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Nature-Based Bioremediation of Coastal Pollution: The Role of Microbes, Mangroves and Wetlands

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Coastal ecosystems absorb heavy metals, petroleum hydrocarbons, and excess nutrients from industrial, agricultural, and urban sources, threatening biodiversity and human health. Conventional remediation methods are often costly and ecologically disruptive, prompting growing interest in nature-based bioremediation. This article reviews three interdependent biological components central to this approach: microbial communities that degrade hydrocarbons and transform heavy metals through biosorption and redox activity; mangrove forests, which combine physiological adaptations such as root sequestration, phytochelatin binding, and metal excretion with symbiotic rhizosphere microbiomes; and natural and constructed wetlands, which remove nitrogen and phosphorus through plant uptake, substrate adsorption, and microbial nitrification–denitrification cycles. Evidence from field and laboratory studies demonstrates substantial pollutant-removal efficiencies across all three systems, though performance is constrained by contamination thresholds, hydrological conditions, and ongoing habitat loss. The review concludes that integrating microbial science, mangrove restoration, and wetland engineering, supported by conservation policy, offers a scalable and cost-effective pathway toward sustainable coastal pollution management.

Keywords: Coastal pollution; Constructed wetlands; Heavy metal bioremediation; Hydrocarbon-degrading bacteria; Mangrove phytoremediation.

Introduction

Coastal ecosystems soak up the aggregate waste load of upstream watersheds, industry, shipping and urban runoff. Heavy metals, petroleum hydrocarbons and nutrient overload all collide on shorelines, endangering biodiversity, fisheries and human health. Traditional remediation such as dredging, chemical precipitation, incineration can be expensive and environmentally invasive. Nature-based bioremediation instead leverages organisms to detoxify, sequester, or transform pollutants in place. Three players dominate this toolkit: pollutant-degrading or transforming microbial communities, mangrove forests that intertwine physical filtration with phytoremediation, and wetlands that strip nutrients from water using plant–microbe–substrate interactions. This article surveys their mechanisms, evidence base, and limitations.

The Scale of the Problem

Heavy metals like cadmium, lead, mercury, arsenic and chromium are introduced into coastal sediments by industrial discharge and urban wastewater, where they bioaccumulate and disrupt microbial function (Kashif et al., 2026). And because they do not break down, they accumulate and biomagnify in the food chain (Khotimah et al., 2025). Petroleum hydrocarbons present a similar problem: worldwide, marine ecosystems are exposed to approximately 67 million tonnes of petroleum waste each year (Onwujekwe, 2022). Nutrient loading from agricultural and domestic wastewater continue to drive coastal eutrophication and hypoxia (Land et al., 2013). And exacerbating this load is the degradation of the ecosystems most capable of buffering it. Global mangrove cover declined approximately 3.4% (5,245 km2) between 1996 and 2020, with Southeast Asia representing almost half of this loss (Bunting et al., 2022). The FAO estimates that more than 20% of the world's mangroves have been lost over four decades, primarily to conversion for aquaculture (Kindgard et al., 2023).

Microbial Bioremediation

Hydrocarbonoclastic bacteria are naturally found at low abundance in marine sediments but expand explosively once hydrocarbons arrive (Nikolova & Gutierrez, 2022). After the 2010 Deepwater Horizon spill, researchers isolated 24 oil-degrading strains from Pensacola beach sands, mostly Gammaproteobacteria including *Alcanivorax*, *Marinobacter*, and *Pseudomonas* (Kostka et al., 2011), demonstrating that intrinsic bioremediation can substantially attenuate spilled oil without intervention. One of the main mechanisms is biosurfactant production, which fragments oil into smaller droplets and enhances bioavailability to degraders (Nikolova et al., 2021). Microbial consortia typically outperform single strains, since one species generally metabolizes only a limited subset of hydrocarbons (Rahmati et al., 2022); one such consortium degraded 51–64% of crude oil, diesel and fuel oil within seven days (Nikolova & Gutierrez, 2022). Biostimulation (adding N and P) and bioaugmentation (adding degrading strains) are typical ways to speed this process up (Onwujekwe, 2022). Heavy metals cannot be biodegraded, but microorganisms modifies their mobility and toxicity by biosorption, precipitation, and redox transformation. Rhizosphere bacteria of mangrove roots tune sediment redox potential and promote cadmium, lead, chromium, copper and mercury immobilization (Kashif et al., 2026). Halotolerant, phosphate-solubilizing bacteria isolated from *Avicennia* rhizospheres, including strains related to *Enterobacter cloacae* and *Kocuria rhizophila*, combine metal tolerance with plant-growth-promoting traits (Dey et al., 2024), effectively acting as a biogeochemical filter that reduces metal bioavailability to higher trophic levels.

