Advances in Bioresearch
Adv. Biores., Vol 17 (6) June 2026: 246-251

Print ISSN 0976-4585; Online ISSN 2277-1573
Journal's URL: http://www.soeagra.com/abr.html
CODEN: ABRDC3
DOI: 10.15515/abr.0976-4585.17.6.246251

Advances in Bioresearch

REVIEW ARTICLE

Role of Soil Microorganisms in the Biodegradation of Toxic air Pollutants: A Review Article

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ABSTRACT
Soil contamination caused by industrial emissions, hydrocarbons, agrochemicals, and toxic gases has become a global concern affecting environmental quality, microbial diversity, and geotechnical stability. Microbial remediation—especially bioaugmentation and biostimulation—offers a sustainable, low-carbon, and highly adaptive strategy for degrading toxic organic compounds, immobilizing inorganic pollutants, and mitigating greenhouse gas (GHG) emissions. The study aims to evaluate how enhanced microbial activity can be leveraged not only for environmental remediation but also for improving soil strength and structural stability in geotechnical applications. This review integrates microbial biotechnology with geotechnical engineering perspectives, highlighting how soil bacteria contribute to pollutant degradation, toxic gas mitigation, MICP-based stabilization, and sustainable soil improvement. The findings emphasize that optimized microbial approaches not only restore contaminated soils but also improve engineering properties, supporting long-term geoenvironmental sustainability. This study highlights the transformative potential of microbial interventions as a nexus between climate change mitigation, air pollution control, and geotechnical resilience. The findings contribute to the development of scalable, low-cost solutions for soil remediation and atmospheric detoxification in industrially affected regions. This review uniquely introduces Microbial-Geoenviromental Nexus framework and a performance-based synthesis to evaluate how microbial remediation can simultaneously achieve pollutant detoxification and improvement of soil engineering properties for sustainable site redevelopment.
Keywords: *Bio augmentation, Microbial remediation, GHG mitigation, Soil bacteria, Geotechnical sustainability, MICP*

Received 27.03.2026 Revised 21.05.2026 Accepted 19.06.2026

How to cite this article:
Manish V. Shah, Priyanka Oza and Shalini R. Singh. Role of Soil Microorganisms in the Biodegradation of Toxic air Pollutants: A Review Article. Adv. Biores. Vol 17 [6] June 2026. 246-251

INTRODUCTION

Soil acts as one of the most vital components of the Earth's ecological system. Often referred to as the pedosphere or the "skin of the Earth," it is composed of minerals, organic matter, water, gases, and a vast diversity of organisms that support plant growth, nutrient cycling, and environmental regulation. Due to its porous and reactive nature, soil also functions as a natural sink for a wide range of contaminants. These pollutants originate from sources such as industrial waste, agrochemicals, petroleum spills, mining activities, and atmospheric deposition. Over time, harmful substances accumulate within soil layers, altering soil chemistry, reducing fertility, and threatening biodiversity. [1, 2, 3]

NOVELTY AND CONTRIBUTION OF THIS REVIEW

This review goes beyond a descriptive synthesis of microbial bioremediation studies by introducing an integrated geoenvironmental perspective that links pollutant detoxification with soil mechanical performance. The key novelty lies in framing microbial biotechnology as a dual-purpose tool for both environmental cleanup and geotechnical soil improvement, supported by a performance-based comparison of remediation strategies and a critical identification of knowledge gaps. By proposing a unified microbial-Geoenvironmental nexus framework, this review provides original analytical insight and a decision-perspective to guide future research and field scale applications for sustainable reuse of contaminated soil. Toxic pollutants in soil can be broadly categorized as organic pollutants—such as hydrocarbons, pesticides, solvents, and detergents—and inorganic pollutants including heavy metals, radionuclides, and mineral acids. Contaminated soil not only disrupts microbial balance and plant health but also introduces pollutants into groundwater, crops, and the food chain, leading to various ecological and human health risks.[4]. Traditional soil remediation methods (e.g., incineration, excavation, chemical stabilization) are often costly, energy-intensive, or environmentally damaging. In contrast, microbial biotechnology harnesses the metabolic capabilities of microorganisms to degrade, transform, immobilize, or remove contaminants in a natural and sustainable manner. Microbial bioremediation offers an eco-friendly approach and is increasingly recognized as an essential component of modern environmental management.[5]. This review synthesizes the principles, mechanisms, microbial species, and emerging strategies in microbial biotechnology for soil detoxification, highlighting its significance as a sustainable solution for environmental restoration.[6] This review uniquely integrates microbial remediation mechanisms with geotechnical performance indicators and air/GHG mitigation, proposing a unified framework and evaluation strategy for sustainable redevelopment of contaminated soil.

