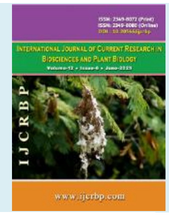
EXCELLENT PUBLISHERS

International Journal of Current Research in
Biosciences and Plant Biology

Volume **12** • Number **6** (June-2025) • ISSN: 2349-8080 (Online)

Journal homepage: www.ijcrbp.com



Original Research Article **doi:** https://doi.org/10.20546/ijcrbp.2025.1206.002

Bioremediation of Pollutant-Induced Toxicants in Aquatic Ecosystem

Ganga Ram Kamalapuri[1], Ram Sagar Gaur[1], Sakshi Tripathi[2, 3], Balwant Singh[3*], Abhinav Singh[1], Vinay Kumar Singh[3] and Piyush Mishra[2]

[1]*Department of Zoology, A. N. D. Kisan PG College Babhnan, Gonda-271313, (UP) India.*
[2]*Department of Botany, Dayanand Anglo-Vedic PG College, Kanpur-208001, (UP) India.*
[3]*Department of Botany, K. S. Saket PG College, Ayodhya-224123, (UP) India.*

*Corresponding author

Article Info

Keywords:
Bioremediation, Ecosystem Health, Toxicants; Heavy Metals; Microbial Degradation; Emerging Contaminants.

Abstract

Marine and water ecosystems are increasingly threatened by pollutant-generated toxicants like heavy metals, hydrocarbons, pesticides, drugs, and newer ones like microplastics. These toxicants disrupt the natural equilibrium, reduce biodiversity, and pose severe threats to human health via bioaccumulation and food chain transfer. Bioremediation has proved to be cost-effective, environmentally friendly, and a sustainable measure for mitigating such impacts by leveraging the metabolic capacity of microorganisms, algae, and higher aquatic plants. Enhanced microbial consortia engineering, nano-bioremediation, and omics-based tool utilization have enhanced pollutant degradation efficiency. The present review consolidates current knowledge on pollutant-induced toxicants in aquatic ecosystems, reports on traditional and novel bioremediation techniques, and outlines their ecological effectiveness and limitations. Besides, it identifies areas of gaps in knowledge, compliance challenges, and directions for future integration of bioremediation with advanced biotechnological interventions to guarantee sustainability of ecosystems.

• *Received: 15 February 2025* • *Revised: 20 April 2025* • *Accepted: 22May 2025* • *Published Online: 6 June 2025*

Introduction

Marine and freshwater ecosystems are the most productive and most diverse ecosystems in the world, contributing to biodiversity, nutrient cycling, and providing essential ecosystem services such as purification of water, provision of food, and climate regulation (Kumar et al., 2019). Rapid industrialization, urbanization, intensive agriculture, and population growth have resulted in unprecedented runoff of pollutants into freshwater and marine systems (Kumar et al., 2019). Pollutants entering water systems range from traditional toxics such as heavy metals, hydrocarbons, and pesticides to emerging ones such as pharmaceuticals, endocrine-disrupting chemicals, microplastics, and per- and polyfluoroalkyl substances (PFAS) (Chakraborty et al., 2021; Mallick et al., 2022). They remain in aquatic systems, persist in sediments, and enter trophic webs, resulting in adverse ecological and human health impacts (Masiello et al., 2023).

The intransigence of water pollution is a result of its multivalence of sources and interactions. The heavy metals cadmium, lead, and mercury are toxically potent even at trace levels, while organic pollutants like polycyclic aromatic hydrocarbons (PAHs) and pesticides are resistant to biodegradation in sediments and biomagnify (Banerjee & Dutta, 2019). It is further complicated by emerging pollutants; for instance, microplastics act as a carrier of hydrophobic toxicants and pathogenic microorganisms, contributing to ecological hazards (Masiello et al., 2023). Such toxicants resulted from pollutants disrupt aquatic biota by hindering reproduction, growth, and survival and hamper ecosystem processes such as oxygen cycling and nutrient turnover (Akpor et al., 2021). Moreover, human exposure through consumption of seafood and drinking water is of concern in terms of carcinogenicity, endocrine disruption, and antimicrobial resistance (Mallick et al., 2022).

Conventional remediation strategies like chemical precipitation, adsorption, membrane filtration, and advanced oxidation have been utilized to mitigate water pollution. Efficient in laboratory environments, these methods are costly, require sophisticated infrastructure, and generate secondary waste streams that require additional treatment (Kumar & Pal, 2020). Moreover, such technologies fail to completely remove intricate mixtures of contaminants and are not sustainable in terms of ecosystem restoration over the long term (Huang et al., 2022).

In such a situation, bioremediation has emerged as an affordable, environmentally friendly, and environmentally sound means of controlling aquatic pollution. By utilizing the metabolic potential of microorganisms, algae, and water plants, bioremediation allows the degradation, transformation, or immobilization of toxicants into less harmful substances (Sharma et al., 2020). Microbial consortia and biofilms, for example, are responsible for hydrocarbon degradation and metal sequestration, whereas algae carry out the role of nutrient uptake and removal of organic pollutants (Jaiswal et al., 2018; Saxena et al., 2022). Aquatic weeds such as Eichhornia crassipes and Lemna minor support phytoremediation by uptaking and depositing heavy metals, thereby removing the polluter loads from water bodies (Akpor et al., 2021).

Emerging advances in molecular biology and environmental biotechnology are enhancing bioremediation techniques by making them more efficient and feasible. Metagenomics and proteomics elucidate microbial community structure and degradation pathways of pollutants, enabling the identification of robust bioremediators with particular toxicants (Chatterjee et al., 2023). Nano-bioremediation techniques involving using nanoparticles in association with biological systems have also shown to be effective for enhancing bioavailability and enhancing pollutant degradation (Khan et al., 2023). Such advancements, coupled with environmental monitoring and control legislation, underscore the growing relevance of bioremediation as an imperative keystone in sustainable aquatic environment management.

Thus, an understanding of pollutant-generated toxicity and bioremediation advancement are critical not just to enhancing aquatic ecosystem well-being but to safeguarding world water security and advancing the United Nations Sustainable Development Goals of clean water and conservation of biodiversity.

Scope of Aquatic Pollution

Aquatic ecosystems are an essential element in maintaining biodiversity, food security, and global biogeochemical cycling, but are increasingly under the threat from a range of pollutants derived from industrial, agricultural, and domestic activities (Kumar et al., 2019). Among the most prevalent toxicants are heavy metals, pesticides, hydrocarbons, medicines, and novel contaminants such as microplastics and per- and polyfluoroalkyl substances (PFAS), which are environmentally persistent and highly bioaccumulative (Chakraborty et al., 2021; Masiello et al., 2023). The ecological effects are extensive, ranging from impaired water quality and loss of biodiversity to biomagnification and bioaccumulation of pollutants in aquatic food webs (Akpor et al., 2021). Further, toxicity due to pollutants erodes ecosystem services and poses significant risks to human health by polluting drinking water and seafood (Mallick et al., 2022).

Traditional remediation technologies such as chemical precipitation, adsorption, and advanced oxidation are expensive to operate, generate secondary waste, and are ineffective for complex mixes of pollutants (Kumar & Pal, 2020). Thus, sustainable, cost-effective, and eco-friendly options are ever more in demand.