Mangroves as Living Filters

Mangroves remediate heavy metal pollution through avoidance, chelation, sequestration, tolerance, excretion and filtration (Rahman et al., 2024). Root uptake takes place through passive diffusion or active transport, with metal levels usually much greater in roots than leaves, an evolved strategy minimizing translocation to photosynthetic tissue (Rahman et al., 2024). Species such as *Avicennia marina*, *Kandelia candel*, and *Rhizophora stylosa* show strong root bioconcentration while keeping translocation to aerial parts low, for example as low as 0.05 for lead (Akbar et al., 2025). Cell-wall immobilization, phytochelatin complexation and root iron plaques additionally sequester metals, while salt-gland excretion and antioxidant defenses govern the unavoidable (Rahman et al., 2024). A meta-analysis of Chinese mangrove forests discovered mangrove presence increased heavy-metal phytoremediation capacity by roughly 38% compared to unvegetated sediments. Because so much spilled oil washes up on mangrove coastlines, the mangrove–microbiome partnership is fundamental to hydrocarbon clean up. Rhizosphere bacteria from mangrove roots both promote plant growth and degrade oil (Eid et al., 2011). In one greenhouse study, *Rhizophora mangle* seedlings inoculated with plant-growth-promoting rhizobacteria showed enhanced degradation of polycyclic aromatic hydrocarbons in diesel-contaminated sediment over 120 days (Dey et al., 2025). More broadly, the mangrove microbiome fuels biogeochemical cycling of nitrogen, phosphorus, carbon, sulfur and iron, and breaks down litter and pollutants that would otherwise hinder ecosystem recovery (Mangrove microbiomes as drivers of ecosystem recovery and restoration success, 2026).

Wetlands: Natural and Constructed Nutrient Filters

Wetlands eliminate nitrogen and phosphorus through microbial conversion, plant absorption, substrate adsorption and sedimentation (constructing wetland's inverse response on nitrogen and phosphorus removal, 2024). Plants absorb nutrients themselves while oxygenating the root zone, altering microbial balance and boosting restoration (Revealing the nitrogen and phosphorus removal capabilities of coastal wetland plants, 2023). Species selection matters: *Spartina alterniflora* and *Phragmites australis* achieve notably higher nitrogen removal than some native alternatives (Gao et al., 2024). Constructed wetlands can be surface-flow or subsurface-flow (horizontal or vertical); vertical-flow systems tend to remove phosphorus more efficiently, horizontal-flow systems nitrogen, and hybrid designs have had total nitrogen removal as high as 89% (Kamilya et al., 2022). A twelve-year study of edge-of-field treatment wetlands in the U.S. Midwest, intercepting agricultural tile drainage before it reaches the Mississippi River and the hypoxic Gulf of Mexico, found consistently high annual reductions in nitrate-nitrogen and dissolved phosphorus, with suspended-solids removal of 71–85% (Lemke et al., 2022), evidence that wetlands can deliver stable water-quality benefits over long timeframes. As coastal eutrophication is largely fueled by land based nutrients, wetlands at the land–sea interface provide a buffer in the same way mangroves do for metals and hydrocarbons, an argument expressed in EU water-quality policy (Land et al., 2013).

Synergies and Limitations

These three components are in fact intimately interconnected: mangrove phytoremediation depends on rhizosphere metals-immobilizing microbes, wetland nutrient uptake cannot be separated from microbial nitrification–denitrification, and hydrocarbon degradation in mangrove sediments relies on plant-growth-promoting bacteria that also support mangrove health under contaminant stress. An almost decade-long experiment in Hainan, China tracked almost 400 hectares of aquaculture ponds taken out of production, and restored over 300 hectares of mangrove forest, demonstrating that habitat restoration and pollution mitigation can be pursued hand-in-hand (Si et al., 2025). Limits remain. Since mangrove tolerance to salinity, redox potential and metal concentration is limited, excessive metal accumulation can also inhibit photosynthesis and growth (Rahman et al., 2024). Wetland performance is sensitive to hydraulic loading, retention time and season, with some studies reporting reversed removal efficiency over long versus short timeframes. Bioaugmentation for oil spills has a patchy history as introduced strains tend to fall short when competing with native populations (Rahmati et al., 2022). And because mangroves and wetlands are threatened ecosystems in their own right with mangrove loss still at 1–2% per year in some areas (Rahman et al., 2024) bioremediation needs to be coupled with active restoration, not considered permission for ongoing pollutant loading.

Conclusion

Microbes, mangroves, and wetlands combine to create a layered, self-organizing system of coastal pollution control that operates at a fraction of the cost and disruption of conventional technologies. Microbial consortia power degradation and immobilization; mangroves provide structural filtration and habitat for pollutant-degrading rhizosphere communities; and wetlands intercept nutrient loads before they spark eutrophication. Such systems work best when the parts work in concert and contamination is within the biological tolerance of the organisms. With pollution pressures increasing as habitat loss persists, incorporating microbial science, mangrove restoration and wetland engineering into a conservation-supported approach provides one of the most hopeful, scalable routes toward resilient coastal ecosystem health.

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