GESA
GLOCAL ENVIRONMENT & SOCIAL ASSOCIATION

International Journal of Biological Innovations
http://ijbi.org.in | http://www.gesa.org.in/journals.php
https://doi.org/10.46505/IJBI.2025.7110
IJBI 7(1): 80-92 **(2025)**
E-ISSN: 2582-1032

BIOREMEDIATION AND ADVANCED RESEARCH FOR DEGRADATION OF DYES

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Article Info:
Review Article
Received
15.03.2025
Reviewed
10.05.2025
Accepted
21.05.2025

Abstract: Synthetic dyes are extensively used in industrial processes such as textiles, paper manufacturing, plastics, and food coloring, resulting in significant environmental pollution. Dealing dye-containing wastewater into aquatic ecosystems leads to severe consequences, including water contamination, reduced light penetration, and toxicity to marine organisms. Due to their complex aromatic structures, synthetic dyes exhibit high chemical stability and resistance to conventional degradation processes, making their removal from wastewater a pressing concern. The current review focuses on biological treatment, which includes the degradation of dyes by using microbial strains, enzymes, enzymatic mechanisms, metabolic pathways, and environmental factors that influence microbial dye degradation. Bacterial strains such as *Pseudomonas, Bacillus* and *Acinetobacter* have shown significant potential in breaking down complex dyes through enzymatic actions involving oxidoreductases, peroxidases, laccases, and azoreductases. Additionally, fungi and yeast contribute to dye degradation through biosorption and extracellular enzymatic activities. The advance technologies can be approached for the biodegradation of dyes such as genetic engineering, enzyme immobilization, metabolic engineering, and nanotechnology by focusing on pathway analysis. More researches are required to challenges the existing dye problem and find future perspectives in the field. Advance technologies for microbial degradation, can develop more effective and environmentally friendly treatment strategies to mitigate dye pollution and ensure sustainable wastewater management.

Keywords: Biodegradation, Dyes, Metagenomics, Pathway analysis, Pollution, Wastewater.

Cite this article as: Khan E., Tiwari N., Agnihotri A. and Awasthi G. (2025). Bioremediation and Advanced Research for Degradation of Dyes. *International Journal of Biological Innovations*. 7(1): 80-92. https://doi.org/10.46505/IJBI.2025.7110

INTRODUCTION

Dyes are extensively used in various industrial sectors, including textiles, food processing, paper production, cosmetics, pharmaceuticals, and leather industries, to impart color to products. However, the discharge of dye-laden effluents into water bodies poses serious environmental and health hazards due to the toxic, mutagenic, and carcinogenic properties of synthetic dyes. Many of these dyes exhibit complex aromatic structures that confer chemical stability, making them resistant to natural degradation processes. As a result, they persist in the environment, leading to water pollution, reduced light penetration by blocking sunlight, thus disrupting the food chain in aquatic ecosystems, and bioaccumulation in living organisms (Ardila-Leal *et al.,* 2021; Singh *et al.,* 2023). Additionally, some dyes and their breakdown products have been linked to severe health issues such as skin irritation, respiratory problems, and even carcinogenic effects upon prolonged exposure. Consequently, efficient dye removal from industrial effluents has become a crucial challenge in environmental management (Das *et al.,* 2023).

Various physical, chemical, and biological methods have been employed to treat dye-contaminated wastewater. Conventional physico- chemical approaches such as coagulation, adsorption, filtration, and advanced oxidation processes are widely used for dye removal. However, these methods often suffer from drawbacks such as high operational costs, incomplete degradation, and the generation of secondary pollutants. Therefore, biological approaches, particularly microbial degradation, have gained significant attention as an eco-friendly and cost-effective alternative (Alsukaibi, 2022).

Microbial degradation of dyes utilizes bacteria, fungi, and yeast capable of metabolizing or transforming dye molecules into non-toxic compounds. Bacterial strains such as *Pseudomonas*, *Bacillus*, and *Acinetobacter* have shown remarkable efficiency in breaking down complex dyes through enzymatic reactions (Ikram *et al.,* 2022). Fungal species, especially white-rot fungi like *Trametes versicolor* and *Phanerochaete chrysosporium*, produce extracellular enzymes such as laccases and peroxidases that facilitate dye degradation (Viswanath *et al.,* 2014).

