

Biotechnological Interventions in Aquatic Resource Management

Divyanshu Kumar Upadhyay, Rajesh Kumar and Priyanka Rani

Department of Aquaculture, College of Fisheries, Govind Ballabh Pant University of Agriculture and Technology (GBPUA&T), Pantnagar, Uttarakhand, 263145, India

SUMMARY

Water makes up three quarters of the earth, however there is a limited supply of fresh water accessible. One of the main concerns in the wide range of environmental challenges of the modern period is water pollution. Overfishing, pollution, habitat destruction and climate changes are some of the significant problems that aquatic habitats have encountered in recent years. These difficulties have prompted the advancement of innovative biotechnological strategies aiming to preserve aquatic biodiversity and advance sustainable resource management. Aquaculture strategies that increase the production of food while reducing environmental consequences are one of the main areas for advancement in aquatic biotechnology. Genetically modified organism is used in sustainable aquaculture methods to increase disease resistance, increase feed efficiency and decrease the environmental impact of fish farming. Furthermore, biotechnology is essential for repairing aquatic ecosystem that have been harmed by methods like habitat restoration and bioremediation. Additionally, investigators now have a greater understanding of the physiology, behavior and adaptation processes of aquatic animals because to developments in molecular biology and genetic studies. Overall, aquatic biotechnology presents viable and sustainable ways to tackle the many problems that confront our aquatic ecosystems. By using the potential of innovation in this area, we can support biodiversity preservation, prudent resource management and the long-term viability of the aquatic ecosystems on our planet.

INTRODUCTION

Biotechnological interventions have emerged as effective tools for managing environmental pollution by utilizing the natural activities of biological organisms to transform or eliminate contaminants and convert them into less harmful substances. These interventions encompass a wide range of advanced techniques designed to enhance and regulate the functions of biological systems for environmental remediation.