Significance of Bioremediation

Bioremediation is a promising remediation mechanism for aquatic pollution that takes advantage of the intrinsic metabolic capacity of microorganisms, algae, and aquatic plants to detoxify, convert, or immobilize pollutants (Sharma et al., 2020). Compared to physicochemical remediation, bioremediation is eco-friendly, scalable, and remediates a wide range of pollutants simultaneously (Banerjee & Dutta, 2019). Microbial communities, algal systems, and aquatic macrophytes have also been observed to hold immense potential for hydrocarbon degradation, heavy metal immobilization, and minimizing the nutrient loads in contaminated water bodies (Jaiswal et al., 2018; Saxena et al., 2022).

The newer developments in genetic engineering, metagenomics, and nanobioremediation are enhancing the effectiveness and versatility of bioremediation strategies to enable targeted pollutant degradation and resistance to shifting environmental conditions (Khan et al., 2023; Chatterjee et al., 2023). Also, the convergence of bioremediation with monitoring technologies and ecological risk assessment protocols offers a holistic pathway for restoring aquatic health and ensuring long-term ecosystem integrity (Huang et al., 2022). Hence, bioremediation not only helps to bridge the challenge of pollutant-induced toxicity but is also a central factor in augmenting circular bioeconomy principles and supporting world water sustainability policies.

Pollutant-Induced Toxicants in Aquatic Ecosystems

Aquatic environments are susceptible to a broad range of toxicants originating from human activities, which are harmful to the ecosystem and human health. The most significant categories are heavy metals, organic pollutants, and an ever-growing group of emerging substances such as microplastics, nanomaterials, and per- and polyfluoroalkyl substances (PFAS). Besides influencing physicochemical water parameters, these toxicants accumulate in sediments and biomagnify through trophic levels, resulting in ongoing ecosystem perturbations.

Aqueous ecosystems are increasingly regarded as ultimate sinks for a wide variety of pollutants that cause toxic stress on biological communities and threaten ecosystem stability. The most pressing categories of toxicants are heavy metals, organic pollutants, and emerging pollutants due to their persistence, bioaccumulation, and trophic transfer potential. These pollutants are introduced through industrial waste, farm runoff, urban emissions, and atmospheric deposition to create a complex mixture that synergistically disrupts aquatic ecology and human health hazards.

Heavy metals such as cadmium, mercury, arsenic, lead, and chromium are among the most persistent pollutants in aquatic ecosystems (Table-1). In contrast to organic compounds, they do not degrade but recycle between sediments, water, and biota, accumulating progressively (Ali et al., 2019). Elevated cadmium has been associated with enzyme function interference and respiratory depression in fish, while mercury bioaccumulation in the form of methylmercury is particularly risky based on its neurotoxicity and food web biomagnification potential (Wang et al., 2021). Arsenic contamination through industrial and mining activities has been linked to genotoxicity in aquatic organisms, whereas growth, reproductive function, and in many cases population decline are affected by lead and chromium (Mishra et al., 2019). Chemical speciation of heavy metals to a great extent defines their toxicity, whereas environmental parameters such as pH and redox potential govern their mobility and bioavailability, further increasing their eco-effect (Saxena et al., 2022).

Organic pollutants constitute another crucial group of toxicants, such as hydrocarbons, pesticides, and medicines. Hydrocarbons, particularly polycyclic aromatic hydrocarbons (PAHs) from oil contamination, incomplete combustion, and industrial waste effluent, are lipophilic in nature and readily adsorb onto sediments, where they persist for a very long time and exert carcinogenic, mutagenic, and teratogenic impacts on aquatic organisms (Varjani et al., 2020). Pesticides, and organophosphates in particular, carbamates, and chlorinated derivatives, find their way into aquatic life through leaching and runoff of agricultural land. Organophosphates and chlorinated derivatives cause acute toxicity and death to fish and invertebrates, endocrine disruption, and behavior that impedes survival and reproduction (Singh et al., 2018). Pharmaceutical residues are now global in rivers, lakes, and sea waters because conventional wastewater treatment plants cannot completely remove them. Antibiotics contribute to the development of antimicrobial resistance within microbial communities, while endocrine-disrupting substances such as synthetic estrogens influence reproductive physiology in fish and amphibians (Kümmerer et al., 2020; Patel et al., 2019). Long-term exposure of aquatic organisms to such pollutants not only alters community structure but also triggers cascading effects at the ecosystem level.

Emerging contaminants add a further layer of complexity by their emergent characteristics, persistence in the environment, and inadequately characterized toxicology. Microplastics is a term used to describe plastic pieces less than 5 mm in length that occur through the breakdown of greater plastic litter and synthetic fabrics. Their ubiquity in marine biomes is of significant concern because they are ingested by plankton, fish, and shellfish, inducing physical damage, impaired feeding performance, and gut blockage (Masiello et al., 2023). Microplastics are also carriers of hydrophobic contaminants and pathogenic microorganisms, hence amplifying ecological and health risks. Nanomaterials such as silver, titanium dioxide, and zinc oxide nanoparticles are steadily leaching into aquatic ecosystems from industrial and consumer goods. Due to their nanoscale size and reactivity, they penetrate biological membranes, cause oxidative stress, and are involved in interactions with cellular macromolecules, resulting in DNA damage and altered metabolic function in aquatic species (Keller et al., 2020). Then there is the issue of per- and polyfluoroalkyl substances (PFAS), man-made fluorinated chemicals used widely for firefighting foam, garments, and non-stick coatings. The so-called "forever chemicals" are not broken down and persist in water supplies, where they bioaccumulate and disrupt endocrine and immune systems in aquatic animals and humans (Ruan et al., 2022). Their ability to be transported over long distances and their global distribution make them candidates for immediate regulatory action and remediation procedures.

The simultaneous presence of heavy metals, organic compounds, and emerging contaminants in water bodies creates complex mixtures that exert additive, synergistic, or antagonistic toxicity.

The interplay complicates ecotoxicological assessments and underscores the need for an integrated strategy to understand and manage pollutant impact. The toxicants not only pose a threat to ecosystem processes and biodiversity but to human health as well through contaminated seafood and water. The persistence and worldwide spread of toxicants due to contaminants emphasize the importance of designing sustainable remediation strategies, with bioremediation providing an acceptable means to mitigate these hazards economically and in an environmentally friendly manner.

Heavy Metals

Heavy metals such as cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and lead (Pb) are among the most stable and toxic aquatic pollutants. Sources of these include mining, electroplating, battery manufacturing, and agricultural runoff (Mishra et al., 2019). Heavy metals, unlike organic compounds, are non-biodegradable; instead, they persist and bioaccumulate in aquatic organisms and exert harmful effects such as oxidative stress, reproductive damage, and genotoxicity (Ali et al., 2019). For example, mercury pollution has been linked with neurological disease in fish and humans via methylmercury bioaccumulation (Wang et al., 2021). Similarly, cadmium prevents enzyme activity and gill function in aquatic wildlife (Saxena et al., 2022). Heavy metal toxicity is also dependent on speciation and bioavailability of heavy metals as a function of environmental parameters such as pH, redox potential, and concentration of organic matter.

