

## Environmental Sustainability, Biogeochemistry, and Microbial-Mediated Pollutant Fate: Implications for Long-Term Remediation

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**Abstract:** The increase in environmental pollution over the past few years due to rapid industrialization and unsafe agricultural practices has become a global challenge. The presence of toxic pollutants such as nuclear waste, heavy metals, pesticides, and hydrocarbons has threatened both the environment and human health. Microbial community-based bioremediation is emerging as a promising, environmentally friendly, and cost-effective strategy to reduce the impact of these toxic pollutants. Traditional physicochemical remediation methods are often costly, invasive, and inefficient, emphasizing the need for sustainable alternatives. This narrative review surveys the current peer-reviewed literature (2020-2025) to identify significant advances in microbial consortia engineering, biofilm- and biochar-supported systems, evolutionary adaptation of degraders, and applications across various pollutant categories. Microbial-mediated biogeochemical processes have become a promising solution, offering environmentally friendly, scalable, and versatile approaches for long-term environmental restoration. Microbial remediation shows several converging trends. Engineered microbial consortia have demonstrated excellent degradation of complex mixtures compared to monocultures. Biochar, as one of the adsorptive carriers, improves pollutant immobilization and supports microbial survival. Microbial communities adapt by enlisting enzymes and rewiring regulatory pathways under pollutant stress, thereby increasing their degradative potential. There is also a growing focus on emerging contaminants and enzymatic degradation pathways. However, environmental limitations such as the presence of co-contaminants, metals, surfactants, and limited bioavailability remain significant barriers. Long-term viability, large-scale implementation, and the fate of hazardous intermediates remain poorly understood and advancing this field requires integrating ecological, evolutionary, and materials science knowledge, with future research focusing on field validation, fate tracking, and combined strategies for complex and mixed-pollutant environments.

**Keywords:** Bioremediation; Microbial consortia, biochar-supported remediation, persistent organic pollutants.

### INTRODUCTION

Environmental pollution has become a global challenge over the years due to rapid industrialization, agricultural intensification, urbanization, and the increase in production and disposal of synthetic chemicals (Rathod *et al.*, 2024; Saxena, 2025). The accumulation of persistent organic pollutants (POPs), heavy metals, petroleum-based hydrocarbons, pesticides, drugs, and microplastics in the environment poses significant threats to ecosystem function, biodiversity, and human health (Abdulai *et al.*, 2024), Misszento & Caesar, 2025). Many of these pollutants are chemically stable, resistant to natural degradation, bioaccumulate within food webs, and undergo long-range environmental transport. They persist for long periods, which leads to chronic exposure through multiple trophic levels and potential bio-magnification in humans (Renuka and Patyal, 2025). The combined effects of chemical toxicity, ecological disturbance, and interference with biogeochemical cycles necessitate urgent strategies for immediate mitigation and sustainable remediation. Conventional remediation methods, such as excavation, soil washing, thermal desorption, chemical oxidation, and immobilization through stabilization, have been used to mitigate

environmental pollution (Lee *et al.*, 2021), Caesar *et al.*, 2025). While these techniques can reduce pollutant concentrations, they are often costly, energy-intensive, destructive to the structure of the soil and sediment, and have limited scalability, especially for large and heterogeneous locations (Khanam *et al.*, 2023). Physicochemical treatments produce hazardous byproducts and transport pollutants into different environmental compartments, failing to eliminate contaminants. With respect to this, there has been a growing interest in developing sustainable remediation techniques for environmental recovery (Santos *et al.*, 2025).

