***Review Article***

**Aquatic Pollution: Sources, Effects, and Biotechnological Approaches for Remediation**

**Abstract:** Aquatic pollution has become a global risk to brackish, marine, and freshwater ecosystems, significantly impairing biodiversity, fisheries productivity, and fundamental ecosystem functions. The sources and effects of major aquatic pollution that are currently known are reviewed, covering toxicological effects on fishes' health, perturbations on aquatic biodiversity, and degradation of water quality. Special emphasis was put on novel biotechnological remediations and monitoring methods to counteract pollution. The dredging and chemical treatment traditional remediations are introduced and compared with biological processes such as microbial bioremediation, phytoremediation, enzyme technology, and Nano bioremediation. Case studies from India and around the world demonstrate the practical efficacy of these strategies under diverse ecological and industrial conditions. While recent advances in genetic engineering, synthetic biology, and biosensor technologies offer promising avenues for real-time pollutant detection and targeted remediation, several knowledge gaps remain particularly regarding long-term field performance, ecosystem integration, and regulatory scalability. The review concludes by highlighting future research directions and the need for integrative policy frameworks that support sustainable and community-engaged deployment of biotechnological interventions.

**Keywords**: Aquatic pollution, Bioremediation, Phytoremediation, Microbial remediation, Biosensors, Nanotechnology, Ecosystem services, Water quality, Environmental biotechnology, Pollution monitoring

**1. Introduction**

**1.1 Definition and Scope of Aquatic Pollution**

Aquatic pollution involves the introduction of harmful substances like heavy metals, nutrients, microplastics, and organic pollutants into water bodies, degrading ecosystem health and water quality (Pandey et al., 2021). Pollutants may originate from industrial discharges, agricultural runoff, domestic sewage, and atmospheric deposition, contributing to the accumulation of toxicants like heavy metals, organic compounds, nutrients, and microplastics in aquatic environments (Jarvis & Younger, 2000). Pollution arises from point sources (e.g., industrial discharges, sewage effluent) and non-point sources (e.g., agricultural runoff, atmospheric deposition), both of which contribute to widespread water contamination (Singh et al., 2024). Toxicants in aquatic environments pose significant threats to human health, especially through bioaccumulation and drinking water contamination, necessitating interdisciplinary efforts in monitoring and management (Ritter et al., 2002).

**1.2 Importance of the Topic**

Aquatic pollution poses direct and indirect threats to fish health, productivity, and biodiversity. Toxic contaminants, such as endocrine-disrupting chemicals, heavy metals, and hydrocarbons, tend to bioaccumulate within the tissues of fish and cause effects on reproduction, changes in behaviour, and higher mortality rates (Akhter *et al.*, 2024). These effects cascade through aquatic food webs, destabilizing entire ecosystems and diminishing the ecological services they provide. In coastal and inland fisheries, water contamination reduces fish yield and economic returns, threatening the food security and livelihoods of millions of people globally. Also, aquaculture systems are particularly prone to contamination because they are semi-permanent systems. Nutrient loading from feed residues, feces, and chemical inputs can exacerbate eutrophication, promote harmful algal blooms, and compromise water quality (Cao *et al.*, 2007). The intricate relationship between water quality and fish health necessitates integrated management strategies that reduce pollutant inputs while ensuring sustainable fish production (Ormerod, 2003).

**1.3 Objectives and Structure of the Review**

This review seeks to critically examine the major sources and effects of aquatic pollution, particularly as they relate to the management of fisheries and aquatic ecosystems. Special emphasis is placed on new biotechnological methods of remediation, e.g., bioremediation, phytoremediation, and gene-engineering techniques. The manuscript consists of four general parts: (1) sources and typologies of aquatic pollution, both natural and man-made; (2) ecological and economic effects on aquatic communities, especially on fish and invertebrates; (3) traditional and state-of-the-art methods of controlling pollution; and (4) applying biotechnology to the creation of more sustainable methods of remediation.

The final section offers a synthesis of findings and outlines future research directions.

**1.4 Emergence of Biotechnology in Pollution Control**

Recent advancements in environmental biotechnology offer promising solutions for mitigating aquatic pollution. The bioremediation strategies involving microorganisms to degrade or sequester contaminants have been shown to work effectively within aquatic and marine ecosystems (Kumar *et al.*, 2010). Genetic engineering technologies, such as CRISPR/Cas9, are currently being utilized to enhance the pollutant-biodegradation capacity within plant and microbial-based systems (Agarwal & Rani, 2022). Phytoremediation, among several others, is set to be an economic and sustainable means of decontaminating water bodies using aquatic macrophytes endowed with pollutant-absorption properties (Abdullah *et al.*, 2020). Similarly, engineered probiotics and phage therapies are being explored to reduce pathogen prevalence and chemical residues in aquaculture settings, linking water quality management with fish health (Khan & Choudhury, 2022). These biotechnological innovations not only offer viable alternatives to conventional treatment methods but also align with global sustainability goals by reducing the ecological footprint of pollution control efforts.