Organic Pollutants

Organic pollutants are the second major category of aquatic toxicants and include hydrocarbons, pesticides, and pharmaceuticals. Hydrocarbons, particularly petroleum-derived chemicals such as polycyclic aromatic hydrocarbons (PAHs), enter aquatic environments via oil spills, industrial effluent, and municipal runoff. They are water-repellent, bioaccumulate in sediments, and are carcinogenic to aquatic biota (Varjani et al., 2020). Pesticides, which are heavily used in agriculture, are prone to get into aquatic environments via leaching and surface runoff. Organophosphates, carbamates, and chlorinated pesticides disrupt aquatic invertebrates' and fish nervous systems and induce death and sublethal effects such as alteration of behavior (Singh et al., 2018). Pharmaceuticals, especially antibiotics and endocrine-disrupting chemicals, occur more commonly in rivers and lakes due to ineffective removal during wastewater treatment plants (Patel et al., 2019). Antibiotic residues not only exert ecotoxicological effects but also fuel antimicrobial resistance, subjecting ecosystems and human health to a double threat (Kümmerer et al., 2020).

Emerging Contaminants

In addition to conventional pollutants, emergent pollutants bring new problems because they are persistent, recalcitrant, and not subject to limited governmental treatment. Microplastics (<5 mm) are formed by the breakdown of larger plastic fragments and synthetic fibers, accumulating in aquatic sediments and ingested by plankton, fish, and shellfish (Masiello et al., 2023). Microplastics' high surface area allows adsorption of hydrophobic pollutants and microorganisms, increasing ecotoxicological hazards. Nanomaterials increasingly applied in electronics, medicine, and industry enter aquatic ecosystems with manufacturing waste streams and degradation products of nanoproducts. Due to their small size and high reactivity, nanomaterials such as silver and titanium dioxide nanoparticles induce oxidative stress and DNA damage in aquatic organisms (Keller et al., 2020). PFAS, a group of extremely persistent fluorinated substances widely utilized in the production of firefighting foams, textiles, and coatings, have become "forever chemicals" worldwide. They evade degradation with long-range transport and aquatic food chain bioaccumulation, as evidenced by reported endocrine disruption, immunotoxicity, and carcinogenicity to target species (Ruan et al., 2022).

The synergetic and residual effect of these toxicants due to the presence of pollutants renders them particularly concerning in aquatic environments. They impair ecosystem functions, alter microbial community processes, and increase ecological sensitivity to climate change. Their origin, fate, and toxicological impacts are necessary information for the improvement of effective remediation approaches, particularly bioremediation methods with emphasis on the utilization of biological systems in eliminating their toxic impacts.

Bioremediation Strategies

Bioremediation is a pillar in green technologies for pollution-sourced toxicant alleviation in water bodies. It entails utilization of native metabolic processes of microorganisms, algae, fungi, macrophytes, and microbial biofilm consortia to degrade, convert, or immobilize polluting substances. The choice of the method of bioremediation depends on pollutant type, environmental habitat, and ecological harmony, with recent advancements documented through utilization of biotechnological and systems-based practices (Figure-1).

Microbial bioremediation is now one of the most investigated and widely applied technologies, thanks largely to the metabolic potential of bacteria and archaea (Table-1). Some aquatic bacteria, such as Pseudomonas, Bacillus, and Shewanella spp., possess enzymatic processes for the degradation of hydrocarbons, pesticides, and pharmaceutical residues, while others eliminate or sequester heavy metals (Varjani et al., 2020). Some of the processes include enzymatic oxidation-reduction reactions, biosorption, and intracellular sequestration. For example, Shewanella oneidensis can reduce toxic hexavalent chromium [Cr(VI)] to its immobile trivalent form [Cr (III)], hence reducing bioavailability and toxicity (Xiao et al., 2017). Additionally, microbial consortia can be designed to offer synergistic interactions that enhance the rates of degradation of pollutants, particularly in multifaceted hydrocarbon-xenobiotic mixtures (Ali et al., 2020).

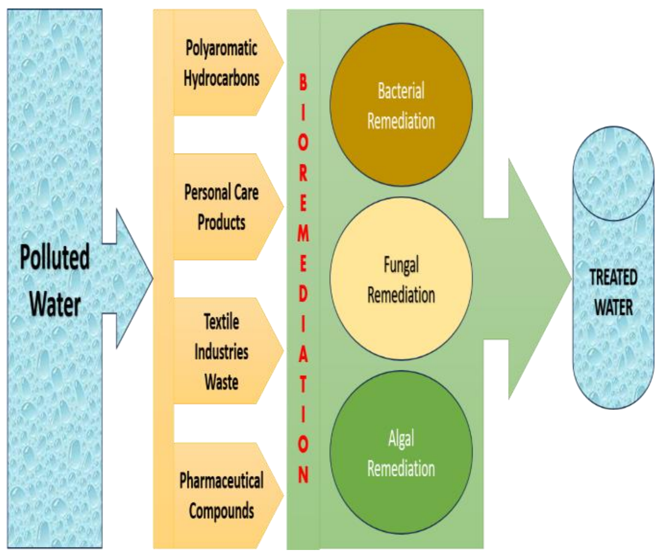


Figure.1 Bioremediation Strategies for Polluted Water Treatment.

Algal bioremediation is gaining increasing attention because algae have the capacity to assimilate nutrients and sequester pollutants while producing precious biomass. Microalgae such as Chlorella vulgaris, Scenedesmus obliquus, and cyanobacteria remove heavy metals through bioaccumulation, biosorption, and extracellular precipitation mechanisms (Wang et al., 2020). Algae are also capable of degrading organic pollutants such as pesticides and dyes via enzymatic activity and solar-powered photodegradation from sunlight-driven photosynthesis (Abinandan et al., 2019). Besides that, algae can eliminate contaminants and CO_2 sequestration, hence providing a dual environmental benefit. Combining algal bioremediation with wastewater treatment not only enhances the efficiency of pollutant removal but also provides a sustainable alternative source of biofuel feedstock and bioproducts.

Mycoremediation, utilization of fungi for the remediation of aquatic contaminants, is becoming increasingly popular due to the great enzymatic potential of white-rot and brown-rot fungi. These fungi produce extracellular ligninolytic enzymes such as laccases, peroxidases, and manganese peroxidases, capable of degrading structurally complex organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), dyes, and pesticides (Singh, 2017; Singh and Singh, 2023; Dwivedi et al., 2024a; 2024b; 2024c). Fungi also demonstrate very good biosorption property for heavy metals, made possible by the cell wall chitin and glucan components (Kiran & Pakshirajan, 2019). Freshwater fungal biofilms have also shown promise in breaking down pharmaceutical wastewater residue, a demonstration of their utility across different aquatic environments.

Phytoremediation using aquatic macrophytes involves utilizing above-ground plants such as Eichhornia crassipes (water hyacinth), Lemna minor (duckweed), and Typha latifolia (cattail) for cleaning or detoxifying pollutants from water ecosystems. Aquatic macrophytes uptake heavy metals and nutrients through roots and shoots, sequester them in tissues, or transform them to less toxic forms (Rezania et al., 2016). Water hyacinth has been thoroughly studied for its lead, cadmium, and arsenic removal, whereas duckweed efficiently assimilates surplus nitrogen and phosphorus, thereby alleviating eutrophication of polluted waters (Bhatia & Goyal, 2018). Macrophyte-mediated rhizodegradation also promotes rhizospheric microbial community development, creating synergistic pollutant removal mechanisms. Large-scale implementation is, however, limited by invasive growth habits and biomass disposal problems. Biofilm-mediated remediation is another efficient approach where microorganisms in extracellular polymeric substances (EPS) create a defensive matrix that also enhances pollutant degradation. Biofilms harbor microbial consortia with complementary metabolic processes to degrade several pollutants at the same time (Flemming & Wuertz, 2019).