Microbial-mediated biogeochemical processes have emerged as a compelling alternative. These strategies utilize natural and engineered microorganisms to degrade, transform, and immobilize pollutants, harnessing metabolic versatility and ecological adaptability. Microorganisms interact with pollutants through multiple mechanisms, such as enzymatic degradation, co-metabolism, biofilm sorption, sequestration within microbial aggregates, and transformation into less-toxic compounds (Xu *et al.*, 2021; Ren and Manfield, 2025). These processes are important because they are

connected to fundamental biogeochemical cycles, integrating carbon, nitrogen, sulphur, and phosphorus transformations with pollutant removal. Microbial consortia show metabolic complementarity, functional redundancy, and cooperative interactions, allowing efficient degradation of complex pollutant mixtures (Pascual-García *et al.*, 2020; Cao *et al.*, 2022). Biofilm formation and carrier-supported systems enhance microbial survival, protect functional consortia from environmental stressors, and improve pollutant bioavailability (Kayoumu *et al.*, 2025). Microbial-mediated remediation research has progressed rapidly during recent years. Studies have explored the design and optimization of microbial species for multi-pollutant degradation, elucidated co-metabolic and enzymatic pathways, and shown the potential of bio-carrier systems to stabilize microbial activity in related fields (Wani *et al.*, 2022). Moreover, research has addressed the evolutionary adaptation of microbial communities under pollutant stress. (Brito, 2021; Li *et al.*, 2025b). With these breakthroughs, the field has been transformed from a largely descriptive science into an integrative discipline combining microbial ecology, biogeochemistry, materials science, and environmental engineering (Akinsemolu *et al.*, 2024). Convergence of these fields presents a promising pathway for scalable, long-term remediation methods capable of restoring contaminated ecosystems while minimizing ecological disruption.

Despite these advancements, significant gaps and challenges still exist. Many studies are conducted at the laboratory level, mainly focusing on single pollutants under controlled conditions (Wu *et al.*, 2025). Environmental pollution often involves complex mixtures, with fluctuating physicochemical conditions and interactions among diverse microbial communities. The long-term fate of degradation intermediates, including the possible formation of toxic metabolites, remains poorly understood (Shah *et al.*, 2024; Setiawardani *et al.*, 2025). The stability, resilience, and functional persistence of microbial communities under changing environmental conditions are not well studied (Avila-Jimenez *et al.*, 2020). There has been limited attention to potential ecological risks, such as the pollutant-metabolizing traits and horizontal gene transfer of resistance (Bardgett and Caruso, 2020). Moving laboratory findings to field applications is a significant challenge, requiring pilot studies, monitoring systems, and predictive models that

consider environmental variability, bioavailability, and ecosystem interactions (Sun *et al.*, 2024; Izah and Ogwu, 2025).

Given the rapid accumulation of research, there is a need for a comprehensive, interpretive synthesis that moves beyond catalogs studies to provide critical insights into mechanistic trends, emergent strategies, and unresolved challenges (Bala *et al.*, 2022). The synthesis must assess the potential of microbial-mediated processes for real-life use, how evolutionary and ecological dynamics influence pollutant fate, and the effectiveness of combined approaches in addressing the complexity of contamination (Devarajan *et al.*, 2025). This review critically evaluates current technologies, identifies knowledge gaps, and highlights future research directions for microbial-mediated biogeochemical remediation as a practical, large-scale, and sustainable method of long-term environmental restoration.

## EMERGING TRENDS

This section synthesizes major advances organized into four interrelated themes: engineered microbial consortia and community-based degradation, bio-carrier (biochar/biofilm) supported systems, evolutionary adaptation and expansion of degradative capacity, and expanding scope of pollutants such as emerging contaminants, plastics, and mixed pollution (Renganathan *et al.*, 2025).