**2. Major Sources of Aquatic Pollution**

The contamination of aquatic ecosystems is driven by a complex array of anthropogenic activities, which introduce diverse pollutants into water bodies through both point and non-point sources. This section details the primary sources of aquatic pollution industrial, agricultural, domestic, and other diffuse origins supported by empirical evidence. Figure 1 shows some of the sources of Aquatic Pollution.



**Figure 1.** *Sources of Aquatic Pollution.*

**2.1 Industrial Pollution**

**2.1.1 Types of Industrial Pollutants**

Industrial pollution encompasses a wide variety of contaminants, including heavy metals (e.g., cadmium, lead, mercury), persistent organic pollutants (POPs), petroleum hydrocarbons, and complex chemical effluents. These substances are commonly released from facilities such as oil refineries, metal plating industries, chemical plants, and textile factories (Ritter *et al.*, 2002). Sediment examinations within estuaries and industry regions, such as Newark Bay, New Jersey, revealed heightened concentrations of polycyclic aromatic hydrocarbons (PAHs) and petroleum hydrocarbons, which cause chronic toxicological threats to aquatic biotas (Huntley *et al.*, 1995).

**2.1.2 Pathways to Aquatic Systems**

Industrial discharges typically enter water bodies through direct outfalls, combined sewer overflows, and indirect deposition via air or surface runoff. In many low-regulation contexts, e.g., certain regions of sub-Saharan Africa, raw effluents from industry are directly released to rivers and coastal basins, thus further enhancing the burden of chemicals within such compartments (Fayiga *et al.*, 2018). Inadequate wastewater treatment infrastructure and lack of compliance monitoring further facilitate pollutant transport into aquatic ecosystems (Ekubo & Abowei, 2011).

**2.2 Agricultural Pollution**

**2.2.1 Nutrient Runoff and Pesticides**

Agricultural activities contribute significantly to non-point source pollution, particularly through the excessive use of synthetic fertilizers and pesticides. Nitrogen (N) and phosphorus (P)-containing runoff causes water bodies to become over-enriched with nutrients, which causes eutrophication, toxic algal blooms, hypoxia, and a decline in aquatic biodiversity (Carpenter *et al.*, 1998). Notably, nutrient inputs from agriculture often exceed plant uptake, creating surpluses that are leached into waterways or volatilized and redeposited elsewhere (Carpenter *et al.*, 1998).

**2.2.2 Livestock Waste and Sediment Loading**

Livestock farming contributes organic pollutants, particularly via manure that contains pathogens, pharmaceuticals, and excess nutrients. High stocking densities amplify this impact by exceeding the land's absorption capacity (Carpenter *et al.*, 1998). Moreover, poorly managed grazing and land disturbance increase sedimentation rates, leading to physical habitat degradation and increased turbidity in aquatic systems.

**2.3 Domestic Pollution**

**2.3.1 Sewage and Wastewater Discharges**

Domestic pollution arises from both treated and untreated sewage. In places where there isn't enough sewage infrastructure, untreated waste is often dumped straight into water bodies, adding a lot of organic matter, nutrients, and pathogens Even in treated wastewater, residual pharmaceuticals, personal care products, and antibiotic-resistant bacteria pose emerging threats to aquatic life and public health (Ritter *et al.*, 2002).

**2.3.2 Solid Waste and Plastics**

Improperly disposed solid waste, particularly plastics, often enters water bodies through runoff and storm drains. These materials stay in the ecosystem, break down into microplastics, and are eaten by aquatic animals, which have been shown to have repercussions on their health and reproduction (Ahmed *et al.*, 2014).

**2.4 Other Sources of Pollution**

**2.4.1 Urban Runoff**

Urbanization results in impervious surfaces that prevent natural infiltration, leading to the accumulation of pollutants on streets and their eventual discharge into nearby water bodies during rainfall events. The concentrations of the pollutants from stormwaters have been several orders of magnitude higher than the threshold values prescribed by regulations and are an acute threat to biological communities (Newman *et al.*, 2001).

**2.4.2 Shipping Activities and Oil Spills**

Maritime activities contribute to aquatic pollution through oil spills, bilge discharge, and antifouling paints. Accidental and operational oil releases lead to persistent hydrocarbon contamination in sediments and biota, severely impairing marine food webs (Oldham, 1979). In the Niger Delta, for example, chronic oil spills have resulted in the destruction of aquatic vegetation and loss of fishery resources (Ekubo & Abowei, 2011).