The EPS matrix not only protects the cells from toxic shock but also extrudes heavy metals, pesticides, and drug residues, maximizing overall bioremediation efficiency. For instance, systems based on biofilm have been found to degrade petroleum hydrocarbons and pharmaceuticals more effectively than planktonic cells (Hou et al., 2020). Furthermore, employing biofilm bioreactors in wastewater treatment plants offers an expandable approach to mitigate aquatic pollution with the additional advantage of having ecological equilibrium.

Together, these bioremediation systems illustrate the wide ability of biological systems to mitigate toxicant-induced stress in aquatic ecosystems. While microbial, algal, fungal, and terrestrial plant-based systems each have their own strengths, systems that couple two or more systems are most likely to escape the complexity and multifaceted nature of aquatic pollution. Advances in genetic engineering, synthetic biology, and omics-based monitoring are continuing to enhance the efficiency and robustness of these bioremediation processes, offering a sustainable pathway to a return of aquatic health.

Microbial Bioremediation

Microbial bioremediation exploits bacteria and archaea's metabolic diversity to degrade, modify, or immobilize toxicants in aquatic environments. Pseudomonas, Bacillus, Shewanella, and Acinetobacter are also frequently quoted for degrading hydrocarbons as well as pesticides (Varjani et al., 2020).

Shewanella oneidensis has shown immense capability to respreate such toxic heavy metals as hexavalent chromium to less toxic trivalent forms, whereas immobilization of cadmium and lead is carried out by sulfate-reducing bacteria via precipitation as sulfides (Xiao et al., 2017). Development of microbial consortia enhances the degradation of pollutants, as synergistic reactions facilitate co-metabolism of a combination of pollutants. Furthermore, genetic engineering and omics approaches are more commonly employed to optimize microbial pathways to enhance the effectiveness of bioremediation under varying aquatic conditions (Ali et al., 2020).

Algal Bioremediation

Two roles play algae in aquatic environments: they engage in primary production as well as bio-remediation of toxic compounds. Microalgae such as Chlorella vulgaris, Scenedesmus obliquus, and Anabaena spp. can bioaccumulate and biosorb heavy metals like cadmium, lead, and mercury from water (Wang et al., 2020). Photosynthetic metabolism enhances pollution removal through the formation of oxygen-saturated microenvironments, permitting microbial breakdown of organic material.

In addition to this, algae are efficient at removing drugs and dyes via enzymatic and photodegradation mechanisms (Abinandan et al., 2019). The biomass that results from algal systems can even be utilized for the generation of biofuel, further enhancing the value of remediation technologies.

Mycoremediation

Mycoremediation, or fungal-based remediation, employs the enzymatic capacity of fungi to degrade complex organic pollutants and immobilize heavy metals. White-rot fungi such as *Phanerochaete chrysosporium* and Trametes versicolor produce lignin-degrading enzymes such as laccases and peroxidases that break down recalcitrant organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and dyes (Singh, 2017; Barwant et al., 2025d). Fungal cell walls with chitin and glucans are good biosorbents of heavy metals, reducing their mobility in water bodies (Kiran & Pakshirajan, 2019). The capacity of fungi to tolerate extreme pH and toxic environments makes them a candidate for bioremediation of heavily polluted aquatic environments where bacterial or algal processes are limited.

Phytoremediation using Aquatic Macrophytes

Phytoremediation utilizes higher aquatic plants for the removal, stabilization, or detoxification of contaminants from contaminated water. Macrophytes such as Eichhornia crassipes (water hyacinth), Lemna minor (duckweed), and Typha latifolia (cattail) have been studied extensively for pollutant uptake potential. They absorb heavy metals from their extensive root system and store them in their tissues in significant amounts (Rezania et al., 2016). Duckweed is particularly effective in removing such amounts of nutrients such as nitrogen and phosphorus, thereby preventing the eutrophication process (Bhatia & Goyal, 2018). The rhizosphere of macrophytes also supports dense populations of microbes that promote biodegradation of organic pollutants, producing a synergistic remediation effect. But large-scale phytoremediation must contend with limitations such as competitive growth patterns and safe disposal of toxic biomass (Singh et al., 2024; Barwant et al., 2025a).

Biofilm Remediation

Biofilm remediation takes advantage of cooperative metabolic processes of microbes that reside in an extracellular polymeric matrix. Biofilms provide mechanical stability and enhanced tolerance to toxic shock, enabling the microbes to grow and function in polluted aquatic systems (Flemming & Wuertz, 2019). Extracellular polymeric materials (EPS) not only protect cells but also bind heavy metals, pesticides, and drugs, facilitating removal of pollutants (Barwant et al., 2025b).

Biofilm consortia are particularly efficient in degrading petroleum hydrocarbon and drug contaminants in wastewater and outcompete planktonic cells on resistance and degradation grounds (Hou et al., 2020). Uses of biofilm-based systems in engineered bioreactors offer scalable, long-lasting solutions for wastewater treatment and restoring aquatic ecosystems.

Advances in Bioremediation Technologies

Emerging biotechnology innovations are reshaping bioremediation processes to yield more efficient, targeted, and scalable cleanup mechanisms for pollutee-caused toxicants in aquatic ecosystems. Traditional biological processes, though efficient, suffer from limitations such as low degradation rates, complete mineralization, or environmental sensitivity. Emerging innovations, including genetic and metabolic manipulation, omics-based insights, and nano-bioremediation, are engaged in addressing these limitations by speeding up pollutant biodegradation processes, clarifying key microbial actors, and introducing novel nanoscale solutions.

Genetic and Metabolic Engineering

Genetic engineering has emerged as a powerful means to enhance the ability of microbes to degrade pollutants by modifying or introducing specific catabolic pathways. For example, genetically modified strains of Pseudomonas putida and Escherichia coli have been engineered to break down hydrocarbons and aromatic pollutants more efficiently by the introduction of plasmid-encoded enzymes (Cases & de Lorenzo, 2020).

Table.1 Pollutant-Induced Toxicants in Aquatic Ecosystems and Bioremediation Strategies.