Similarly, yeasts also contribute for dye removal through biosorption and enzymatic transformation. The study of the kinetics of dye degradation by microbial strains provides valuable insights into the efficiency, rate, and mechanisms of microbial dye removal. The kinetic studies are conducted for several factors, including pH, temperature, oxygen availability, and microbial adaptation, influence the rate of dye degradation. Understanding these kinetics helps in optimizing bioremediation conditions. It also helps in improving the performance of microbial consortia, and designing large-scale wastewater treatment strategies. Researchers have explored mathematical models such as first-order and Michaelis-Menten kinetics to describe the degradation process and predict treatment efficiency (Pinheiro *et al.,* 2022). Various physicochemical and biological approaches have been explored to eliminate dyes from industrial effluents, but many methods remain costly, inefficient, or environmentally hazardous. Biological treatment, particularly microbial degradation, has emerged as a promising and sustainable alternative to conventional methods.

The present review provides an in-depth analysis of the kinetic aspects of microbial dye degradation, and various treatment approaches, like enzymatic mechanisms, degradation pathways, and recent advance technologies applicable in research. The understanding of fundamental processes and advance technologies involved in dye degradation can support researchers and industries to come together and develop effective and sustainable treatment strategies to mitigate dye pollution and protect environmental health.

PHYSICOCHEMICAL TREATMENT

Physicochemical treatment methods are widely employed for the removal of dyes from wastewater, relying on physical and chemical principles to separate or degrade contaminants. These methods are often used as primary or complementary treatments in wastewater management due to their efficiency and relatively fast processing times. However, they may generate secondary pollutants or require high operational costs, necessitating further treatment or waste management strategies (Alsukaibi, 2022).

One of the most common physicochemical treatments is adsorption, where dyes are removed by adhering to the surface of solid materials such as activated carbon, clay minerals, biochar, and polymeric resins. Adsorption is highly effective in removing a broad spectrum of dyes, particularly non-biodegradable and toxic compounds. However, the efficiency of adsorption depends on factors such as adsorbent surface area, pore size, and environmental conditions such as pH and temperature. Moreover, the disposal and regeneration of spent adsorbents remain significant challenges (Rápó and Tonk, 2021).

Another widely used approach is coagulation-flocculation, which involves the addition of coagulants such as aluminum sulfate (alum), ferric chloride, and polyaluminum chloride to destabilize dye molecules in wastewater. This process leads to the formation of large flocs that can be easily separated via sedimentation or filtration. Coagulation is particularly effective in treating wastewater with high concentrations of suspended particles and colloidal dyes. However, excessive use of coagulants can generate sludge, which requires proper handling and disposal (Rápó and Tonk 2021).

Advances in Physicochemical Treatment

Hybrid treatment approaches that combine biological and physicochemical methods are also being investigated to improve dye removal efficiency. Combining microbial degradation with advanced oxidation processes (AOPs) or membrane filtration can help break down recalcitrant dyes that resist biological treatment alone. Electrochemical bioremediation is another emerging field where microbial cells are used in bioelectrochemical systems to enhance dye degradation through electron transfer processes (Cuerda-Correa *et al.,* 2019).

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) have gained attention as efficient methods for dye degradation. These processes utilize highly reactive species, such as hydroxyl radicals (-OH), to break down dye molecules into smaller, biodegradable fragments. Common AOPs include Fenton's reaction (a combination of hydrogen peroxide and iron catalysts), photocatalysis (using titanium dioxide and UV light), and ozonation (application of ozone gas). AOPs can achieve near-complete mineralization of dyes but may require high energy inputs and careful monitoring to prevent the formation of toxic intermediates (Cuerda-Correa *et al.,* 2019; Ledakowicz and Pazdzior, 2021).

Membrane filtration technologies such as ultrafiltration, nanofiltration, and reverse osmosis are also effective in dye removal. These methods rely on semi-permeable membranes to selectively separate dye molecules from wastewater based on molecular size and charge. Reverse osmosis, in particular, can achieve high removal efficiencies but is associated with high operational costs and membrane fouling issues. Additionally, the concentrated dye sludge generated as a by-product requires further processing or disposal (Moradihamedani, 2022).

