;16(1):14. <https://doi.org/10.1186/s12951-018-0334-5>
 45. Essghaier B, Dridi R, Mottola F, Rocco L, Zid MF, Hannachi H. Biosynthesis and characterization of silver nanoparticles from the extremophile plant *Aeonium haworthii* and their antioxidant, antimicrobial and anti-diabetic capacities. *Nanomaterials*. 2022;13(1):100. <https://doi.org/10.3390/nano13010100>
 46. Mikhailova EO. Gold nanoparticles: biosynthesis and potential of biomedical application. *J Funct Biomater*. 2021;12(4):70. <https://doi.org/10.3390/jfb12040070>
 47. Mahlaule-Glory LM, Mapetla S, Makofane A, Mathipa MM, Hintsho-Mbita NC. Biosynthesis of iron oxide nanoparticles for the degradation of methylene blue dye, sulfisoxazole antibiotic and removal of bacteria from real water. *Heliyon*. 2022;8(9):e10536. <https://doi.org/10.1016/j.heliyon.2022.e10536>
 48. Alsaiani NS, Amari A, Katubi KM, Alzahrani FM, Harharah HN, Rebah FB, et al. The biocatalytic degradation of organic dyes using laccase immobilized magnetic nanoparticles. *Appl Sci*. 2021;11(17):8216. <https://doi.org/10.3390/app11178216>
 49. Parvathiraja C, Paulkumar K, Gupta JK, Mouni L, Almutairi TM, Nguyen VH. Biogenic synthesis of SnO₂ nanoparticles using *Albizia saman* leaf extract for visible light-driven photocatalytic dye degradation and antibacterial applications. *Arab J Sci Eng*. 2026;51(2):1639–49. <https://doi.org/10.1007/s13369-025-10200-2>
 50. Rouhani S, Azizi S, Kibechu RW, Mamba BB, Msagati TA. Laccase immobilized Fe₃O₄-graphene oxide nanobiocatalyst improves stability and immobilization efficiency in the green preparation of sulfa drugs. *Catalysts*. 2020;10(4):459. <https://doi.org/10.3390/catal10040459>
 51. Gao Z, Yi Y, Zhao J, Xia Y, Jiang M, Cao F, et al. Co-immobilization of laccase and TEMPO onto amino-functionalized magnetic Fe₃O₄ nanoparticles and its application in acid fuchsin decolorization. *Bioresour Bioprocess*. 2018;5(1):1–8. <https://doi.org/10.1186/s40643-018-0215-7>
 52. Wang H, Zhang W, Zhao J, Xu L, Zhou C, Chang L, et al. Rapid decolorization of phenolic azo dyes by immobilized laccase with Fe₃O₄/SiO₂ nanoparticles as support. *Ind Eng Chem Res*. 2013;52(12):4401–7. <https://doi.org/10.1021/ie302627c>
 53. Nandasana M, Ghosh S. Biogenic nanoparticles for dye removal. In: *Advances in Chemical Pollution, Environmental Management and Protection*. Elsevier; 2024. p. 1–33. <https://doi.org/10.1016/bs.ampp.2023.06.013>
 54. Miyawaki A, Sakai S. Immobilization of laccases on mechanically ground silk fibroin nanofibers for enhanced stability. *Int J Biol Macromol*. 2024;282:136745. <https://doi.org/10.1016/j.ijbiomac.2024.136745>
 55. Farastoon Dashti SS, Ansari I, Emamshoushtari MM, Helchi S, Lessage G, Heran M, et al. Comparison of batch and continuous operation modes for maxilon red azo dye removal using *Chlorella vulgaris* microalgae within photobioreactor (PBR) and a dynamic membrane photobioreactor (DMPBR). *Front Membr Sci Technol*. 2025;4:1653159. <https://doi.org/10.3389/frmst.2025.1653159>
 56. Zdarta J, Jankowska K, Bachosz K, Degórska O, Kaźmierczak K, Nguyen LN, et al. Enhanced wastewater treatment by immobilized enzymes. *Curr Pollut Rep*. 2021;7(2):167–79. <https://doi.org/10.1007/s40726-021-00183-7>
 57. Peñaranda PA, Noguera MJ, Florez SL, Hussler J, Ornelas-Soto N, Cruz JC, et al. Treatment of wastewater, phenols and dyes using novel magnetic torus microreactors and laccase immobilized on magnetite nanoparticles. *Nanomaterials*. 2022;12(10):1688. <https://doi.org/10.3390/nano12101688>
 58. Ilyas A, Batool K. Innovative enzymatic and microbial approaches for wastewater bioremediation: Advances in enzyme engineering, biotechnology and nanotechnology for sustainable water management-A comprehensive review. *Premier J Sci*. 2025;9. <https://doi.org/10.70389/PJS.100074>