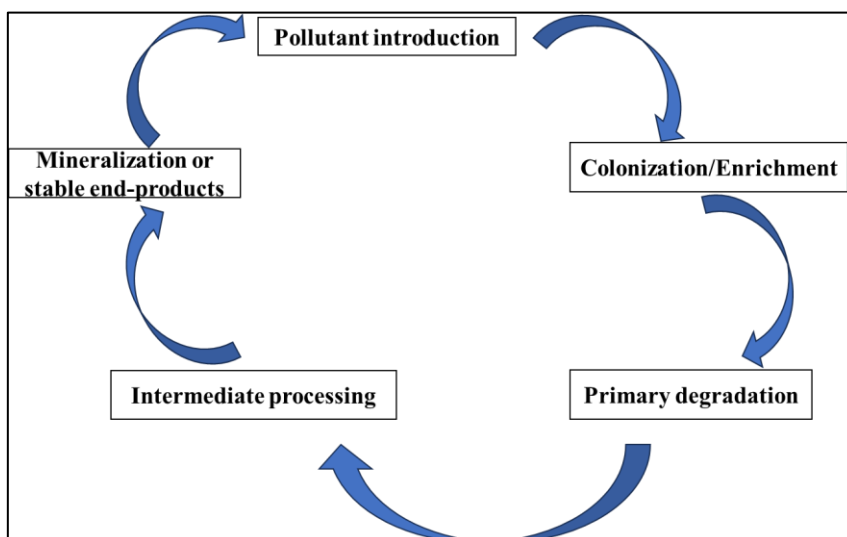
### Microbial Consortia: From Monocultures to Cooperative Degradation

Biodegradation research initially focused on single microbial strains (monocultures) capable of degrading specific pollutants (Hu *et al.*, 2025). However, ecological realism rarely occurs in isolation, and the degradation involves several steps, which has led to the research of microbial consortia (Shokunbi *et al.*, 2025). These consortia, whether naturally occurring or man-made, are composed of complex communities where different species perform complementary functions. A recent review by Lü *et al.*, (2024), points out that consortia can achieve high degradation efficiencies of almost 100% for PAHs, total petroleum hydrocarbons (TPHs), and phthalates. Moreover, lower efficiencies (around 85%) are reported for polychlorinated biphenyls (PCBs) under laboratory conditions (Chen *et al.*, 2024).

The advantages of consortia over monocultures arise from several factors. Metabolic complementarity facilitates primary degraders to

begin the breakdown of pollutants while secondary consumers detoxify and process the intermediates, leading to more complete mineralization (Cao *et al.*, 2022; Shokunbi *et al.*, 2025). Mixed communities also show resilience and ecological robustness and withstand stressors such as pollutant mixtures and environmental fluctuations better than monocultures (Trivedi *et al.*, 2021). Several taxa encode the same degradative function, reducing the risk of failure if one strain declines (Lin *et al.*, 2025). However, there are drawbacks. Monocultures typically show higher initial degradation rates (35%/day) compared to mixed cultures (+8%/day) in sterilized media, indicating that the consortia might be slower in the beginning, a trade-off relevant for field applications with variable residence times (Dharmasiddhi *et al.*, 2025).

Despite their potential, most consortia studies remain confined to highly controlled laboratory settings with ideal nutrients and oxygen availability, minimal competitors, and few co-contaminants (Kumar *et al.*, 2025). This raises questions about their applicability in field conditions. To fully leverage microbial consortia for sustainable remediation, future research should characterize their dynamics under fluctuating, field-like conditions and examine interspecies relationships. Additionally, incorporating environmental parameters such as soil, water chemistry, and nutrient cycles is essential (Boularbah *et al.*, 2025). Figure 1 shows a conceptual way of a microbial consortium remediation cycle overlaid with environmental modifiers. This model can guide the rational design of consortia tailored to specific contaminated environments.