Chemical precipitation, ion exchange, and electrochemical treatments are the other physicochemical methods that have been explored for dye removal. Chemical precipitation involves the addition of chemical agents to form insoluble dye precipitates that can be separated from water. Ion exchange utilizes resins to swap dye ions with benign ions, making it effective for treating dye-laden wastewater. Electrochemical treatments, including electrocoagulation and electro-oxidation, use electrical currents to degrade dyes or facilitate coagulation (Alkhadra *et al.,* 2022).

Despite their effectiveness, physicochemical treatments have some limitations. They can be costly due to high energy demands, chemical consumption, and the need for post-treatment sludge management. Additionally, they may not completely mineralize dyes, leading to the formation of secondary pollutants that require additional treatment. To enhance overall treatment efficiency, physicochemical methods are often integrated with biological treatments, where microbial degradation complements the removal of residual dye components (Karimifard and Moghaddam, 2018).

As research advances, novel physicochemical approaches are being explored to improve efficiency and sustainability. Hybrid treatment systems combining adsorption with AOPs, or membrane filtration with biodegradation, are being developed to maximize dye removal and to reduce secondary waste production (Asheghmoalla and Mehrvar, 2024). The use of environmentally friendly and cost-effective adsorbents derived from agricultural or industrial waste is also being investigated to address cost and sustainability concerns. Overall, while physicochemical treatment methods remain vital in dye wastewater management, ongoing advancements seek to optimize their efficiency, reduce operational costs, and minimize environmental impacts.

BIOLOGICAL TOOLS FOR DYES DEGRADATION

Bioremediation is an environmentally friendly approach that utilizes microorganisms to degrade or transform pollutants into less harmful substances. It is particularly advantageous in treating dye pollution due to its efficiency, cost-effectiveness, and ability to degrade complex dye structures that are resistant to conventional treatments (Bala *et al.,* 2024). Microorganisms such as bacteria, fungi, and yeast have evolved enzymatic systems capable of breaking down various dye compounds, making them effective agents in wastewater treatment and environmental restoration.

Bacteria

Bacterial bioremediation is one of the most extensively studied processes for dye degradation. Bacterial degradation of dyes is an effective and widely studied method due to the adaptability and rapid growth of bacterial strains in diverse environmental conditions. Bacteria utilize enzymes to degrade dyes either by breaking down their complex structures or by utilizing them as a source of energy (Mishra *et al.,* 2022). Bacteria have shown the ability to degrade synthetic dyes through metabolic pathways that involve oxidation, reduction, and hydrolysis. Some bacterial strains, such as *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Acinetobacter baumannii* and *Rhodococcus* species, have demonstrated high degradation efficiency. These bacteria either use the dyes as a carbon source or produce enzymes such as azoreductases, laccases, peroxidases, and oxidoreductases, to break down the dye molecules into simpler, non-toxic forms. The kinetics of bacterial dye degradation often follow first-order or second-order reaction models, depending on the bacterial strain, dye concentration, and environmental conditions (Saratale *et al.,* 2011).

Bacterial degradation can occur under aerobic and anaerobic conditions. In aerobic environments, oxidative enzymes break down dyes through oxidation and ring cleavage, leading to complete mineralization into carbon dioxide and water. This process is highly effective but requires a continuous oxygen supply. In anaerobic conditions, many bacteria use reductive pathways to decolorize dyes by breaking azo bonds. However, anaerobic degradation often leads to the formation of aromatic amines, which may require further treatment to prevent secondary pollution. Aerobic bacteria further oxidize these intermediate compounds, leading to complete mineralization into non-toxic end products such as carbon dioxide and water. A combination of anaerobic and aerobic treatments is often employed to achieve complete degradation and mineralization of dyes (Cui *et al.,* 2012).

The efficiency of bacterial degradation is influenced by factors such as pH, temperature, dye concentration, and the availability of co-substrates that enhance microbial growth and enzyme production. Their high tolerance to harsh environmental conditions makes them suitable for industrial applications where extreme pH and temperature variations are common. Several environmental factors influence the efficiency of microbial bioremediation such as pH and temperature are critical parameters, they affect microbial metabolism and enzyme activity. Most bacteria and fungi exhibit optimal dye degradation at pH 6-8 and temperatures between 25-40°C. High dye concentrations can be inhibitory to microbial growth, requiring adaptation or acclimatization of microbial strains for enhanced degradation efficiency. The presence of co-substrates, such as glucose or acetate, can enhance dye degradation by providing additional energy sources for microbial metabolism (Qiu *et al.,* 2022).