**2.4.3 Atmospheric Deposition**

Airborne pollutants such as nitrogen oxides, sulfur compounds, mercury, and PAHs can be deposited into aquatic systems via precipitation and dry fallout. This route contributes significantly to nutrient loading and the transport of persistent pollutants across regional and even continental scales (Carpenter *et al.*, 1998). Atmospheric deposition is particularly relevant for remote or pristine areas otherwise shielded from direct pollution sources (Ritter *et al.*, 2002).

**3. Affected Aquatic Environments**

**3.1 Freshwater Ecosystems**

Freshwater ecosystems comprising rivers, lakes, wetlands, and groundwater systems are among the most ecologically valuable yet vulnerable environments globally. Important ecological services like habitat provision, flood control, fishing resources, and water purification are provided by these systems. However, multifactorial pollution from industrial discharges, household sewage, agricultural runoff, and atmospheric deposition is posing a growing threat to them (Kumaraswamy *et al.*, 2019).

 In freshwater habitats, pollutants like pesticides, heavy metals, microplastics, and medications are common and can affect aquatic life both acutely and over time. High levels of heavy metals and persistent organic pollutants, for instance, impair fish immunological and endocrine systems, increasing illness and death (Malik *et al.*, 2020).

Emerging contaminants, notably microplastics, pose novel threats. These particles are now ubiquitous in freshwater systems and act as vectors for heavy metals and pathogens, compounding their ecological risks (Gao *et al.*, 2025). Ingestion of microplastics by freshwater organisms has been linked to oxidative stress, DNA damage, and gut microbiota dysbiosis (Khedre *et al.*, 2023). Moreover, freshwater salinization, primarily driven by road de-icing salts, alters osmoregulatory processes and food web dynamics. Elevated chloride levels reduce biodiversity and shift community structure in both lentic and lotic systems (Dugan & Arnott, 2023). Collectively, these pressures have made freshwater ecosystems the most degraded and least resilient among global biomes (Amoatey & Baawain, 2019).

**3.2 Brackish Water Ecosystems**

Brackish water environments often exhibit high biodiversity due to the presence of species with varying salinity tolerances (Pape et al., 2013). Brackish lagoons and estuaries host fish communities adapted to fluctuating salinity, including both resident and marine species that use these habitats temporarily (Milardi et al., 2019). However, Semi-enclosed estuaries are highly vulnerable to nutrient and pollutant input from upstream agriculture and urban development, contributing to eutrophication and habitat degradation (Mallin et al., 2000). Eutrophication is a predominant concern in brackish systems, resulting from nutrient over-enrichment, particularly nitrogen and phosphorus. Excessive primary production leads to hypoxic or anoxic zones, causing mass mortality of benthic fauna and fish kills. These conditions alter community composition, reduce biodiversity, and encourage the proliferation of opportunistic and invasive species (Geist & Hawkins, 2016).

Hydrocarbon pollution, including oil and grease, is another prevalent issue in brackish water ecosystems. Oil contamination increases biochemical oxygen demand, lowers dissolved oxygen, and disrupts metabolic and immune functions in fish and invertebrates (Enujiugha & Nwanna, 2004). These effects are especially severe in mangrove-fringed estuaries, where hydrocarbon persistence undermines sediment stability and trophic linkages. The biological monitoring of brackish water systems has increasingly relied on indicator organisms, such as oligochaetes, due to their tolerance to contaminants and their utility in bioassessment frameworks (Bae *et al.*, 2016). The degradation of these transitional ecosystems compromises their role as biological filters and disrupts the connectivity between freshwater and marine environments.

**3.3 Marine Ecosystems**

Marine ecosystems are vast and diverse, yet not immune to anthropogenic degradation. Plastic waste, oil spills, heavy metals, and nitrogen loading from terrestrial runoff are the main causes of marine pollution. Pollutants travel long distances due to oceanic circulation patterns, impacting even far-flung marine habitats (Häder *et al.*, 2020). Numerous marine animals, such as fish, seabirds, and marine mammals, are at risk of ingesting plastic garbage, especially microplastics, which are ubiquitous in marine systems. In addition to creating physical obstructions, ingested plastics release chemicals that disrupt hormones and impede development and reproduction (Gao *et al.*, 2025). Furthermore, hazardous algal blooms (HABs), which produce toxins dangerous to human health and marine life, are encouraged by nutrient pollution from sewage and agricultural sources.