Pollutant Category	Examples	Ecological Impact	Bioremediation Strategy	References
Heavy Metals	Lead (Pb), Cadmium (Cd), Mercury (Hg), Arsenic (As)	Bioaccumulation in aquatic organisms, neurotoxicity, reproductive impairment	**Microbial bioremediation:** Metal-resistant bacteria (e.g., *Pseudomonas*, *Bacillus*) immobilize or transform metals. **Phytoremediation:** Aquatic plants (*Eichhornia crassipes*, *Lemna minor*) absorb and accumulate metals.	Ali et al., 2019; Riaz et al., 2021
Organic Pollutants	Hydrocarbons (oil spills), pesticides (DDT, organophosphates), pharmaceuticals (antibiotics, analgesics)	Endocrine disruption, mutagenicity, decline in aquatic biodiversity	**Algal bioremediation:** Microalgae degrade hydrocarbons and assimilate pesticides. **Mycoremediation:** Fungi (*Aspergillus*, *Trametes*) degrade hydrocarbons and pesticides. **Biofilm-mediated remediation:** Mixed microbial consortia degrade pharmaceutical residues.	Varjani, 2017; Sharma et al., 2021
Emerging Contaminants	Microplastics, nanomaterials, PFAS (per- and polyfluoroalkyl substances)	Physical blockage in aquatic fauna, oxidative stress, bioaccumulation, persistent pollution	**Microbial bioremediation:** Certain bacteria degrade plastics (e.g., *Ideonella sakaiensis*). **Algal bioremediation:** Algae adsorb nanomaterials and degrade plastics. **Phytoremediation:** Aquatic macrophytes trap microplastics and adsorb PFAS. **Biofilm-mediated remediation:** Biofilms enhance surface degradation of plastics.	Enyoh et al., 2020; Ghosal et al., 2022

Metabolic engineering still refines these processes by controlling intracellular fluxes in order to optimize pollutant metabolism and reduce toxic by-products. Genetically engineered Shewanella oneidensis, for instance, has been reported to have higher reduction rates of heavy metals like chromium and uranium through electron transfer manipulation (Wang et al., 2019).

Synthetic biology breakthroughs are now making it possible to engineer "designer microbes" with modular genetic circuits to sense pollutants and activate the degradation pathways accordingly, creating responsive and adaptive remediation systems (Raman & Rogers, 2021).

Omics-Based Approaches

Omics technologies like genomics, metagenomics, transcriptomics, proteomics, and metabolomics are transforming the understanding of microbial communities that participate in bioremediation (Barwant et al., 2025c). Metagenomics helps identify nonculturable microorganisms and their pollutant-degrading enzyme-encoding genes, expanding the array of potential bioremediators (Nayak et al., 2021).

Proteomics and transcriptomics elucidate protein function during pollutant stress and gene expression, revealing the enzymic routes for hydrocarbon, pesticide, and heavy metal degradation (Sharma et al., 2020). Metabolomics supplements these by analyzing intermediate metabolites, enabling complete mineralization rather than partial degradation. Comprehensive multi-omics approaches are being applied to engineer microbial consortia with synergistic functionalities, enhancing degradation of pollutants in complex water ecosystems (Singh et al., 2022). These system-level understandings have revolutionized bioremediation from empirical processes to precision-driven ecological engineering.

Nanobioremediation

Nanobioremediation combines the advantages of nanotechnology and biological remediation, offering a high surface area, reactivity, and specificity for pollutant removal. Nanoparticles such as zero-valent iron (nZVI), titanium dioxide (TiO_2), and silver nanoparticles have been utilized for the reduction, immobilization, or degradation of heavy metals, dyes, and organic pollutants (Reddy et al., 2018). nZVI, for instance, converts dangerous Cr(VI) into Cr(III), while TiO_2 nanoparticles enable photocatalytic decomposition of persistent organic pollutants under sunlight irradiation (Sharma et al., 2019). With application together with microorganisms or plants, nanoparticles enhance pollutant uptake and degradation by facilitating electron transfer, promoting bioavailability, or inhibiting microbial enzymes against inactivation (Prasad et al., 2021). Ecological safety and toxicity of nanoparticles are still major challenges that need to be carefully assessed before large-scale application. Nanobioremediation is thus a promising area but requires sustainable design to avoid secondary contamination.

Ecological Effectiveness and Limitations

Bioremediation is normally considered a green, environmentally friendly method for the mitigation of pollutan;t-caused toxicants in aquatic ecosystems. Its biological efficiency heavily depends on a range of environmental factors controlling microbial processes, bioavailability of pollutants, and ecosystem functions. In addition to this, the scaling-up of laboratory results to successful application at field scale is faced with a series of limitations restraining widespread use. Appreciation of these limitations is critical for maximizing the predictability and scalability of bioremediation technologies.

Environmental Parameters Regulating Bioremediation

The success of bioremediation processes in aquatic ecosystems is largely regulated by abiotic factors such as temperature, pH, dissolved oxygen, salinity, and nutrient concentrations. Temperature affects enzymatic activity and microbial metabolism, and most bioremediating microbes have optimal functioning in mesophilic regimes (20–37 °C). Deviation from these conditions has been found to reduce pollutant degradation rates (Dangi et al., 2019). pH regulates pollutant solubility and microbial enzyme activity; for instance, acidity increases the solubility of heavy metals, hence enhancing bioavailability but also toxicity (Saxena et al., 2022). Dissolved oxygen acts both as a helper and a hinderer since aerobic microbes require sufficient oxygen to break down hydrocarbons and pesticides, but anaerobic bacteria support the processes like sulfate or nitrate reduction that immobilize heavy metals (Ali et al., 2019).

Biotic factors also have roles. The composition and complexity of microbial communities determine potential for degradation, with consortia typically outcompeting single strains due to synergistic interactions (Varjani et al., 2020). Competition between native and introduced microbial populations can affect the effectiveness of pollutant removal, while predator–prey interactions within microbial food webs can decrease bioremediating population stability (Sharma et al., 2020). Physicochemical properties of the pollutants themselves, including solubility, hydrophobicity, and chemical structure, also control the rates of degradation. Resistant pollutants such as polycyclic aromatic hydrocarbons (PAHs) and per- and polyfluoroalkyl substances (PFAS) are not easily attacked by microbes, hence lowering overall efficiency (Ruan et al., 2022).

Challenges Facing Large-Scale Application

Although bioremediation has proven to be exceedingly successful under laboratory conditions, field-scale utilization in aquatic systems is not without limitations. Perhaps the most essential of these limitations is natural system heterogeneity, where fluctuating temperature, oxygen, and pollutant concentration create unstable environments that inhibit microbial activity (Sharma & Shukla, 2020). Moreover, pollutant bioavailability in sediment or particulate-bound form reduces availability to microbes and slows degradation (Patel et al., 2019). Another significant hindrance is the regulation of genetically engineered microorganisms (GEMs) or nanomaterials, which generate biosafety and ecological concerns. Uncontrolled increase in GEMs or unexpected nanoparticle toxicity would kill natural microbial communities and aquatic food webs (Cases & de Lorenzo, 2020; Prasad et al., 2021). Furthermore, the invasive macrophyte introduction or introduction of algal blooms under phytoremediation procedures may destabilize ecosystems if uncontrolled (Rezania et al., 2016).

Logistically, extensive bioremediation requires a long period to achieve measurable pollutant reduction, which would not be synchronized with acute remediation in highly contaminated regions. Monitoring cost, biomass handling, and disposal after treatment also limit application in resource-poor regions (Khan et al., 2017). Regulatory and public acceptance barriers also exist, particularly with emerging biotechnologies such as synthetic biology or nanobioremediation, with uncertain long-term risks to ecosystems.

In general, while bioremediation is theoretically effective ecologically, its limitations highlight the imperative for inter-disciplinary approaches grounded on biological, physicochemical, and engineered methods.