**Figure 1:** Microbial consortium remediation cycle

### Bio Carrier and Biofilm Supported Systems: Stabilizing Microbial Function in Complex Environments

One of the major challenges in the bioremediation process is sustaining microbial viability, activity, and proximity to pollutants under environmental stresses (Kour *et al.*, 2022). The use of bio-carriers, such as biochar, to maximize microbial survival and activity, is a recent strategy to tackle these challenges (Wu *et al.*, 2025). One of the recent articles, which is titled Biochar Supported Microbial Systems: A Strategy for Remediation of Persistent Organic Pollutants, highlights that combining biochar with pollutant-degrading microbes offers a transformative approach (Wu *et al.*, 2025). Biochar, which is obtained from biomass pyrolysis, provides a porous, high-surface-area, chemically functionalized matrix that

contains hydroxyl, carboxyl, and quinone groups (Tomczyk *et al.*, 2020). This matrix immobilizes pollutants, provides a protective microhabitat for microbes, and concentrates nutrients and substrates near cells. It also facilitates extracellular electron transfer, especially for anaerobic degradation pathways. Empirical studies support this integration, that is, reed-biochar-immobilized microbes remediated petroleum hydrocarbon contaminated soil with ~55% removal after 40 days, outperforming biochar alone (~46%) and untreated soil (~25%) (Itam *et al.*, 2023).

Similar to biochar carrier systems, structured microbial communities embedded in extracellular polymeric substances (EPS) have been the recent focus due to their bioremediation potential (Wu *et al.*, 2025). The recent review, Biofilm mediated

bioremediation of xenobiotics and heavy metals: a comprehensive review, states that the biofilm matrix enhances pollutant degradation compared to planktonic bacteria. EPS offers a sorption site for pollutants, protects microbes from toxicity, promotes horizontal gene transfer to improve adaptation, and allows metabolic cooperation among community members (Atmakuri *et al.*, 2024). Biofilm reactors or carrier-assisted biofilm systems further allow for microbial immobilization, biomass reuse, and potential scale-up, making them a great choice for remediation applications.

The convergence of materials science (biochar and carriers), microbial ecology (biofilms), and environmental engineering is an indicator of the evolution of bioremediation from planktonic, suspension-based laboratory assay toward engineered, stable systems capable of persisting in soils or sediments. Hybrid systems that employ both carriers and biofilms are suitable for hydrophobic pollutants, marking a green future for remediation (Sarkar and Bhattacharjee, 2025). However, challenges remain. These include long-term microbial viability (due to biochar degradation or nutrient depletion), fate of bound pollutants (desorption and leaching), ecological impact (competition with indigenous microbiota), and economic possibility at the field scale (Rao *et al.*, 2024). Overcoming these barriers requires an integrated long-term study that tracks pollutant fate, microbial dynamics, and geochemical parameters over months to years.

### **Evolution and Adaptation: How Microbial Communities Broaden Their Degradative Nature**

Evolutionary adaptation is the most fundamental and often overlooked aspect of microbial remediation. A mini-review article "Evolution of pollutant biodegradation" (2025) highlights how bacteria, under pollutant pressure, can recruit enzymes, modify metabolic pathways, and optimize gene regulation to break down compounds. Pollutants impose toxicity on multiple cellular levels, damaging membranes, enzymes, and transcription, making survival a prerequisite for adaptive biodegradation (Ren and Manfield, 2025). Microbes often use enzymes with broad substrate specificity to initiate the transformation of new compounds. Through mutation and selection, these enzymes, along with auxiliary metabolic and electron-transfer proteins, are often reallocated into new degradation pathways (Zhang *et al.*, 2024). However, evolutionary adaptation is

limited by epistatic interactions, where mutations beneficial for enzyme function may impose cellular costs, such as increased energy demands and cellular toxicity, which limit evolutionary progress (Johnson *et al.*, 2023).

Viewing bioremediation through an evolutionary lens shifts the perspective on degradation capacity as dynamic rather than fixed. Over time, native microbial communities at polluted sites can adapt to natural attenuation, especially with bioaugmentation, bio-carriers, and nutrient management (Ossai *et al.*, 2024). Evolution can also be intentionally harnessed through adaptive laboratory evolution, selective enrichment, directed enzyme and consortium evolution, expanding the range of degradable pollutants (Renganathan *et al.*, 2025). However, these evolutionary approaches have drawbacks; that is, pathways are often slow and unpredictable, and may select for undesired traits, raising ecological and regulatory concerns if modified microorganisms escape target sites. Sustainable, long-term remediation requires balancing the potential of microbial evolution with careful monitoring and contaminant strategies.