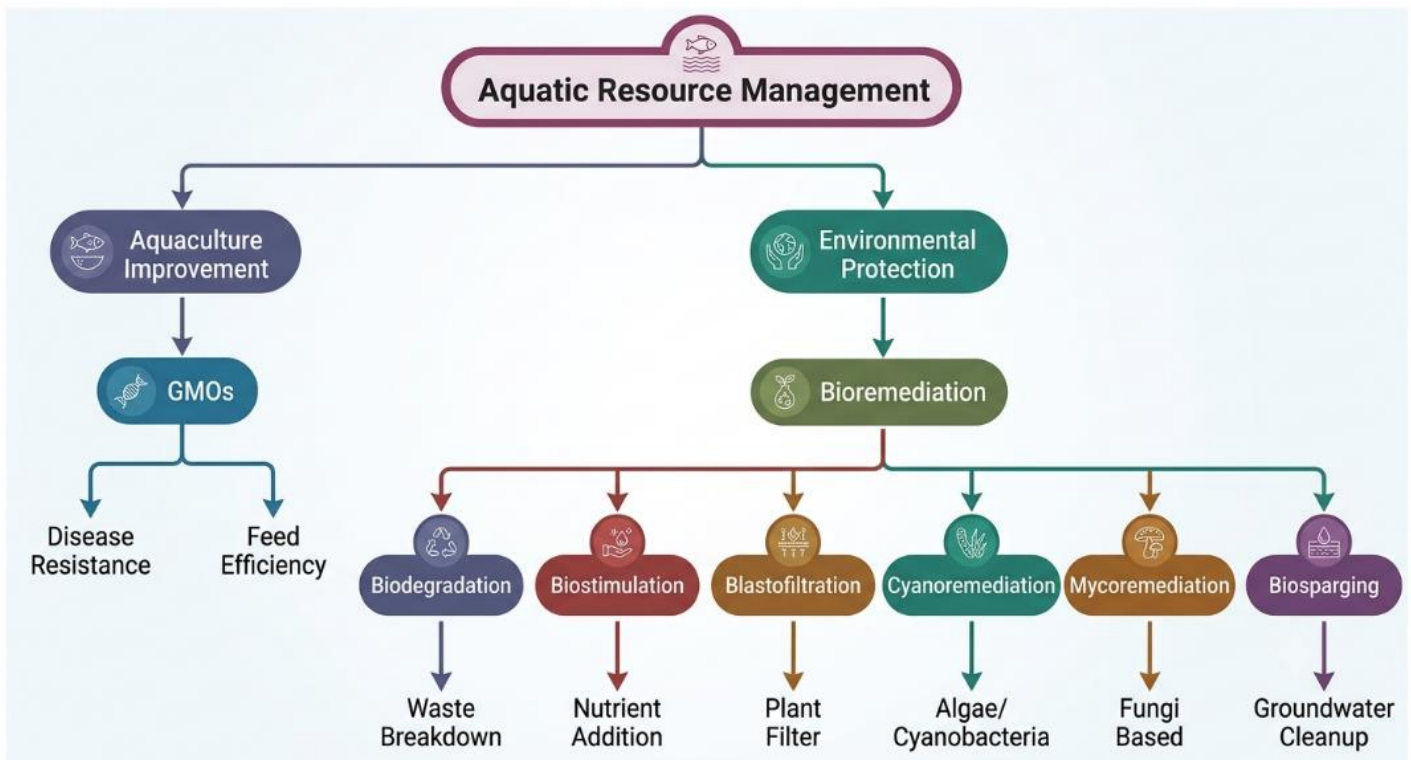


Fig 1. Applications of Biotechnology in Aquatic Resource Management

Aquatic ecosystems worldwide are increasingly threatened by continuous inputs of pollutants, including oil spills, solid wastes, heavy metals and plastic debris. Such pollutants adversely affect the physicochemical properties, biological integrity and aesthetic value of water bodies. To address these challenges, biotechnology

offers environmentally friendly cleanup approaches collectively known as bioremediation. Bioremediation can be carried out either in situ (at the contaminated site) or ex situ (after removing the contaminated material). These approaches work by either removing pollutants from the environment through decontamination and cleanup processes or by stabilizing contaminants to minimize their mobility and ecological risks. Several biotechnological methods are employed in bioremediation, including biosorption, biodegradation, biostimulation, biofiltration, cyanoremediation, biosparging and mycoremediation. These techniques utilize microorganisms, algae, fungi and other biological agents to remove, degrade or neutralize environmental contaminants. Beyond pollution control, biotechnology also contributes to sustainable development through innovations such as microbial fuel cells, which generate bioelectricity from biological processes and the production of biodiesel using microbial resources.

Biodegradation

Biodegradation in aerobic environments is a biological process in which microorganisms break down waste materials in the presence of oxygen. The successful application of this process depends on a thorough understanding of the biogeochemical cycles, metabolic pathways and genomic characteristics of the microbial communities involved. Detailed knowledge of microbial consortia and their interactions enables the efficient degradation of pollutants and organic wastes, thereby enhancing environmental remediation efforts.

Mycoremediation

Mycoremediation is a bioremediation technique that utilizes fungi to remove, degrade or immobilize pollutants from contaminated environments. Due to their extensive enzymatic systems and high pollutant-accumulating capacity, fungal species are considered highly effective agents for the remediation of contaminated aquatic and terrestrial ecosystems. Several fungi, including *Aspergillus niger*, *Aureobasidium pullulans*, *Cladosporium resinae*, *Funalia trogii*, *Ganoderma lucidum*, *Penicillium* spp., *Rhizopus arrhizus* and *Trametes versicolor*, have demonstrated significant potential for the removal and recovery of heavy metals from polluted environments. These fungi can absorb, accumulate and transform toxic metal ions, thereby reducing their environmental impact. For instance, *Aspergillus versicolor* exhibited high bioaccumulation efficiencies for chromium, nickel and copper in wastewater, achieving removal rates of 99.89%, 30.05% and 29.06%, respectively (Tastan et al., 2010). Likewise, *Aspergillus fumigatus* effectively removed lead (Pb) from aqueous solutions derived from electronic waste, with an adsorption efficiency of 85.41% at an initial lead concentration of 100 mg/L.

Biostimulation

Microorganisms, especially bacteria and fungi, serve as natural biotransformers capable of converting a wide range of xenobiotic compounds into usable energy sources. Their metabolic versatility makes them valuable agents in environmental remediation and pollution control. Biostimulation, a form of in situ bioremediation, involves the addition of nutrients and other essential compounds to contaminated environments to stimulate the growth and activity of indigenous microorganisms. This approach accelerates the degradation of pollutants in areas affected by accidental spills and long-term contamination. Microbial cultures with enhanced bioremediation potential can be isolated from sites contaminated with heavy metal wastes and utilized for environmental cleanup. The effectiveness of biostimulation depends on providing optimal conditions for microbial activity, including supplementation with nitrogen, phosphorus, oxygen as an electron acceptor and suitable carbon substrates. These amendments promote microbial growth and enhance their ability to degrade or transform environmental contaminants. Certain bacterial species isolated from polluted environments possess plasmid-mediated resistance to chromium, enabling them to enzymatically reduce toxic chromate compounds and thereby facilitate chromium bioremediation. Advances in molecular biotechnology have further enabled the development of microbial strains with improved stress tolerance and remediation capabilities. For example, the bacterial merC gene has been identified as a promising molecular tool for enhancing cadmium phytoremediation efficiency. In addition, sulfate-reducing bacteria (SRB) have demonstrated significant potential in the treatment of heavy metal-contaminated wastewater. When incorporated into a bioreactor containing sulfate and metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu) and zinc (Zn), SRB achieved approximately 50% sulfate reduction while completely removing the heavy metals from the system.