Oil pollution, from chronic discharge and accidental spills, has long-lasting impacts on marine habitats. It adheres to sediments, bioaccumulates in the food web, and causes sublethal toxicity in benthic and pelagic species (Enujiugha & Nwanna, 2004). Furthermore, coral reefs among the most biodiverse marine ecosystems are especially sensitive to pollution, with sedimentation and chemical runoff contributing to coral bleaching and reef degradation (Neckles *et al.*, 1997). Despite their vastness, marine ecosystems display significant vulnerability due to slow recovery rates and cumulative pollution effects. Restoration efforts, such as the establishment of marine protected areas (MPAs) and bioremediation strategies, are increasingly advocated to mitigate anthropogenic impacts (Geist & Hawkins, 2016).

**4.** **Impacts of Aquatic Pollution**

Figure 2 depicts the impacts of Aquatic pollution on Aquatic ecosystems.

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**Figure 2.** *Aquatic Pollution Impacts.*

**4.1 Impacts on Fish Health**

**4.1.1 Acute and Chronic Toxicity**

Aquatic pollution exerts both acute and chronic toxicological effects on fish species, affecting their physiology, behaviour, and survival. Exposed fish populations may die quickly from acute toxicity, which is frequently brought on by high concentrations of contaminants like pesticides, heavy metals, or hydrocarbons. Large-scale fish kills, for instance, have been connected to runoff from agricultural lands treated with pesticides, especially in species that lack detoxifying enzymes that are efficient against pyrethroids and organophosphates (Ali *et al.*, 2011). Long-term exposure to sublethal levels of pollutants, such ammonia, microplastics, or polychlorinated biphenyls, can cause immune system impairment, gill damage, metabolic inhibition, and developmental abnormalities. These chronic conditions reduce growth, increase vulnerability to disease, and lower reproductive success (Malik *et al.*, 2020); (Satkar *et al.*, 2024). Behavioral changes such as altered aggression, escape response, and reduced feeding efficiency have also been observed following pollutant exposure, reflecting both physiological stress and potential evolutionary adaptations (Breckels & Neff, 2010).

**4.1.2 Bioaccumulation and Biomagnification**

Bioaccumulation and biomagnification of pollutants such as mercury, PCBs, and microplastics within aquatic food webs further exacerbate fish health risks. Fish exposed to contaminated sediments and prey gradually accumulate toxins in their tissues, particularly in lipid-rich organs like the liver and gonads. These toxins can persist throughout a fish’s life and are transferred up the food chain, reaching piscivorous species and even human consumers (Gokul *et al.*, 2023). For instance, microplastic ingestion has been documented in several freshwater fish species, leading to gut inflammation, energy depletion, and endocrine disruption (Amarie & Onochie, 2024). The compounding effects of pollutant persistence, bioavailability, and trophic transfer reinforce the need for long-term biomonitoring and pollution control measures.

**4.2 Impacts on Aquatic Biodiversity**

**4.2.1 Species Loss and Changes in Community Structure**

Aquatic ecosystems are experiencing severe biodiversity declines primarily due to pollution, habitat degradation, and anthropogenic stressors like nutrient enrichment and contaminants (Geist, 2011). Freshwater biodiversity is declining due to habitat loss, oxygen depletion, and an increase in opportunistic species that replace sensitive native fauna (Reshetniak, 2017). The ability of aquatic systems to recover from additional disturbances is undermined by community simplification, which frequently leads to a loss of ecosystem resilience and a reduction in functional diversity. Pollutants act as selective pressures, reducing genetic diversity and potentially erasing unique evolutionary lineages, thereby weakening long-term adaptive capacity (Geist, 2011).

**4.2.2 Effects on Sensitive and Keystone Species**

Sensitive species, including many benthic macroinvertebrates and endemic fish, are often the first to decline following pollution exposure. Keystone species such as top predators or sediment-burrowing organisms play critical ecological roles; their loss can cascade through ecosystems, leading to algal blooms, oxygen depletion, and reduced primary productivity (Lionetto *et al.*, 2023). Pesticide exposure, for example, has been known to affect amphibians, fish larvae, and aquatic mammals, reducing their reproductive rates and disrupting developmental pathways (Ali *et al.*, 2011). The loss of such taxa alters predator-prey dynamics, nutrient cycling, and ecosystem connectivity (Meinam *et al.*, 2023).

**4.3 Impacts on Ecosystem Services**

**4.3.1 Water Quality Degradation**

Pollution from nutrients, pathogens, and chemical contaminants directly reduces water quality, impairing its suitability for human consumption, irrigation, and industrial use. Large amount of nutrient loading promotes eutrophication, which results in harmful algal blooms, hypoxia, and fish kills (Häder *et al.*, 2020). Pathogen proliferation in polluted waters poses public health risks, particularly in regions with limited water treatment infrastructure. Fish and sediment can harbor human pathogens such as *Salmonella*, *Leptospira*, and *Aeromonas*, linking aquatic pollution to outbreaks of waterborne diseases (Obasohan *et al.*, 2010).