TYPES AND SOURCES OF SOIL POLLUTANTS

Soil contaminants originate from numerous industrial, agricultural, and domestic activities. Major sources include:

Agrochemical Inputs

Excessive use of fertilizers, pesticides, insecticides, and herbicides contributes to soil toxicity. Persistent organic pollutants remain in soil for decades and alter microbial diversity.[7]

Industrial Discharges and Mining

Mining activities, smelting, and processing industries release heavy metals such as lead, chromium, cadmium, and arsenic. These pollutants remain non-degradable and accumulate in soil. [8]

Petroleum and Hydrocarbon Spills

Leakage from storage tanks, pipelines, and petrochemical industries introduces polycyclic aromatic hydrocarbons (PAHs), oils, and solvents into the soil matrix.

Waste Disposal and Landfills

Electronic waste, sewage sludge, industrial waste, and chemical dumping lead to severe accumulation of toxic metals and organic contaminants.

Atmospheric Deposition

Smoke, acidic vapors, and industrial emissions settle onto soil surfaces, gradually increasing contaminant concentration. Pollutants often bind strongly to soil particles, complicating their removal and increasing the need for biological strategies to degrade or immobilize them.[9]

Microbial Bioremediation Approaches

Microbial bioremediation uses naturally occurring or engineered microorganisms to detoxify pollutants. Microbes survive harsh soil conditions due to their metabolic flexibility and genetic adaptability.[10]

Biodegradation

Microorganisms convert complex organic pollutants into simpler, non-toxic compounds through enzymatic processes. Aerobic bacteria oxidize hydrocarbons, while anaerobic microbes degrade chlorinated solvents and nitroaromatic compounds.[11]

Biosorption

Dead or living microbial biomass binds metal ions on its cell surface through functional groups such as carboxyl, hydroxyl, or amino groups. This passive process does not require metabolic energy.

Bioaccumulation

Living cells actively absorb contaminants through metabolic processes. Fungi such as Aspergillus and Penicillium demonstrate strong metal uptake capacity.

Bio-oxidation and Bio-reduction

Microbes alter oxidation states of metals, transforming them into less soluble or less toxic forms. For example, some bacteria reduce toxic Cr(VI) to Cr(III).