Fungi

Fungi play a significant role in biological dye degradation due to their ability to produce extracellular enzymes that break down complex organic molecules (Verma and Prakash, 2020). Fungi, such as *Phanerochaete chrysosporium*, *Trametes versicolor*, and *Aspergillus niger*, have been extensively studied for their ability to degrade synthetic dyes (Sen *et al.,* 2016; Muzaffar *et al.,* 2020). These fungi produce ligninolytic enzymes, including laccases, manganese peroxidases, and lignin peroxidases, which are highly effective in oxidizing and breaking down recalcitrant dye molecules (Sen *et al.,* 2016; Temporiti *et al.,* 2022).

Unlike bacterial degradation, which primarily occurs in liquid-phase environments, fungi can degrade dyes in both submerged and solid-state conditions, making them useful for treating dye-contaminated soils and solid waste. Fungi can degrade a wide range of dye types, including azo, anthraquinone, and triphenylmethane dyes, due to their robust enzymatic systems. The fungal degradation of dyes generally follows an oxidative pathway, wherein reactive species generated by enzymatic activity attack the chromophoric groups of dyes, leading to decolorization and breakdown (Ngo and Tischler, 2022). Their ability to secrete these enzymes into their surroundings allows for large-scale degradation, making them suitable for industrial wastewater treatment applications.

Fungal dye degradation is influenced by environmental factors such as pH, temperature, oxygen levels, and the presence of inducers that enhance enzyme production. The ability of fungi to tolerate harsh environmental conditions makes them particularly useful for industrial wastewater treatment applications (Emami *et al.,* 2010).

Yeast

Yeasts have also been explored for their potential in dye bioremediation, primarily through biosorption and enzymatic transformation. Yeast species such as *Saccharomyces cerevisiae* and *Candida tropicalis* and *Debaryomyces hansenii*, have shown promising capabilities in dye bioremediation and exhibit strong adsorption capacities, in removing dyes from wastewater by binding them to their cell walls (Nicula *et al.,* 2023). Additionally, yeasts produce oxidative and reductive enzymes that contribute to dye degradation.

Unlike bacteria and fungi, yeast primarily removes dyes through biosorption, a process in which dye molecules adhere to the cell surface via electrostatic interactions, hydrogen bonding, or van der Waals forces. Some yeast species are also capable of enzymatic biodegradation, producing oxidoreductases that transform dye molecules into less toxic derivatives (Segal-Kischinevzky *et al.,* 2023). Yeast cells can survive in extreme environmental conditions, including high salt concentrations and fluctuating pH levels, making them suitable for industrial-scale wastewater treatment (Verma, 2017). The biosorption ability of yeast can be enhanced through genetic modifications or by immobilizing yeast cells onto bio-carriers, which increase their adsorption capacity and facilitate repeated use in bioreactors. Additionally, yeast-based dye degradation processes generate minimal sludge, making them a more sustainable and cost-effective option for dye removal compared to traditional physicochemical treatments (Azeez and Al-Zuhairi, 2022).

The integration of bacterial, fungal, and yeast-based treatments in biological remediation strategies has shown significant potential in achieving complete dye degradation. Many studies have explored the use of microbial consortia, where different microorganisms work synergistically to enhance degradation efficiency and reduce treatment time.

ENZYMES IN DYE DEGRADATION

Enzymes play a crucial role in microbial dye degradation, catalyzing reactions that break down complex dye molecules into smaller, less toxic compounds. The primary classes of enzymes involved in dye degradation include oxidoreductases, peroxidases, laccases, and hydrolases, each targeting specific chemical bonds within dye structures. These enzymes are produced by various bacterial, fungal, and yeast strains and are essential for initiating and completing the degradation process. The mechanisms by which microorganisms degrade dyes vary and are based on the type of dye and the microbial species (Xu *et al.,* 2021).