Future directions must tackle the issues of optimizing microbial consortia, enhancing pollutant bioavailability, and developing environmentally friendly technologies to counteract scalability and complexity issues in aquatic systems.

Regulatory, Socioeconomic, and Ecological Considerations

The use of bioremediation technologies in aquatic ecosystems is beyond the technical capacity, requiring cautious examination of the regulatory frameworks, socioeconomic factors, and ecological risk. These factors determine the pace, acceptability, and longevity of bioremediation technologies, and whether cutting-edge solutions progress from laboratory scale to full-scale environmental management.

Legislatively, bioremediation operations are governed by global pacts, national environmental protection laws, and local water quality parameters. For example, the U.S. Environmental Protection Agency (EPA) regulates microbial amendments and engineered organisms by the Toxic Substances Control Act, while the European Union employs the Water Framework Directive to ensure ecological safety (Hazen, 2018). Regulatory agencies concentrate on monitoring and risk assessment of genetically engineered microorganisms (GEMs) and nanomaterials due to concerns over unintended gene transfer, ecological disturbance, or nanoparticle toxicity (Cases & de Lorenzo, 2020; Prasad et al., 2021). Regulatory harmonization between nations remains a challenge as uneven guidelines hinder worldwide adoption of advanced bioremediation techniques.
Socioeconomic considerations are also important, particularly in low- and middle-income economies where toxicants elicited by pollutants disproportionately affect vulnerable groups depending on aquatic economies. Bioremediation offers a cost-effective and locally sustainable alternative compared to expensive physicochemical remediation, but restricted technology, inadequate infrastructure, and lacking finance can hinder adoption (Khan et al., 2017). Moreover, public perception and acceptability are influencers. Fears of releasing engineered organisms or nanomaterials can

lead to resistance from local stakeholders, wherein open communication and participatory decision-making (Raman & Rogers, 2021) are warranted. Synthesis of indigenous ecological understanding and modern biotechnology can promote cultural acceptability and stimulate remediation programs at the community level (Varjani et al., 2020).

Ecological issues are interested in potential dangers and unexpected consequences of bioremediation. Though microbial consortia, macrophytes, and algae can ensure effective pollution burden decrease, they may also destabilize native biodiversity when non-native species are introduced (Rezania et al., 2016). Overgrowth of invasive macrophytes, algae blooms, or excessive biofilm overgrowth may alter trophic processes and oxygen levels, trading one ecological problem for another (Ali et al., 2019). Similarly, genetically engineered microbial cultures can outcompete indigenous species or horizontally transfer genes, causing unforeseen ecological consequences (Saxena et al., 2022).

Hence, long-term monitoring and ecological risk assessment are essential to ensure that bioremediation enhances ecosystem resilience rather than compromising it.

Overall, regulatory, socioeconomic, and ecological considerations point to the complexity of implementing bioremediation in real aquatic ecosystems. It needs multidisciplinary negotiation between policymakers, scientists, industries, and local populations in order to develop governing mechanisms involving innovation and precaution.

By balancing ecological safety, economic feasibility, and social acceptability, bioremediation can go from a conceptualized hope to an accepted environmental management strategy for pollutant-induced toxicants.

Conclusion and Future Prospectives

Water ecosystems are exposed to increasing stress arising from pollutant-derived toxicants like heavy metals, hydrocarbons, pesticides, pharmaceuticals, and emerging compounds such as microplastics, nanomaterials, and PFAS. Bioremediation has emerged as an economic, sustainable, and environmentally friendly strategy compared to conventional physicochemical treatments. Microbial, algal, fungal, and plant-based strategies, in combination with biofilm-mediated systems, have proven significantly promising in degrading or immobilizing contaminants, thereby reestablishing ecological balance and human health protection. Genetic engineering innovations, omics-based technologies, and nano-bioremediation have now expanded the scale and efficiency of bioremediation strategies to render them increasingly convergent with sophisticated and mixed-pollutant scenarios (Cases & de Lorenzo, 2020; Sharma et al., 2020).

While such advances, numerous limitations to the extensive application of bioremediation remain. Heterogeneity of the environment, bioavailability of contaminants, and ecological risks of genetically engineered microorganisms or nanomaterials remain major concerns.

Their application on a massive scale is also precluded by socioeconomic and regulatory concerns, particularly in regions that have limited infrastructures or low public acceptance (Prasad et al., 2021; Varjani et al., 2020). These problems must be addressed through an integrated and multidimensional strategy that includes ecological risk assessment, stakeholder participation, and policy coordination.

In the coming times, research must be focused on maximizing microbial consortia and designing synthetic biology-based "designer microbes" that can sense, react to, and detoxify pollutants with extremely high specificity (Raman & Rogers, 2021). More use of multi-omics methods must be made to unlock the metabolic networks and ecological interactions that control pollutant breakdown, enabling predictive modeling and precision bioremediation (Singh et al., 2022). Besides that, combining bioremediation with other technologies like advanced oxidation processes, membrane systems, or constructed wetlands can optimize treatment efficiency for persistent pollutants like PFAS (Ruan et al., 2022).

The future of bioremediation also holds potential through the assurance of long-term ecological security and sustainability. Nature-based solutions, environment-friendly nanomaterials, and bio-augmented wetland ecosystems will have a central role in aligning remediation with ecosystem resilience objectives and the circular economy. Most importantly, balancing science, policy, and public engagement will make or break the success and acceptance of these strategies. By harmonizing these facets, bioremediation can be reformed from promising technology to a cornerstone of world aquatic ecosystem management.

References

Abinandan, S., Subashchandrabose, S. R., Venkateswarlu, K., & Megharaj, M. (2019). Microalgae–bacteria synergistic interactions and their applications in wastewater treatment and bioremediation. *Bioresource Technology, 276*, 258–265. https://doi.org/10.1016/j.biortech.2019.01.020

Akpor, O. B., Otohinoyi, D. A., Olaolu, T. D., & Aderiye, B. I. (2021). Bioremediation of polluted water resources: A review. *Applied Water Science, 11*(1), 1–13. https://doi.org/10.1007/s13201-021-01355-0

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry, 2019*, 6730305. https://doi.org/10.1155/2019/6730305

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Hazardous Materials, 369*, 467–479. https://doi.org/10.1016/j.jhazmat.2018.12.043

Ali, H., Khan, E., & Sajad, M. A. (2020). Phytoremediation of heavy metals—Concepts and applications. *Chemosphere, 91*(7), 869–881. https://doi.org/10.1016/j.chemosphere.2020.127002

Banerjee, A., & Dutta, T. K. (2019). Bioremediation of heavy metals by microbial communities: A promising approach. *Critical Reviews in Microbiology, 45*(3), 258–274. https://doi.org/10.1080/1040841X.2019.1589985

Barwant, M.M., Ogidi, O.I., Singh, B., Patil, V.S., Sharma, S.A.B. (2025b). Climate Change and Pesticide Dynamics. In: Babaniyi, B.R., Babaniyi, E.E. (eds) The Interplay of Pesticides and Climate Change. Springer, Cham. https://doi.org/10.1007/978-3-031-81669-7_7