Blast Filtration

Blastofiltration is an eco-friendly biological remediation technique in which aerated water containing precipitated contaminants and heavy metal-polluted effluents is passed through selected plant seedlings for purification. These seedlings act as natural biofilters, absorbing and accumulating heavy metals from the

contaminated water. Studies have demonstrated the effectiveness of blastofiltration in reducing lead (Pb) concentrations from 100 mg/L to approximately 5 mg/L within 72 hours through the use of suitable crop seedlings. The efficiency of this technique depends on the metal uptake capacity of the plant species employed. To enhance the application of blastofiltration in environmental management, further research is needed to evaluate the heavy metal accumulation potential of different crop species. Such investigations can help identify highly efficient plants for the remediation of heavy metal-contaminated aquatic ecosystems and contribute to the development of sustainable water treatment strategies.

Cyanoremediation

Cyanoremediation refers to the use of cyanobacteria and certain algal species for the removal of heavy metals and other pollutants from contaminated aquatic environments and wetlands. This bioremediation approach utilizes naturally occurring strains, mutant varieties or genetically engineered cyanobacteria to enhance pollutant removal efficiency. Several cyanobacterial species have demonstrated remarkable capabilities for heavy metal uptake and accumulation. For example, *Synechocystis* sp. PCC6803, a blue-green alga, has shown significant potential for arsenic accumulation. Similarly, *Spirogyra* species can effectively bioaccumulate a wide range of heavy metals, including chromium (98.23%), copper (89.6%), iron (99.73%), manganese (99.6%), selenium (98.16%) and zinc (81.53%). Another cyanobacterial genus, *Spirulina*, has also exhibited strong metal removal capabilities, achieving removal efficiencies of 98.3% for chromium, 81.2% for copper, 98.93% for iron, 99.73% for manganese, 98.83% for selenium and 79% for zinc at an initial metal concentration of 5 mg/L. In addition, algal species such as *Hydrodictyon*, *Oedogonium* and *Rhizoclonium* efficiently absorb heavy metals from wastewater. The accumulated metals become incorporated into the algal biomass, contributing to an increase in their dry weight while simultaneously reducing contaminant levels in the aquatic environment.

Biosparging

Groundwater pollution has become a significant environmental concern alongside the contamination of surface water resources. One effective bioremediation technique used to address groundwater contamination is biosparging. This method involves injecting air beneath the groundwater table to increase the concentration of dissolved oxygen in the subsurface environment. The increased oxygen availability stimulates the activity of aerobic microorganisms, thereby enhancing the biodegradation of organic contaminants present in groundwater. As a result, pollutants are broken down more rapidly and efficiently. The effectiveness of biosparging largely depends on the rate of air injection, which directly influences oxygen distribution and microbial activity. Higher and properly controlled air injection rates can significantly accelerate biodegradation processes, making biosparging a valuable technique for the remediation of heavily contaminated groundwater systems.

CONCLUSION

Biotechnological interventions provide sustainable and cost-effective solutions for managing aquatic pollution. Techniques such as biosorption, biodegradation, biostimulation, blastofiltration, cyanoremediation, biosparging and mycoremediation utilize microorganisms and other biological agents to remove or transform pollutants. In addition, microbes contribute to renewable energy production through microbial fuel cells and biodiesel generation, while biosensors enable efficient monitoring of water quality. Together, these technologies support the conservation and sustainable management of aquatic ecosystems.

REFERENCES

- Tastan, B. E., Ertugrul, S., & Donmez, G. (2010). Effective bioremoval of reactive dye and heavy metals by *Aspergillus versicolor*. *Bioresource Technology*, 101(3), 870–876. <https://doi.org/10.1016/j.biortech.2009.08.101>
- Ayangbenro, A. S., & Babalola, O. O. (2017). A new strategy for heavy metal polluted environments: A review of microbial biosorbents. *International Journal of Environmental Research and Public Health*, 14(1), 94. <https://doi.org/10.3390/ijerph14010094>
- Dixit, R., Wasiullah, Malaviya, D., Pandiyan, K., Singh, U. B., Sahu, A., Shukla, R., Singh, B. P., Rai, J. P., Sharma, P. K., Lade, H., & Paul, D. (2015). Bioremediation of heavy metals from soil and aquatic environment: An overview of principles and criteria of fundamental processes. *Sustainability*, 7(2), 2189–2212. <https://doi.org/10.3390/su7022189>