**4.3.2 Impacts on Fisheries Productivity**

Degraded water quality contributes to parasitic infections in fish, reducing their health and acting as a vicious cycle of declining immunity and productivity (Biswas et al., 2023). A study on the Nyumba ya Mungu Dam found that water quality parameters like turbidity, dissolved oxygen, and nutrient levels significantly affected fish biomass, with productivity dropping by 95% between 1972 and 2018 (Mangi et al., 2023).

**4.3.3 Loss of Recreational and Cultural Values**

Pollution also undermines the aesthetic, recreational, and spiritual values associated with aquatic environments. Degraded water bodies become unsuitable for swimming, boating, or cultural practices, reducing community engagement and ecotourism potential (Gopal & Zutshi, 2000). In regions where water bodies hold significant cultural and religious importance, pollution erodes heritage and local identity.

Some Major Pollutants which are present in Aquatic Ecosystems and the Ecological Impacts caused by them are shown in Table 1.

**5. Remediation of Aquatic Pollution**

**5.1 Conventional Remediation Methods**

**5.1.1 Physical Removal Techniques**

Physical methods, including dredging and skimming, are commonly employed to extract pollutants such as oil, sediments, or floating debris from water bodies. Dredging can lessen the impact of heavy metals and persistent organic pollutants (POPs) by mechanically excavating contaminated sediments. But it can also cause short-term ecological harm by upsetting benthic ecosystems and resuspending contaminants into the water column (Singh & Tripathi, 2007). Skimming is used for surface pollutants such as oil, employing booms and vacuum devices to capture floating hydrocarbons. While effective for rapid response, these techniques often require integration with other treatment processes to fully restore water quality (Rhodes, 2013).

**5.1.2 Chemical Treatments**

Chemical remediation methods, such as coagulation-flocculation, oxidation, and precipitation, are widely used for the removal of suspended solids, metals, and organics. However, these approaches often produce large volumes of secondary sludge and may introduce additional chemical hazards. Chlorine and ozone treatments, for instance, can form toxic by-products like trihalomethanes and bromates (Biju & Krishnaswamy, 2021). As a result, these methods are increasingly being phased out in Favor of green biotechnological alternatives.

**5.2 Biological and Biotechnological Remediation Methods**

**5.2.1 Microbial Bioremediation**

Bioremediation harnesses the metabolic activity of microorganisms to degrade or transform pollutants into less harmful forms. Through redox reactions and enzymatic pathways, bacterial and fungal strains have proven effective in breaking down hydrocarbons, heavy metals, and xenobiotics (Singh & Tripathi, 2007).

**5.2.2 Genetically Engineered Microorganisms**

To enhance degradation efficiency, genetically modified microorganisms (GEMs) have been developed. For example, recombinant strains of Deinococcus radiodurans and Pseudomonas have been designed to break down radionuclides and heavy metals in harsh environments (Rhodes, 2013).

**5.2.3 Phytoremediation**

Phytoremediation is a novel, nature-inspired strategy that utilizes the extraordinary powers of green plants and the advantageous bacteria residing in their root zones to eliminate, convert, or immobilize hazardous contaminants from the environment (Chaturvedi *et al.*, 2025). Phytoremediation employs aquatic plants to absorb, sequester, and detoxify pollutants. Macrophytes like Typha latifolia and Eichhornia crassipes have shown the ability to eliminate chemical pollutants like atrazine and metals like arsenic and cadmium (Giri& Kumar, 2024); (Hoang, 2018). Mycorrhizal fungi and microbial consortia can be added to phytoremediation to increase its effectiveness.

**5.2.4 Bioaugmentation**

Bioaugmentation involves the intentional introduction of specialized microbial strains to accelerate the degradation of specific contaminants. This technique is particularly effective in environments where native microbial populations lack the metabolic capacity for pollutant breakdown (Biju & Krishnaswamy, 2021).

**5.2.5 Biopolymer-Assisted Remediation**

Natural biopolymers such as chitosan, alginate, and cellulose have emerged as biosorbents due to their high affinity for metals and dyes. These substances, which frequently work in concert with microbial and enzymatic systems, provide a biodegradable and affordable substitute for synthetic adsorbents (Ramezani *et al.*, 2021).

**5.2.6 Enzyme-Based Bio-Oxidation**

Enzyme-mediated remediation uses isolated enzymes such as laccases and peroxidases to oxidize complex pollutants into less toxic compounds. Compared to whole-cell systems, enzymes offer higher specificity, faster kinetics, and fewer by-products (Kumar & Bharadvaja, 2019); (Sharma *et al.*, 2018).