Barwant, M.M., Singh, B., Rashid, R., Rasool, N., Lone, R. (2025d). Lignin as Biofertilizer. In: Jawaid, M., Ahmad, A., Meraj, A. (eds) Handbook of Lignin. Springer, Singapore. https://doi.org/10.1007/978-981-97-2664-6_55-1

Barwant, M.M., Singh, B., Sharma, S., Gore, N.T., Mohammad, A. (2025a). Role of Mycorrhizal Association in Leguminous Plant Growth. In: Mathur, P., Gupta, A. (eds) Recent Trends and Applications of Leguminous Microgreens as Functional Foods. Springer, Cham. https://doi.org/10.1007/978-3-031-75678-8_13

Barwant, M.M., Singh, B. et al. (2025c). Proteome Engineering: An Evolutionary Perspective of Biochemical Systems. In: Kaur, S., Dhiman, S., Tripathi, M. (eds) Microbial Metabolomics. Springer, Singapore. https://doi.org/10.1007/978-981-96-4824-5_6

Bhatia, P., & Goyal, D. (2018). Analyzing remediation potential of *Lemna minor* for heavy metals and nutrients. *Environmental Monitoring and Assessment, 190*(10), 573. https://doi.org/10.1007/s10661-018-6965-1

Cases, I., & de Lorenzo, V. (2020). Genetically modified organisms for the bioremediation of pollutants in aquatic and terrestrial habitats. *Current Opinion in Biotechnology, 64*, 39–46. https://doi.org/10.1016/j.copbio.2019.08.003

Chakraborty, P., Sarkar, A., & Bhattacharya, T. (2021). Aquatic pollution and its impact on ecosystem health: An overview. *Environmental Monitoring and Assessment*, *193*(2), 1–15. https://doi.org/10.1007/s10661-020-08822-3

Chatterjee, P., Mukherjee, S., & Bhattacharya, P. (2023). Advances in microbial bioremediation strategies for aquatic systems. *Frontiers in Microbiology, 14*, 1173045. https://doi.org/10.3389/fmicb.2023.1173045

Dangi, A. K., Sharma, B., Hill, R. T., & Shukla, P. (2019). Bioremediation through microbes: Systems biology and metabolic engineering approach. *Critical Reviews in Biotechnology*, *39*(1), 79–98. https://doi.org/10.1080/07388551.2018.1500997

Dwivedi, S., Singh, B., Singh, A. K., & Singh, V. K. (2024a). Cultivation of oyster mushroom (*Pleurotus ostreatus*) by using two different substrates in laboratory conditions. *Exon*, *1*(2), 67–75.

Dwivedi, S., Singh, B., Singh, A. K., & Singh, V. K. (2024b). Preparation of *Pleurotus* spawn on different grain substrates. *International Journal of Biological Innovations, 6*(1), 39–43. https://doi.org/10.46505/IJBI.2024.6105

Dwivedi, S., Singh, B., Singh, A. K., & Singh, V. K. (2024c). Cultivation of oyster mushroom (*Pleurotus djamor*) by using different substrates in laboratory conditions. *Kavak, 60*(3), 1–6. https://doi.org/10.36460/Kavaka/60/3/2024/1-6

Enyoh, C. E., Verla, A. W., Verla, E. N., Ibe, F. C., & Amaobi, C. E. (2020). Airborne microplastics: A review study on method for analysis, occurrence, movement and risks. *Science of the Total Environment, 137599.* https://doi.org/10.1016/j.scitotenv.2020.137599

Flemming, H. C., & Wuertz, S. (2019). Bacteria and archaea on Earth and their abundance in biofilms. *Nature Reviews Microbiology*, *17*(4), 247–260.

https://doi.org/10.1038/s41579-019-0158-9

Ghosal, D., Ghosh, S., Dutta, T. K., & Ahn, Y. (2022). Current state of knowledge in microbial degradation of plastics and microplastics: A review. *Journal of Environmental Management, 302*, 114566. https://doi.org/10.1016/j.jenvman.2022.114566

Hazen, T. C. (2018). Environmental biotechnology: Applications in bioremediation and environmental monitoring. *Current Opinion in Biotechnology, 50*, 1–3. https://doi.org/10.1016/j.copbio.2017.10.003

Hou, J., Wang, C., Mao, D., & Luo, Y. (2020). The role of biofilms in the removal of pharmaceuticals in aquatic environments. *Water Research, 182*, 115965. https://doi.org/10.1016/j.watres.2020.115965

Huang, L., Liu, J., & Sun, X. (2022). Emerging bioremediation approaches for aquatic pollution control: A review. *Journal of Environmental Management, 323*, 116221. https://doi.org/10.1016/j.jenvman.2022.116221

Jaiswal, S., Singh, D. K., & Shukla, P. (2018). Bioremediation of industrial effluents: An overview. *3 Biotech, 8*(4), 1–12. https://doi.org/10.1007/s13205-018-1195-4

Keller, A. A., Vosti, W., Wang, H., & Lazareva, A. (2020). Release of engineered nanomaterials from personal care products throughout their life cycle. *Journal of Nanoparticle Research, 22*(1), 7. https://doi.org/10.1007/s11051-019-4675-3

Khan, N., Nahar, N., & Ahmed, S. (2023). Nanobioremediation in water treatment: Opportunities and challenges. *Environmental Nanotechnology, Monitoring & Management, 20*, 100738. https://doi.org/10.1016/j.enmm.2023.100738

Khan, S., Afzal, M., Iqbal, S., & Khan, Q. M. (2017). Plant–bacteria partnerships for the remediation of hydrocarbon contaminated soils. *Chemosphere, 173*, 68–78. https://doi.org/10.1016/j.chemosphere.2016.12.118

Khan, S., Afzal, M., Iqbal, S., & Khan, Q. M. (2017). Plant–bacteria partnerships for the remediation of hydrocarbon contaminated soils. *Chemosphere, 173*, 68–78. https://doi.org/10.1016/j.chemosphere.2016.12.11

Kiran, B., & Pakshirajan, K. (2019). Fungal biosorption and biotransformation of heavy metals: A review. *Environmental Engineering Research, 24*(3), 363–378. https://doi.org/10.4491/eer.2018.282

Kumar, A., & Pal, D. (2020). Physicochemical and biological treatment of water pollutants: A review. *Environmental Technology & Innovation, 18*, 100670. https://doi.org/10.1016/j.eti.2020.100670

Kumar, V., Parihar, R. D., Sharma, A., et al. (2019). Global aquatic pollution: Causes, effects, and bioremediation strategies. *Science of the Total Environment, 695*, 133836. https://doi.org/10.1016/j.scitotenv.2019.133836

Kümmerer, K., Dionysiou, D. D., Olsson, O., & Fatta-Kassinos, D. (2020). A path to clean water. *Science, 361*(6399), 222–224. https://doi.org/10.1126/science.aau5721

Mallick, S., Saha, S., & Ghosh, A. (2022). Emerging contaminants in aquatic environments and their implications. *Environmental Research, 214*, 113877. https://doi.org/10.1016/j.envres.2022.113877

Masiello, C. A., et al. (2023). Microplastics in aquatic ecosystems: Sources, impacts, and remediation. *Nature Reviews Earth & Environment, 4*(7), 461–477. https://doi.org/10.1038/s43017-023-00453-6