### **Expanding Pollutant Scope: Emerging Contaminants, Microplastics & Mixed Pollution Systems**

Traditional bioremediation efforts mainly focused on persistent organic pollutants (POPs), petroleum, and heavy metals. However, recent research is increasingly looking at the use of bioremediation in combination with other methods in the treatment of more complex pollution cases. A recent publication titled Biodegradation of Emerging Contaminants Controlled by Biological and Chemical Factors (Mqambalala *et al.*, 2025) highlights that native microbes in aquatic and terrestrial ecosystems are capable of breaking down ECs through either metabolic or co-metabolic pathways. However, the degradation's effectiveness relies heavily on environmental factors such as the amount of nutrients available, the levels of oxygen, the presence of co-substrates, and the concentrations of pollutants, illustrating the context-specific challenges of EC remediation.

Microbial and enzymatic degradation of plastics and microplastics has gained considerable attention. A recent paper titled Recent trends in microbial and enzymatic plastic degradation: a solution for plastic pollution predicaments (Dhali *et al.*, 2024) unfolds the advances in identifying plastic-degrading enzymes, such as the

identification of enzymes (mainly hydrolases and oxidoreductases), microbial strains, and the plastisphere are potential agents for plastic remediation. The studies conducted highlight the recognition that microbes can be engineered to tackle new pollutants, beyond traditional contaminants.

On a larger scale, practically polluted areas usually have a blend of different pollutants such as polyaromatic hydrocarbons (PAHs), heavy metals, microplastics, and emerging chemicals requiring comprehensive remediation strategies. Articles like *Microbial Degradation of Soil Organic Pollutants: Mechanisms, Challenges, and Advances in Forest Ecosystem Management* (Mqambalala *et al.*, 2025) propose the use of blending microbial consortia, plant-microbe systems (phytoremediation), nano-bioremediation, and carrier-supported approaches to tackle such complexity. This increase in microbial remediation reflects the urgency posed by evolving global pollution profiles. While microbes, especially in the form of consortia, biofilms, or carrier-supported systems, provide a very flexible and adaptive toolbox, challenges remain. They have low bioavailability, lack or inefficient metabolic pathways, and possibly toxic intermediates (Das *et al.*, 2023). Consequently, there is a growing demand for interdisciplinary strategies that combine microbial ecology, materials science, enzymology, toxicology, and environmental monitoring to design robust remediation techniques suitable for mixed pollutant settings (Mohan *et al.*, 2025).

## FUTURE DIRECTIONS AND RESEARCH GAPS

Despite recent advances, there are critical gaps and challenges that need to be addressed to transform microbial-mediated biogeochemical remediation into sustainable and long-term environmental solutions.

### Field Scale Validation and Long-Term Monitoring

A major gap in current microbial remediation research is that most studies are conducted at the laboratory scale, under controlled conditions using sterile media, pure pollutants, and optimal nutrients and oxygen (Kour *et al.*, 2022). The microbial performance, persistence, and community stability under environmental fluctuations are largely untested. There is a complete lack of long-term field studies, which limits the understanding of how biodegradation processes influence temperature, moisture, co-

contaminants, and competition with native microbiota (Sun *et al.*, 2024). Future research should focus on developing pilot-scale field experiments in soils, sediments, and aquifers where engineered microbial consortia or bio-carrier systems are implemented. Periodic monitoring of pollutant concentrations, metabolite fate, and microbial community dynamics using metagenomics and metatranscriptomics should be studied. Techniques such as stable-isotope probing (SIP) can be used to directly link active taxa to degradation processes and, at the same time, to evaluate ecological side effects, thereby bridging the gap between laboratory efficiency and real-world application (Li *et al.*, 2025a).

