https://scienceinkrishi.com

Chennu et al., 2026

Popular article ISSN:2583-4150

MANAGEMENT MEASURES FOR THE ENVIRONMENT: BIOREMEDIATORS AND BIOCONTROL AGENTS

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Accepted on July 06, 2026

Introduction

Aquatic environments are vital ecosystems that uphold a rich diversity of life and offer important resources for humans with numerous ecological benefits. In recent years, shrimp and fish farming in brackish and freshwater systems has grown considerably to meet the increasing demand for aquatic food products (Krishnani et al*.,* 2025). However, the rapid expansion and intensification of aquaculture practices have also increased the risk of environmental stressors, including harmful microorganisms and heavy metals, which can adversely affect water quality and threaten aquatic organisms (Mallik et al*.,* 2024). Traditionally, chemical and physical remediation methods have been employed to manage such contaminants, but these approaches are often expensive and may result in the accumulation of toxic by-products. As a result, biological strategies such as bioremediation and biocontrol agents are gaining significant interest as sustainable alternatives. These biological approaches make use of living organisms, including bacteria, fungi, algae, and plants, to degrade pollutants and control harmful microorganisms (Prabu and Santhiya, 2016). Owing to their effectiveness, affordability and eco-friendly nature, these biological methods are increasingly being adopted for maintaining water quality and ensuring the health of aquatic ecosystems.

Bioremediators in Environmental Management

Bioremediation refers to the use of living organisms, particularly microbes and plants, to detoxify and restore polluted environments. These organisms break down or transform harmful pollutants into non-toxic forms (Zhou and Liu, 2024). Depending on the type of contamination and site conditions, bioremediation can be carried out either directly at the contaminated site (in situ / on-site) or after the removal of contaminated material to another location (ex situ / off-site). Similarly, biocontrol involves the use of beneficial living organisms to control pests or invasive species that damage crops, natural habitats, or other ecosystems (Soares et al., 2025). The pollutants and pathogenic organisms present in aquatic environments can be effectively mitigated employing both bioremediators and biocontrol agents (Figure 1).

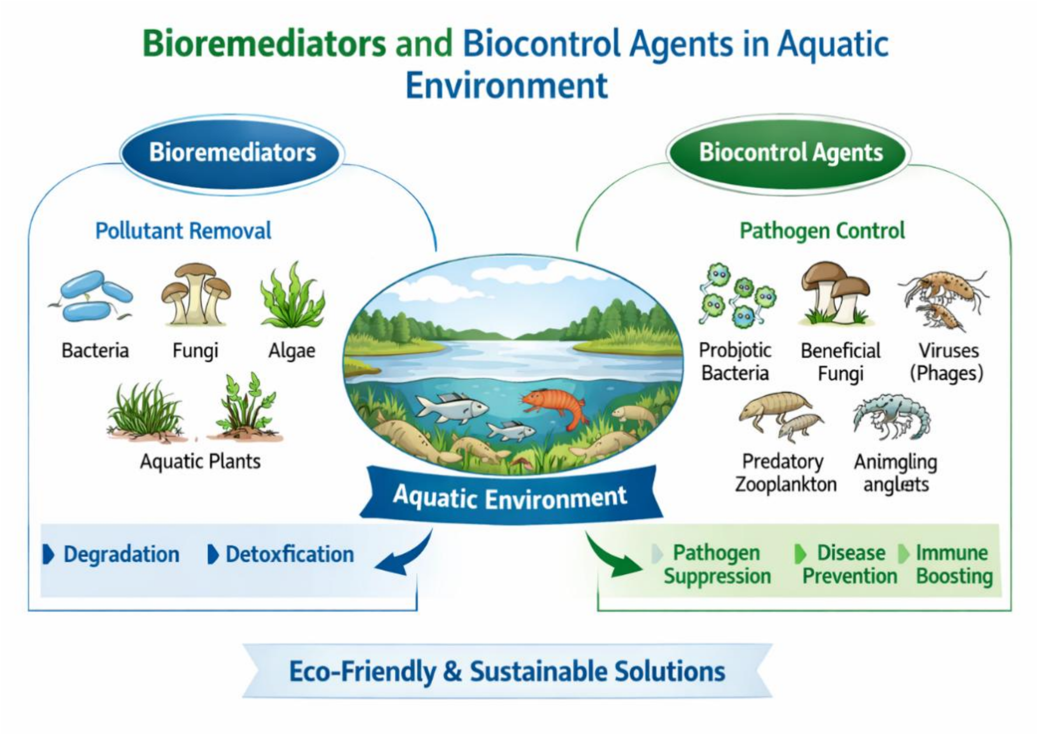

Figure 1. Bioremediators and Biocontrol agents employed for the mitigation of pollutants and pathogens in aquatic environments for sustainable and eco-friendly management.

Microorganisms as Bioremediators

Microorganisms play a crucial role in bioremediation and are widely recognized as effective agents for the removal of environmental pollutants. Various groups of microorganisms, including archaebacteria, yeasts, and fungi, possess the ability of metabolizing and break down a wide range of pollutants, including heavy metals, industrial solvents, and petroleum hydrocarbons. The list of bioremediators employed for the mitigation of heavy metals from various sources and their mechanism of action is summarized in Table 1.