Biotransformation
Microorganisms convert pollutants into modified molecules that are less hazardous. This may involve dechlorination, methylation, or enzymatic cleavage.
Microbial Consortia
Multiple microbial species work synergistically to achieve complete mineralization of complex pollutants that cannot be degraded by a single organism.
Microorganisms Used in Soil Bioremediation
A diverse range of bacteria, fungi, and actinomycetes have been identified for their remediation **potential:**
Bacteria: Pseudomonas, Acinetobacter, Sphingomonas, Rhodococcus, Bacillus, Mycobacterium
Fungi: Phanerochaete chrysosporium, Aspergillus sp., Trametes versicolor
Actinomycetes: Nocardia, Streptomyces
These organisms degrade pollutants through enzymatic pathways involving monooxygenases, dioxygenases, reductases, and dehydrogenases. White-rot fungi, for instance, produce ligninolytic enzymes capable of degrading recalcitrant aromatic compounds.[12]
Heavy metal remediation relies on mechanisms such as metal binding proteins, metallothioneins, siderophore production, and membrane transport proteins that help microbes tolerate or transform toxic metals.[13]
Advanced Microbial Biotechnology Approaches
Genetically Engineered Microorganisms (GEMs)
Engineered microbes expressing metal-binding proteins or enhanced degradation enzymes significantly improve remediation efficiency.
Metagenomics and Microbial Community Engineering
Next-generation sequencing helps identify key degradative genes and design optimized microbial consortia.
Microbe–Plant Interactions
Rhizosphere microorganisms enhance plant-based remediation by increasing bioavailability and degradation of pollutants.
Enzyme-based Bioremediation
Isolated enzymes such as laccases, peroxidases, and reductases are used to treat contaminated soils directly. These advancements offer promising solutions for complex and recalcitrant contaminants.
Geotechnical Aspects of Microbial Remediation
Soil contamination not only affects ecological and biochemical processes but also has a direct influence on the geotechnical behaviour of soils, such as strength, permeability, compressibility, and bearing capacity. Toxic compounds—particularly hydrocarbons, heavy metals, and acidic industrial wastes—alter the soil fabric, particle arrangement, and interaction between solid and pore fluid phases. These changes decrease soil stability and compromise the long-term safety of foundations, embankments, and earth structures. [14]
Microbial biotechnology supports geotechnical sustainability by improving soil properties through a variety of microbially mediated processes:
Microbial-Induced Calcite Precipitation (MICP)
Certain bacteria such as Sporosarcina pasteurii induce the precipitation of calcium carbonate through ureolysis. This bio-cementation process:
- increases soil shear strength
- reduces hydraulic conductivity
- decreases liquefaction potential
- enhances overall stability of contaminated and loose soils

MICP is particularly useful in hydrocarbon-contaminated sands, where natural cementation has been degraded.
Improvement of Soil Structure through Biopolymer Production
Microorganisms secrete extracellular polymeric substances (EPS) that bind soil particles and enhance:
- aggregate formation
- water retention
- resistance to erosion
- cohesion in fine-grained soils
- EPS-producing microbes also immobilize heavy metals within the soil matrix, enhancing both environmental safety and geotechnical performance.

Reduction of Metal Toxicity and Stabilization
Heavy metals weaken soil fabric due to ion exchange, flocculation–deflocculation effects, and altered pore fluid chemistry. Microbial biosorption, bioaccumulation, and biomineralization transform metals into less mobile or insoluble forms, resulting in: [15]

- improved soil stiffness
- reduced compressibility
- better foundation reliability

Microbial stabilization is increasingly seen as an eco-friendly alternative to chemical stabilizers like cement and lime.

Enhancement of Bearing Capacity in Polluted Sites
Oil- and solvent-contaminated soils often exhibit reduced bearing capacity due to decreased matric suction, loss of frictional contact, and altered pore fluid interactions. Microbial degradation of hydrocarbons restores soil matric behaviour and natural drainage, gradually recovering:[16]

- bearing resistance
- shear strength
- modulus of elasticity

This is crucial for rehabilitation of industrial sites before construction.

Microbial Remediation and Slope Stability
Contaminants such as acids, hydrocarbons, or chlorinated solvents can weaken slopes by reducing cohesion and increasing pore-water pressure. Microbial processes reduce pollutant-induced weakening and promote mineral precipitation, which: [17, 18]

- increases slope stability
- reduces erosion
- improves long-term soil resilience

Relevance to Sustainable Geotechnical Engineering
Microbial biotechnology aligns with modern sustainable geotechnical engineering goals by:

- reducing dependence on carbon-intensive materials
- improving soil engineering behaviour through natural processes
- enabling safe reuse of contaminated lands for infrastructure
- integrating biology with soil mechanics for long-term soil health