Mishra, S., Bharagava, R. N., More, N., Yadav, A., & Zainith, S. (2019). Heavy metal contamination: An alarming threat to environment and human health. In R. N. Bharagava (Ed.), *Environmental pollutants and their bioremediation approaches* (pp. 103–123). CRC Press. https://doi.org/10.1201/9780429025440-6

Nayak, S., Rath, D., & Mohapatra, S. (2021). Metagenomics and its application in bioremediation: Unlocking the microbial dark matter. *Environmental Research, 194*, 110660. https://doi.org/10.1016/j.envres.2020.110660

Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., & Mohan, D. (2019). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. *Chemical Reviews, 119*(6), 3510–3673. https://doi.org/10.1021/acs.chemrev.8b00299

Prasad, R., Kumar, V., & Prasad, K. S. (2021). Nanobiotechnology in sustainable remediation of pollutants: Advances and challenges. *Environmental Technology & Innovation, 22*, 101497. https://doi.org/10.1016/j.eti.2021.101497

Raman, R., & Rogers, J. K. (2021). Synthetic biology approaches for microbial bioremediation: Engineering designer consortia and responsive systems. *Trends in Biotechnology, 39*(2), 112–124. https://doi.org/10.1016/j.tibtech.2020.07.006

Reddy, K. R., Xie, T., & Dastgheibi, S. (2018). Nanomaterials for environmental cleanup: A review of nanobioremediation technologies. *Critical Reviews in Environmental Science and Technology, 48*(11), 1121–1166. https://doi.org/10.1080/10643389.2018.1477418

Rezania, S., Taib, S. M., Din, M. F. M., Dahalan, F. A., & Kamyab, H. (2016). Comprehensive review on phytoremediation of heavy metals in water: Opportunities and challenges. *Environmental Science and Pollution Research, 23*(20), 20183–20200. https://doi.org/10.1007/s11356-016-7413-6

Riaz, U., Murtaza, G., & Anwar-ul-Haq, M. (2021).

Phytoremediation of heavy metals in water and soil: Progress and perspectives. *Chemosphere, 263,* 129300. https://doi.org/10.1016/j.chemosphere.2020.129300

Ruan, T., Lin, Y., Wang, T., & Jiang, G. (2022). PFAS pollution in aquatic ecosystems: Sources, fate, and toxicological implications. *Environmental Science & Technology*, *56*(3), 1305–1321. https://doi.org/10.1021/acs.est.1c06024

Saxena, G., Bharagava, R. N., Kaithwas, G., Raj, A., & Saxena, A. (2022). Microbial approaches in bioremediation of pollutants: Technologies and future directions. *Environmental Sustainability*, *5*(1), 1–15. https://doi.org/10.1007/s42398-021-00202-9

Sharma, B., Dangi, A. K., & Shukla, P. (2020). Contemporary approaches in bioremediation: A review. *3 Biotech*, *10*(11), 1–12. https://doi.org/10.1007/s13205-020-02422-9

Sharma, B., Dangi, A. K., & Shukla, P. (2021). Contemporary enzyme-based technologies for bioremediation: A review. *Environment International*, *146*, 106678. https://doi.org/10.1016/j.envint.2021.106678

Sharma, B., Dangi, A. K., Shukla, P., & Sharma, S. (2020). Biotechnological approaches for omics-driven bioremediation: A paradigm shift in environmental microbiology. *Biotechnology Advances*, *42*, 107572. https://doi.org/10.1016/j.biotechadv.2020.107572

Sharma, P., & Shukla, P. (2020). Microbial community dynamics for sustainable bioremediation: Recent advances and future challenges. *Current Opinion in Environmental Science & Health*, *13*, 132–138. https://doi.org/10.1016/j.coesh.2019.11.007

Sharma, P., Pandey, A. K., & Singh, A. (2019). TiO_2 nanoparticles as an efficient photocatalyst for degradation of organic pollutants: Mechanisms and applications. *Environmental Nanotechnology, Monitoring & Management*, *12*, 100261. https://doi.org/10.1016/j.enmm.2019.100261

Singh, B., & Singh, V. K. (2023). Diversity of wood-inhabiting macrofungi from District Ayodhya, Uttar Pradesh, India. *Kavak*, *59*(3), 1–11.

Singh, B., Tripathi, S., Tyagi, S., Tripathi, A., Dubey, P., Kumar, S. (2024). Phytostimulation and Induction of Systemic Resistance by Plant Growth Promoting Fungi. In: Mathur, P., Roy, S. (eds) Plant Microbiome and Biological Control. Sustainability in Plant and Crop Protection, vol 20. Springer, Cham. https://doi.org/10.1007/978-3-031-75845-4_10

Singh, H. (2017). *Mycoremediation: Fungal bioremediation*. John Wiley & Sons.

Singh, N. S., Gupta, V. K., & Kumar, A. (2018). Pesticides and their impact on soil microbial diversity. *Applied Soil Ecology*, *123*, 404–417. https://doi.org/10.1016/j.apsoil.2017.09.024

Singh, R., Kumar, M., Mittal, A., & Mehta, P. K. (2022). Multi-omics strategies for bioremediation: Recent developments and future prospects. *Frontiers in Microbiology*, *13*, 840312. https://doi.org/10.3389/fmicb.2022.840312

Varjani, S. J. (2017). Microbial degradation of petroleum hydrocarbons. *Bioresource Technology, 223*, 277–286. https://doi.org/10.1016/j.biotechadv.2017.02.001

Varjani, S. J., Gnansounou, E., & Pandey, A. (2020). Bioremediation of petroleum hydrocarbons: Constraints and opportunities. *Science of the Total Environment*, *727*, 138063. https://doi.org/10.1016/j.scitotenv.2020.138063

Wang, L., Min, M., Li, Y., Chen, P., Chen, Y., Liu, Y., Wang, Y., & Ruan, R. (2020). Cultivation of microalgae in dairy wastewater for nutrient removal and biomass production. *Bioresource Technology*, *273*, 456–463. https://doi.org/10.1016/j.biortech.2018.11.041

Wang, Y., Kern, S. E., & Newman, D. K. (2019). Enhancing microbial bioremediation of metals via genetic and metabolic engineering. *Nature Reviews Microbiology*, *17*(8), 493–504. https://doi.org/10.1038/s41579-019-0225-8

Wang, Z., Xie, Z., & Mi, W. (2021). Mercury bioaccumulation and its impacts on aquatic ecosystems. *Ecotoxicology and Environmental Safety*, *219*, 112343. https://doi.org/10.1016/j.ecoenv.2021.112343

Xiao, X., Wu, Z., Chai, L., & Qiu, G. (2017). Bioremediation of hexavalent chromium by *Shewanella oneidensis MR-1* and factors influencing its efficiency. *Journal of Hazardous Materials, 338*, 355–364. https://doi.org/10.1016/j.jhazmat.2017.05.001

How to cite this article:

G. R. Kamalapuri, Ram Sagar Gaur, Sakshi Tripathi, Balwant Singh, Abhinav Singh, Vinay Kumar Singh and Piyush Mishra. 2025. Bioremediation of Pollutant-Induced Toxicants in Aquatic Ecosystem. Int. J. Curr. Res. Biosci. Plant Biol., 12(3): 13-26. **doi:** https://doi.org/10.20546/ijcrbp.2025.1203.002