**.3 Emerging and Advanced Biotechnological Technologies**

**5.3.1 Nanotechnology Applications**

Nanomaterials, such as zero-valent iron (nZVI), carbon nanotubes, and metal oxides, have demonstrated exceptional efficiency in pollutant adsorption due to their high surface area and reactivity. These particles facilitate in-situ remediation by targeting inaccessible or deeply embedded contaminants (Nwadinigwe & Ugwu, 2019); (Ramezani *et al.*, 2021).

**5.3.2 Biosensors for Monitoring**

Enzyme-based biosensors are increasingly utilized for real-time detection of heavy metals, pesticides, and pharmaceutical residues in water bodies. These devices offer high sensitivity, rapid detection, and potential integration with automated monitoring systems (Nigam & Shukla, 2015); (Čvančarová *et al.*, 2020).

**5.3.3 Integration with Digital Tools**

Recent developments integrate biotechnological tools with Internet-of-Things (IoT) platforms, allowing for real-time water quality assessment, data visualization, and predictive modeling of contamination spread (Kumar *et al.*, 2021). These systems support adaptive management strategies and regulatory compliance.

Some of the Biotechnological Remediation Techniques to counter Aquatic Pollution are mentioned in Table 2.

**5.4 Policy and Management Approaches**

**5.4.1 Regulatory Frameworks**

The success of remediation initiatives often hinges on effective policy enforcement. Environmental regulations such as the Clean Water Act (U.S.) and Water Framework Directive (EU) establish pollutant thresholds and mandate pollution source control. Yet, enforcement remains inconsistent, especially in low- and middle-income countries (Shmaefsky, 2020).

**5.4.2 Community Participation and Awareness**

Public engagement in monitoring and restoring local water bodies has proven crucial in sustaining long-term remediation outcomes. Community-based water quality testing, citizen science initiatives, and environmental education campaigns can promote pollution reduction and behavioral change (Cosmo *et al.*, 2023).

Figure 3 depicts various detailed types of Remediation methods for Aquatic Pollution and Table 3 shows some of the Selected Case Studies of the Biotechnological Remediation Projects.



**Figure 3.** *Aquatic Pollution Remediation methods.*

**6. Case Studies**

**6.1 Phytoremediation Projects in India**

**6.1.1 Remediation in the Industrial Regions of West Bengal**

A notable application of phytoremediation in India was conducted in the Barjora and Durgapur industrial zones of West Bengal. The best places for phytoremediation using native aquatic and riparian plants were determined by researchers using a Geographic Information System (GIS)-based site suitability study. The study highlighted regions along the Damodar River near Andal Block as promising zones for large-scale phytoremediation implementation, citing favorable soil productivity, pollution load, and land use characteristics (Chatterjee, 2024).

**6.1.2 Dye Effluent Remediation in Tamil Nadu**

In Tamil Nadu, the phytoremediation potential of freshwater macrophytes including *Pistia stratiotes*, *Hydrilla verticillata*, and *Salvinia adnata* was assessed for treatment of dye-contaminated wastewater from textile industries. P. stratiotes demonstrated the best remediation ability of the three, reducing color by 86%, total dissolved solids (TDS) by 66%, and chemical oxygen demand (COD) by 77%. Post-treatment, levels of toxic metals such as Cr and Pb were reduced below detectable thresholds, underscoring the species’ robust uptake and detoxification potential (Ahila *et al.*, 2020).

**6.1.3 Paper Mill Effluent Remediation in Odisha**

At the JK Paper Mill in Rayagada, Odisha, a controlled experiment evaluated six aquatic macrophytes including *Lemna minor*, *Trapa natans*, and *Eichhornia crassipes* for their capacity to remove Cu and Hg from effluent. *L. minor* demonstrated the highest bioconcentration factor, achieving reductions of 71.4% for Cu and 66.5% for Hg over a 20-day period. This outcome not only affirmed the phytoremediation viability of *L. minor* but also emphasized its potential application in paper and pulp industrial zones (Mishra *et al.*, 2013).

**6.2 Microbial and Plant-Assisted Heavy Metal Remediation**

A comprehensive review of microbial and plant-assisted bioremediation in Indian aquatic ecosystems emphasized the dual role of bacteria and macrophytes in managing heavy metal pollution. The authors noted that bacterial species enhance phytoremediation through metal bioavailability modulation, siderophore production, and oxidative stress alleviation. However, they also observed a limited number of field-scale implementations, suggesting a research-to-practice gap that must be addressed through targeted pilot projects and stakeholder engagement (Haldar & Ghosh, 2020).