 59. Orasugh JT, Gabi B, Zaman A, Banerjee P, Chattopadhyay D. Challenges in the scale-up of MES for wastewater treatment. In: *Development in Wastewater Treatment Research and Processes*. Elsevier; 2023. p. 257–76. <https://doi.org/10.1016/B978-0-323-88505-8.00006-1>
 60. Kuremaganahalli Basavaraja A, Kyathanahally Rajashekarappa K, Basavarajappa A, Neelagund SE, Hanumanthanaik D, Dummi Mahadevan G. Efficient biodegradation of textile azo dye Congo red by thermophilic *Geobacillus thermoleovorans*. *Bioremediation J*. 2025;1–13. <https://doi.org/10.1080/10889868.2025.2549005>
 61. Schultz J, Modolon F, Peixoto RS, Rosado AS. Shedding light on the composition of extreme microbial dark matter: alternative approaches for culturing extremophiles. *Front Microbiol*. 2023;14:1167718. <https://doi.org/10.3389/fmicb.2023.1167718>
 62. Guo MT, Rotem A, Heyman JA, Weitz DA. Droplet microfluidics for high-throughput biological assays. *Lab Chip*. 2012;12(12):2146–55. <https://doi.org/10.1039/c2lc21147e>
 63. Murray EM, Allen CF, Handy TE, Huffine CA, Craig WR, Seaton SC, et al. Development of a robust and quantitative high-throughput screening method for antibiotic production in bacterial libraries. *ACS Omega*. 2019;4(13):15414–20. <https://doi.org/10.1021/acsomega.9b01461>
 64. Jasińska A, Walaszczyk A, Paraszkiewicz K. Omics-based approaches in research on textile dye microbial decolorization. *Molecules*. 2024;29(12):2771. <https://doi.org/10.3390/molecules29122771>
 65. Zhou X, Fornara D, Ikenaga M, Akagi I, Zhang R, Jia Z. The resilience of microbial community under drying and rewetting cycles of three forest soils. *Front Microbiol*. 2016;7:1101. <https://doi.org/10.3389/fmicb.2016.01101>
 66. Zhu D, Adebisi WA, Ahmad F, Sethupathy S, Danso B, Sun J. Recent development of extremophilic bacteria and their application in biorefinery. *Front Bioeng Biotechnol*. 2020;8:483. <https://doi.org/10.3389/fbioe.2020.00483>
 67. Jirasaranporn A, Jantharadej K, Wongwailikhit K, Chawengkijwanich C, Lohwacharin J, Suwannasilp BB. A pilot-scale anaerobic moving-bed biofilm reactor with PVA gel beads as media for the treatment of fish canning industry wastewater. *Water*

- Reuse. 2022;12(2):206–22. <https://doi.org/10.2166/wrd.2022.090>
68. Miah MS, Hossain MS, Ali MS, Shahid SB, Sharmin S, Zakir HM. Textile effluent treatment in a pilot-scale UASB bioreactor followed by biofilter and aerobic processes. *Case Stud Chem Environ Eng*. 2025;11:101075. <https://doi.org/10.1016/j.cscee.2024.101075>
 69. Papadia S, Rovero G, Fava F, Di Gioia D. Comparison of different pilot scale bioreactors for the treatment of a real wastewater from the textile industry. *Int Biodeterior Biodegradation*. 2011;65(3):396–403. <https://doi.org/10.1016/j.ibiod.2011.01.002>
 70. Uddin M, Islam MK, Dev S. Investigation of the performance of the combined moving bed bioreactor-membrane bioreactor (MBBR-MBR) for textile wastewater treatment. *Heliyon*. 2024;10(10):e31358. <https://doi.org/10.1016/j.heliyon.2024.e31358>
 71. Justino CI, Duarte AC, Rocha-Santos TA. Recent progress in biosensors for environmental monitoring: a review. *Sensors*. 2017;17(12):2918. <https://doi.org/10.3390/s17122918>
 72. Darwish MA, Abd-Elaziem W, Elsheikh A, Zayed AA. Advancements in nanomaterials for nanosensors: a comprehensive review. *Nanoscale Adv*. 2024;6(16):4015–46. <https://doi.org/10.1039/D4NA00214H>
 73. Shamshad J, Rehman RU. Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies. *Environ Sci Adv*. 2025;4(2):189–222. <https://doi.org/10.1039/D4VA00136B>
 74. Agarwala O, Das M, Bhandary S, Ghosh A. Bio-nanotechnology for effluent treatment. In: *Sustainable Effluent Treatment and Resource Recovery*. Vol. 1. ACS Publications; 2025. p. 181–209. <https://doi.org/10.1021/bk-2025-1517.ch006>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.