### Fate And Toxicity Of Degradation Intermediates

One of the main problems in the research of microbial remediation is that the majority of the studies concentrate on the disappearance of parent pollutants without tracking the fate of the intermediate metabolites (Zhao *et al.*, 2024). Some of these metabolites may be toxic, persistent, or mobile than the original compounds. This concern is particularly critical for emerging contaminants and complex pollutant mixtures (Jeyaseelan, 2025). Future research should integrate the application of comprehensive analytical techniques such as LC-MS/MS, GC-MS, and high-resolution mass spectrometry, along with toxicity assays, to thoroughly evaluate degradation products (Belaid *et al.*, 2021). The incorporation of risk assessment frameworks for these by-products will offer a better understanding of environmental safety and the true efficacy of bioremediation methods.

### Enhancing Microbial Survival, Activity, And Adaptability

A significant gap in real-world microbial remediation is that the consortia are often due by environmental stresses such as toxicity, nutrient deficiency, predation, desiccation, and competition with native microbes (Semwal *et al.*, 2025). While bio-carrier and biofilm systems offer improvements, long-term microbial viability, nutrient depletion, and ecological interactions remain major challenges (Paul *et al.*, 2024). Future directions include creating smart bio-carrier systems such as biochar doped with nutrients or electron donors/acceptors, slow-release nutrient matrices, and responsive carriers that change with redox conditions and pH. These methods can be combined with periodic bioaugmentation or adaptive laboratory evolution to sustain functional

degraders and improve long-term remediation performance (Wang *et al.*, 2023).

### Broadening Pollutant Scope And Tailoring Remediation To Context

A notable gap in current bioremediation research is that many emerging pollutants, such as microplastics, new synthetic chemicals, and complex waste streams, remain under-investigated for microbial degradability, and studies rarely tackle mixed-pollutant or real-world waste profiles (Mqambalala *et al.*, 2025). Future research should expand metagenomic and functional screening of contaminated sites worldwide. This should include soils, sediments, wastewater, and landfills to identify new microbial degraders and enzymes adapted to local conditions (Ayilara and Babalola, 2023). Synthetic biology and directed evolution approaches can be used to develop strong context-specific degraders to effectively address these diverse and complex pollutants (Chernova *et al.*, 2025).

### Ethical, Regulatory, And Ecological Considerations

A major issue in microbial remediation is that the ecological risks of applying engineered and evolution-adapted microbes are not well understood, including gene flow to native microbiota, unintended ecological consequences, and insufficient regulatory frameworks (Kuzma, 2020). Future directions should focus on developing clear guidelines for environmental release, containment, and control of microbes. Evaluating ecological risks through mesocosm studies, actively engaging policymakers and stakeholders to ensure safe and responsible integration of microbial remediation into regulatory frameworks (Luiselli and Pacini, 2025).

### CONCLUSION

Microbial-mediated biogeochemical remediation has advanced substantially over the past few years. This is driven by advancements in consortium engineering, bio-carrier and biofilm technologies, as well as a comprehensive understanding of microbial evolutionary adaptation, which have expanded the potential for sustainable, long-term remediation of various pollutants. The increasing awareness of emerging pollutants, microplastics, and complex pollutant mixtures is an indication of evolving environmental challenges of the Anthropocene. However, the complete potential of microbial techniques requires field-scale validation supported by long-term monitoring, comprehensive tracking of degradation by-

products, adaptive carrier and consortia design, and robust ecological and regulatory frameworks. A holistic, interdisciplinary approach that combines microbial ecology, materials science, analytical chemistry, toxicology, and environmental policy will be essential for developing durable and scalable remediation systems. This will enable microbial biogeochemical remediations to transition from a promising research frontier to a fundamental component of sustainable environmental management that strengthens ecosystem resilience, supports circular resource use, and improves global environmental health.

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