**6.3 Wetland-Based Remediation in Gujarat**

A field-based study at Pariyej Community Reserve, Gujarat an internationally recognized wetland evaluated heavy metal uptake in aquatic plants such as *Typha angustata*, *Ipomoea aquatica*, and *Nelumbo nucifera*. The largest amount of accumulation of Zn, Cu, and Pb was found in N. nucifera, particularly in its root tissues, according to the results. The study found that native macrophytes have the ability to provide scalable phytoremediation for damaged wetland ecosystems in addition to serving as trustworthy biomonitors (Kumar *et al.*, 2008).

**6.4 International Applications of Aquatic Phytoremediation**

**6.4.1 Oil Pollution Mitigation Using Aquatic Plants**

A recent study evaluated the phytoremediation of oil-contaminated water bodies using *Eichhornia crassipes* and *Pistia stratiotes*. Although the plants did not directly degrade alkanes, their rhizospheres fostered microbial communities capable of hydrocarbon degradation. Furthermore, the presence of plants significantly reduced water-oil interfacial tension, improving hydrocarbon bioavailability and enhancing microbial remediation performance (Zhilkina *et al.*, 2024).

**6.4.2 Degradation of Triazophos in Hydroponic Systems**

In a hydroponic setup, *Canna indica* was used to degrade triazophos, an organophosphorus pesticide. Gram-negative bacteria predominated in the rhizosphere, according to microbial community profiling using phospholipid fatty acid (PLFA) analysis, which also revealed a substantial correlation with the effectiveness of pollutant removal. This study provided critical mechanistic insight into plant-microbe interactions in pesticide phytoremediation systems (Xiao *et al.*, 2010).

**7. Knowledge Gaps and Future Research Directions**

**7.1 Insufficient Long-Term and Field-Scale Data**

One of the most prominent gaps is the lack of long-term, field-based studies evaluating the efficacy of biotechnological remediation methods under real environmental conditions. Because of shifting physicochemical parameters and biotic interactions, laboratory research frequently show encouraging pollution removal efficiency, but these findings may not necessarily translate to complex wild ecosystems (Ekperusi *et al.*, 2018). For instance, although aquatic macrophytes like *Pistia stratiotes* are effective in absorbing petroleum hydrocarbons in lab settings, limited data exist on their seasonal performance, degradation kinetics, or long-term resilience in open water systems. Additionally, most studies do not assess post-remediation ecological recovery or the potential for pollutant re-release from plant or microbial biomass, thereby obscuring the full environmental cost-benefit analysis (Matyssek *et al.*, 2012).

**7.2 Limited Understanding of Plant–Microbe Interactions**

Phytoremediation strategies increasingly rely on synergistic interactions between aquatic plants and their rhizospheric microbiomes to enhance pollutant degradation. However, the underlying biochemical and ecological mechanisms governing these interactions remain poorly understood. Research has shown that root exudates modulate microbial community composition and activity, yet the specific metabolic pathways involved in pollutant breakdown are often unidentified or unquantified (Xiao *et al.*, 2010).

**7.3 Underexplored Genetic Engineering and Synthetic Biology Applications**

While genetically modified microorganisms (GMMs) have shown enhanced capabilities for pollutant degradation, concerns related to biosafety, horizontal gene transfer, and regulatory uncertainty have limited their deployment in natural systems. Yet the potential of synthetic biology to design biosystems with programmable responses to pollutants is a promising area that remains largely theoretical in aquatic contexts (Ramezani *et al.*, 2021).Future work should focus on engineering microbial consortia with controllable gene expression pathways, minimal ecological disruption, and rapid self-limiting mechanisms to mitigate environmental risks.

**8. Conclusion**

Aquatic pollution represents a complex, multifaceted challenge that threatens freshwater, brackish, and marine ecosystems, with profound implications for biodiversity, fish health, and essential ecosystem services. Both acute and long-term ecological effects have resulted from the persistence and spread of pollutants such heavy metals, microplastics, hydrocarbons, and synthetic chemicals. Many of these effects cascade through trophic levels and ultimately jeopardize human health. Traditional remediation strategies, while useful in localized applications, are often limited by high costs, incomplete removal, and the generation of secondary pollutants. Enzyme-based degradation, microbial bioremediation, phytoremediation, and bioaugmentation are examples of biological techniques that have demonstrated encouraging outcomes in eliminating a variety of contaminants with high selectivity and little disturbance to the environment. The use of nanomaterials, biosensors, and genetically modified microbes are examples of emerging technologies that are increasing the breadth and accuracy of pollution detection and control. Furthermore, real-time, adaptive water quality management may be made possible by integrating biotechnological platforms with digital monitoring tools and decision-support systems.