Table 1. Heavy metal bioremediators and their efficiency

Microorganism	Heavy Metals Removed	Mechanism of Action	Source
Bacillus subtilis	Pb, Cd, Zn, Cu, Ni	Biosorption, precipitation	Soil, wastewater
Pseudomonas aeruginosa	Cd, Pb, Fe, Cu, U, Ni	Bioaccumulation, enzymatic degradation	Industrial effluents
Streptomyces sp.	Cu, Zn, Cd, Pb	Chelation, complexation	Contaminated water
Saccharomyces cerevisiae	Cd, Pb, Cu, Zn	Cell wall binding, passive uptake	Brewery waste
Candida utilis	Cd, Cr	Metal ion complexation	Activated sludge
Escherichia coli (engineered)	Hg, Cr, Pb	Genetic bioadsorption	Lab strains

Algae and Fungi in Bioremediation

Algae and fungi are widely used in environmental cleanup because of their ability to remove pollutants from contaminated water and soil. Algae, particularly cyanobacteria and green algae, are employed in phycoremediation, where they help remove excess nutrients, heavy metals, and other contaminants from polluted water bodies. Similarly, fungi, especially white-rot fungi, play a significant role in mycoremediation due to their ability to degrade a wide range of complex organic pollutants and absorb heavy metals. Their adaptability and pollutant-removal capabilities make them valuable tools for improving environmental quality. Examples of algae and fungi used in the bioremediation of various pollutants, along with their applications, are presented in Table 2.

Table 2. Algae and fungi as bioremediators of pollutants

Organism	Pollutants	Type
Chlorella vulgaris	Cd, Cu, Pb, Zn	Algae
Scenedesmus obliquus	Cd, Zn	Algae
Aspergillus niger	Heavy metals, pesticides	Fungus
Ganoderma lucidum	Cr, Cu	Fungus
Phanerochaete chrysosporium	PAHs, dioxins	Fungus

Phytoremediation Using Plants

Phytoremediation is an eco-friendly approach that uses plants to remove, transfer, stabilize, or destroy contaminants in polluted soil and water. Certain plants, have the ability to absorb, accumulate and remove contaminants known as hyper accumulators, can take up exceptionally high amounts of heavy metals or organic pollutants without being adversely affected. Different plant species used for bioremediation of pollutants is listed in Table 3.

Table 3. List of Plant species used for bioremediation of pollutants

Plant species	Pollutants
Brassica juncea	Se, Pb, Cu
Helianthus annus	As, U
Thlaspi caerulescens	Cd, Zn
Pteris vitata	As, Hg, Cs
Medicago sativa	PAHs

Role of Biotechnology in Bioremediation

The application of biotechnology has significantly expanded the scope of bioremediation. Through genetic engineering, microorganisms can be modified to degrade specific contaminants more efficiently, making bioremediation a more effective and targeted approach.

Examples:

- *Deinococcus radiodurans* modified to digest radioactive waste (Lakshmi et al., 2022).
- *Escherichia coli* engineered to bind heavy metals using metallothione in proteins (Li et al., 2021).
- TERI's Oilzapper: a microbial consortium developed in India for petroleum clean up (Shinde et al., 2020).

These approaches use genetic engineering to enhance microbial resistance, increase metabolic rates, and expand substrate range.

Limitations and Challenges

Despite their advantages, bioremediation and biocontrol technologies face several limitations:

- Not all pollutants are biodegradable.
- Environmental factors such as pH, temperature, and oxygen availability affect performance.
- Some by-products of biodegradation may be more toxic than the original pollutant.
- Large-scale field applications are often hindered by ecological and regulatory concerns.

- Phycoremediation is limited by the surface area of plant roots, while phytoremediation can lead to bioaccumulation of toxins in plant tissues, potentially entering the food chain.

Future Prospects

The future of environmental management is likely to depend on the combined use of bioremediation and biocontrol approaches alongside modern biotechnological advancements. Integrating the capabilities of microorganisms, plants, and fungi may offer more efficient and sustainable solutions for addressing environmental pollution. Emerging technologies such as nanotechnology and synthetic biology further expand the potential of these biological systems by improving their effectiveness and versatility. However, several challenges remain, including the development of region-specific microbial consortia, the optimization of large-scale field applications, and the assessment of the environmental safety of genetically modified organisms. Continued research in these areas is essential to maximize the benefits of biological remediation strategies. In addition, increasing public awareness and encouraging community participation will play an important role in the successful implementation and long-term acceptance of these environmentally friendly approaches.

Conclusion

Bioremediators and biocontrol agents offer promising, environmentally safe, and cost-effective approaches to managing environmental pollution. Through microbial degradation, algal and fungal absorption, and plant-based accumulation, these biological agents help restore ecosystem health. When supported by biotechnology, their potential expands further, offering solutions to even the most persistent pollutants. For a cleaner, greener future, embracing such sustainable techniques is not just beneficial; it is essential.

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