Oxidoreductases are a broad category of enzymes that mediate oxidation-reduction reactions, crucial in dye degradation. Reductive enzymes like azoreductases target azo dyes, breaking the azo bonds (-N=N-) to form colorless amine derivatives. This results in the formation of aromatic amines, requires further degradation via oxidative pathways. Oxygenases, including monooxygenases and dioxygenases, play a role in breaking down aromatic dye structures by introducing oxygen atoms, leading to ring cleavage and complete mineralization (Mahmood *et al.,* 2016).

Peroxidases are another essential group of enzymes that degrade dyes through oxidation. Manganese peroxidase (MnP) and lignin peroxidase (LiP), primarily produced by white-rot fungi such as *Phanerochaete chrysosporium*, catalyze the breakdown of complex dye structures by generating reactive oxygen species. These enzymes are particularly effective against anthraquinone dyes and triphenylmethane dyes, which are resistant to conventional degradation methods (Kalsoom *et al.,* 2015).

Laccases, a subset of multicopper oxidases, are widely used in dye degradation due to their ability to oxidize a wide range of synthetic dyes. These enzymes, found in fungi such as *Trametes versicolor* and *Aspergillus niger*, catalyze the oxidation of dye molecules by transferring electrons to molecular oxygen, generating water as a byproduct. Laccases are particularly effective in the degradation of phenolic and polyaromatic dyes, making them valuable for bioremediation applications (Legerská *et al.,* 2016).

Hydrolases, enzymes such asesterases and amidases, facilitate the breakdown of ester and amide bonds in dye molecules,by hydrolyzing these bonds in dye molecules, leading to structural fragmentation and enhanced biodegradability. These enzymes are especially relevant in the degradation of indigo and sulfur-based dyes, where hydrolytic cleavage facilitates further microbial metabolism. The action of hydrolases is often complemented by other enzymatic processes that complete dye mineralization (Chen, 2006).

Enzymatic dye degradation is influenced by several factors, including pH, temperature, substrate concentration and the presence of cofactors or inhibitors. Most enzymes involved in dye degradation function optimally within a specific pH range, typically between 5 and 8, and within moderate temperature conditions (25-45°C) (Robinson, 2015).

Overall, enzymatic dye degradation represents a promising and sustainable approach to tackling industrial dye pollution. By harnessing the catalytic power of microbial enzymes, researchers and industries can develop efficient, eco-friendly treatment strategies that minimize environmental impact while ensuring effective pollutant removal.

PATHWAY ANALYSIS FOR DEGRADATION OF DYE

Dye degradation follows a series of complex biochemical pathways that depend on the type of dye, microbial species involved, and environmental conditions. The degradation of dyes generally occurs through oxidative, reductive, or hydrolytic mechanisms, which lead to the breakdown of the dye structure and the eventual formation of non-toxic end products such as carbon dioxide, water, and biomass. Understanding the metabolic pathways of dye degradation is essential for optimizing treatment efficiency and minimizing the accumulation of toxic intermediates.

In the case of azo dyes, which are the most commonly used synthetic dyes, degradation typically begins with the reductive cleavage of the azo bond (-N=N-) under anaerobic conditions. Bacteria such as *Pseudomonas*, *Bacillus*, and *Clostridium* produce azoreductases, which use electrons from metabolic reactions to break the azo bond, resulting in the formation of aromatic amines (Zafar *et al.,* 2022). These amines, however, are often toxic and require further breakdown under aerobic conditions. Subsequent oxidative reactions facilitated by laccases, peroxidases, and oxygenases convert these intermediates into simpler compounds that can be completely mineralized.

Anthraquinone dyes, which are characterized by their stable aromatic structures, require different enzymatic mechanisms for degradation. These dyes undergo initial oxidation by Laccases or Peroxidases, followed by ring cleavage via dioxygenases (Shraddha *et al.,* 2011). This results in the production of smaller organic acids, which are further metabolized by microbial pathways such as the tricarboxylic acid (TCA) cycle. Certain fungal species, such as *Trametes versicolor* and *Phanerochaete chrysosporium*, have been found to be particularly effective in breaking down anthraquinone dyes through extracellular enzyme secretion.

Triphenylmethane is another significant class of dyes, which is degraded through a sequential oxidation process. Microorganisms such as *Sphingomonas* and *Corynebacterium* oxidize the dye molecules using monooxygenases and dioxygenases, leading to the breakdown of the triphenyl structure into simpler benzene derivatives (Cheriaa *et al.,* 2012). These derivatives are further processed through hydroxylation and ring cleavage, resulting in complete mineralization.