Case studies from India and around the world further illustrate the practical viability of biotechnological interventions across varied ecological and industrial contexts. Nonetheless, several critical knowledge gaps persist, particularly regarding long-term field efficacy, ecological safety, and regulatory oversight. The scalability of biological methods, the complex interactions between plant and microbial communities, and the deployment of synthetic biology applications all require continued interdisciplinary research. A concerted effort to bridge scientific, regulatory, and societal dimensions will be crucial in realizing the full potential of biotechnology in aquatic pollution remediation and monitoring.

**Table 1. Major Pollutants in Aquatic Ecosystems and Their Ecological Impacts**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Pollutant Type** | **Primary Sources** | **Affected Ecosystems** | **Ecological Effects** | **References** |
| **Heavy metals (e.g., Pb, Cd, Hg)** | Mining, industrial effluents, urban runoff | Freshwater, brackish | Bioaccumulation, oxidative stress, reproductive failure in fish | Malik *et al.* (2020) |
| **Nutrients (N, P)** | Agricultural runoff, sewage, aquaculture waste | Lakes, estuaries | Eutrophication, algal blooms, hypoxia, fish kills | Häder *et al.* (2020) |
| **Hydrocarbons** | Oil spills, petrochemical industries | Estuarine, coastal waters | Immune suppression, gill damage, sediment toxicity | Zhilkina *et al.* (2024) |
| **Microplastics** | Urban waste, wastewater treatment effluent | Marine, freshwater | Physical injury, gut blockage, endocrine disruption in aquatic fauna | Gao *et al.* (2025) |
| **Pesticides (e.g., triazophos)** | Agricultural drainage | Rivers, wetlands | Neurotoxicity, developmental delays in amphibians and fish larvae | Xiao *et al.* (2010) |

**Table 2. Biotechnological Remediation Techniques for Aquatic Pollution**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Technique** | **Biological Agents** | **Target Pollutants** | **Mechanism** | **Advantages** | **Limitations** | **References** |
| **Microbial Bioremediation** | *Pseudomonas*, *Deinococcus*, fungi | Hydrocarbons, nitrates, metals | Enzymatic degradation, redox reactions | In situ applicability, cost-effective | Sensitivity to environmental fluctuations | Singh & Tripathi (2007) |
| **Phytoremediation** | *Eichhornia*, *Lemna*, *Typha* | Metals, nutrients, dyes | Uptake, translocation, rhizofiltration | Eco-friendly, aesthetic, low maintenance | Slower, dependent on biomass growth | Ahila *et al.* (2020) |
| **Bioaugmentation** | Introduced pollutant-degrading microbes | Persistent organic pollutants | Enhanced biodegradation | Targeted and fast | Microbial competition, ecosystem disruption | Haldar & Ghosh (2020) |
| **Enzyme-based Biodegradation** | Laccases, peroxidases | Synthetic organics, industrial dyes | Catalytic oxidation, substrate breakdown | High specificity, faster kinetics | Expensive enzymes, activity loss over time | Sharma *et al.* (2018) |
| **Nanobioremediation** | Nanoparticles + microbes or plants | Metals, pesticides | Adsorption + enzymatic conversion | High efficiency, rapid action | Ecotoxicological concerns, cost | Ramezani *et al.* (2021) |

**Table 3. Selected Case Studies of Biotechnological Remediation Projects**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Location** | **Pollutant Type** | **Remediation Method** | **Biological Agent(s)** | **Key Findings** | **References** |
| **Tamil Nadu, India** | Textile dye wastewater | Phytoremediation | *Pistia stratiotes*, *Hydrilla verticillata* | >75% reduction in COD, TDS, and color | Ahila *et al.* (2020) |
| **Rayagada, Odisha, India** | Paper mill effluent (Cu, Hg) | Phytoremediation | *Lemna minor*, *Trapa natans* | Up to 71.4% Cu and 66.5% Hg removal in 20 days | Mishra *et al.* (2013) |
| **Barjora, West Bengal** | Industrial pollution zone | GIS-guided phytoremediation planning | Native macrophytes | Identified suitable sites for scalable phytoremediation interventions | Chatterjee (2024) |
| **Russia** | Oil-contaminated wetland | Plant-assisted rhizoremediation | *Eichhornia crassipes*, microbial consortia | Enhanced oil degradation via rhizosphere microbial stimulation | Zhilkina *et al.* (2024) |
| **China** | Organophosphate pesticide (triazophos) | Hydroponic microbial phytoremediation | *Canna indica* with rhizosphere microbes | High microbial abundance linked to pesticide degradation efficiency | Xiao *et al.* (2010) |

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