Hydrolytic degradation plays an essential role in the breakdown of indigo dyes and other sulfur-based dyes. Esterases and amidases hydrolyze the dye molecules, leading to fragmentation into water-soluble products. These intermediates can then be utilized as secondary carbon sources by microorganisms, allowing complete degradation under aerobic or facultative anaerobic conditions (Sornaly *et al.,* 2024).

In many cases, microbial degradation pathways involve cometabolism, where the degradation of dyes occurs in the presence of an additional carbon or nitrogen source. This is especially crucial for complex dye structures that require energy input from external substrates to facilitate enzymatic activity (Mohapatra and Phale, 2021). The addition of glucose, acetate, or yeast extract has been found to enhance microbial dye degradation rates by providing necessary cofactors and reducing power.

Environmental factors such as pH, temperature, oxygen availability, and the presence of inhibitors influence the efficiency of dye degradation pathways. Aerobic and anaerobic degradation can be sequentially combined in hybrid treatment systems to ensure complete mineralization of dyes (Guo *et al.,* 2010). Additionally, recent advances in metagenomics and transcriptomics have provided insights into the genetic regulation of dye degradation pathways, allowing for the development of genetically engineered microorganisms (GMOs) with enhanced degradation capabilities.

The study of dye degradation pathways has a very significant implication for industrial wastewater treatment, as it enables the selection of optimal microbial consortia, enzymatic cocktails, and bioreactor configurations for efficient and cost-effective remediation. By elucidating the metabolic networks involved in dye breakdown, researchers can develop strategies to enhance degradation kinetics, minimize toxic by-products, and improve the sustainability of dye remediation processes (Tiwari *et al.,* 2023).

ADVANCE TECHNOLOGIES FOR BIOREMEDIATION OF DYES

Advances in microbial treatment of Dye

The recent advancements in microbial bioremediation have focused on enhancing degradation efficiency through immobilization techniques, genetic engineering, and metabolic pathway optimization. Immobilizing bacteria or fungi onto solid supports, such as alginate beads, biochar, or polymeric matrices, enhances their stability, protects them from environmental stress, and allows for continuous dye degradation in bioreactors (Wang *et al.,* 2023). Immobilization techniques, such as biofilms formation and carrier-based microbial encapsulation, improve microbial stability and reusability in large-scale wastewater treatment applications. Biofilms are structured microbial communities attached to surfaces, shows increased resistance towards toxic dye pollutants and can sustain degradation activity over longer periods, making the biofilms technique ideal for industrial applications (Nzila *et al.,* 2016).

Recent advances in dye treatment have focused on improving efficiency, sustainability, and scalability through innovative techniques. One of the most promising areas of research involves the use of genetically engineered microorganisms that are specifically designed to enhance dye degradation. Genetically engineered bacteria with enhanced enzyme production have shown improved degradation rates for resistant dye compounds. Scientists have successfully modified bacterial and fungal strains to over express key dye-degrading enzymes such as azoreductases, laccases, and peroxidases, increasing their catalytic efficiency and stability under industrial conditions. Synthetic biology approaches are also being employed to construct microbial consortia with complementary degradation pathways, allowing for more complete and faster dye mineralization (Santhanarajan *et al.,* 2022).

Metagenomics and proteomics studies are being conducted to understand microbial community interactions and optimize bioremediation processes (Arya and Hemprabha, 2025). The metagenomics and proteomics have revolutionized our understanding about microbial communities involved in dye degradation. Advanced sequencing techniques allow researchers to identify novel dye-degrading genes and enzymes from environmental samples, leading to the discovery of previously unknown microbial strains with high degradation potential (Zhang *et al.,* 2021). Metabolic engineering and transcriptomics are also being applied to optimize microbial pathways for enhanced degradation efficiency, while bioinformatics tools help predict and design optimal enzyme structures for improved catalytic performance (Santhanarajan *et al.,* 2022).

Advances in Enzyme for the treatment of dyes

Recent advances in protein engineering and immobilization techniques have been explored to enhance enzyme stability and efficiency under extreme environmental conditions. The development of immobilization and biofilm-based systems has gained traction in dye treatment research. Immobilization of enzymes onto solid carriers or within biofilms has been found to improve their reusability and catalytic activity, making them more effective in large-scale wastewater treatment applications (Khan *et al.,* 2023).

The application of enzymatic bioremediation is expanding, with genetic engineering being used to enhance enzyme production and activity. Recombinant DNA technology has allowed for the overexpression of dye-degrading enzymes in microbial hosts, increasing their degradation efficiency. Additionally, enzyme cocktails combining multiple oxidative and reductive enzymes have been developed to achieve complete dye mineralization, reducing the accumulation of toxic intermediates (Sutherland *et al.,* 2004).

Another major advancement is the integration of nanotechnology with bioremediation, where nanomaterials such as metal nanoparticles, carbon nanotubes, and graphene-based catalysts are combined with microbial or enzymatic systems to enhance dye breakdown. These nanocomposites improve reaction rates by increasing surface area, enhancing electron transfer, and stabilizing enzyme activity. Some studies have explored the use of immobilized enzymes on nanomaterials to create highly efficient, reusable biocatalysts that can be deployed in wastewater treatment plants (Kumar and Gopinath, 2017).

Advance AI tools for dye degradation

Artificial Intelligence (AI) and Machine Learning (ML) are also being explored to optimize dye treatment strategies. By analyzing large datasets of microbial degradation kinetics, AI models can predict optimal treatment conditions, suggest genetic modifications for improved enzyme activity, and design more efficient bioreactor configurations for large-scale wastewater treatment (Niazi, 2023).

Microbial bioremediation offers a sustainable solution for dye pollution, with applications in wastewater treatment plants, soil remediation, and industrial effluent management. While the challenges still remain such as incomplete mineralization, by-product toxicity. The ongoing research and technological advancements continue to improve the feasibility and efficiency of microbial dye degradation. The integration of microbial bioremediation with other treatment methods, such as advanced oxidation processes and membrane filtration, can further enhance the dye removal efficiency and ensure environmental safety.

Advances in bioreactor design, immobilization techniques, and microbial metabolic engineering continue to improve the feasibility of biological treatments in real-world applications. It can also find solutions against the challenges such as slow degradation rates and incomplete mineralization persist. These ongoing research efforts also focus on optimizing microbial activity, enzyme stability, and process scalability for large-scale industrial wastewater treatment.

Overall, advanced research in dye treatment is moving towards interdisciplinary approaches that integrate microbiology, nanotechnology, bioinformatics, and engineering to develop cost-effective, scalable, and sustainable solutions. These innovations hold significant potential for improving industrial wastewater management and reducing the environmental impact of synthetic dyes.

CONCLUSION

The degradation of synthetic dyes remains a major environmental challenge, necessitating the development of efficient and sustainable treatment strategies. This review has explored various approaches to dye degradation, including physicochemical and biological methods, enzymatic pathways, and recent advancements in research. Among these, bioremediation has emerged as a promising and eco-friendly alternative due to the ability of microorganisms such as bacteria, fungi, and yeast to break down complex dye structures. The enzymatic degradation mechanisms, involving oxidoreductases, peroxidases, and laccases, play a crucial role in facilitating this process. Moreover, advanced research in microbial engineering, nanotechnology, and hybrid treatment strategies continues to improve the efficiency and scalability of dye degradation technologies.

Despite significant progress, several challenges remain, such as the incomplete mineralization of dyes, the toxicity of intermediate degradation products, and the operational limitations of large-scale wastewater treatment systems. Addressing these challenges requires a multidisciplinary approach integrating biotechnology, chemical engineering, and computational modeling. Future research should focus on optimizing microbial consortia, improving enzyme stability, and exploring novel treatment technologies such as bioelectrochemical systems and AI-driven process optimization.

Ultimately, the successful implementation of dye degradation technologies will depend on continued innovation, regulatory support, and collaboration between researchers, industries, and policymakers. By advancing sustainable and cost-effective treatment solutions, it will be possible to significantly reduce the environmental impact of synthetic dyes and ensure cleaner water resources for future generations.

ACKNOWLEDGEMENT

Authors would also like to acknowledge the Amity Institute of Biotechnology, Amity University Uttar Pradesh, Lucknow Campus, Lucknow for providing necessary facilities to study.

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