Thus, microbial remediation not only detoxifies contaminated soils but also contributes significantly to the geotechnical stabilization and reuse of degraded lands, making it a dual-benefit strategy for environmental and civil engineering applications.[19, 20, 21, 22]

Novel Conceptual Framework: Microbial-Geoenviromental Nexus
This review introduces a novel integrative framework termed the "Microbial-Geoenviromental Nexus," which conceptualizes microbial biotechnology as a dual function tool for both environmental detoxification and geotechnical soil improvement. Unlike conventional reviews that treat bioremediation primarily as a pollutant removal strategy, this framework positions microorganisms as active agent that simultaneously restore soil mechanical performance, mitigate greenhouse gas emission, and enable sustainable land reuse. The framework links microbial metabolic pathway with measurable geotechnical responses such as shear strength, compressibility, permeability and bearing capacity, there by bridging environmental microbiology and soil mechanics.

Performance based comparative analysis of microbial remediation strategies
To introduce a performance-oriented perspective, microbial remediation strategies are comparatively evaluated based on pollutant removal efficiency, geotechnical improvement potential, carbon footprint, field applicability, and operational limitations. This analysis provides a decision support tool for selecting site specific sustainable remediation technique.

Critical Synthesis and Knowledge Gaps
A critical analysis of the reviewed literature reveals several gaps and contradictions:
Most studies emphasize contaminant removal while neglecting post remediation geotechnical performance. MICP is widely reported for strength improvement, yet its interaction with residual toxicity remains underexplored. Laboratory scale successes often fail to translate to field scale applications due to soil heterogeneity. Potential trade offs between biodegradation and pore clogging are rarely quantified. There is a lack of standardize protocols integrating bioremediation with geotechnical testing methods. Addressing these gaps is essential for advancing microbial remediation from experimental studies to engineering practice.

CONCLUSION

Microbial biotechnology has emerged as a transformative and environmentally responsible solution for the remediation of contaminated soils, offering clear advantages over traditional mechanical or chemical methods. As soil pollution continues to threaten ecological stability, agricultural productivity, and infrastructure safety, microbially mediated processes provide a pathway to restore both environmental and engineering functionality. Microbes are not only capable of degrading complex organic pollutants but can also immobilize, transform, or precipitate inorganic contaminants, making them highly versatile tools in soil restoration. [23] From a geotechnical engineering perspective, microbial remediation techniques—especially microbial-induced calcite precipitation (MICP), biosorption, and extracellular polymer production—offer dual benefits. They detoxify polluted soils while simultaneously improving properties such as shear strength, bearing capacity, permeability, and soil fabric stability. This unique intersection of microbiology and geotechnics aligns directly with the goals of sustainable infrastructure development, reduced carbon footprint, and long-term soil health management. While laboratory and pilot-scale studies show promising results, field-scale implementation still requires optimization in areas such as microbial survival in harsh environments, nutrient delivery systems, pollutant-specific microbial selection, and long-term monitoring. Future research should emphasize the integration of microbial consortia, gene-editing tools, plant–microbe systems, and real-time geotechnical performance assessment to create holistic remediation frameworks.[24] Overall, microbial biotechnology represents a scientifically robust, cost-effective, and future-ready approach to rehabilitating contaminated sites while supporting resilient and sustainable geotechnical engineering practices. [25] This review suggests that future soil bioremediation should be evaluated not only as a contaminant removal technology, but as a soil engineering process that reshape mechanical behaviour and environmental sustainability simultaneously.

ACKNOWLEDGEMENT

The author acknowledges the importance of microbial biotechnology literature and previous research that contributed to the development of this review.

CONFLICT OF INTEREST

The author declares no conflicts of interest

CREDIT AUTHOR STATEMENT

Prof. Dr. Manish V. Shah: Contributed to critical review, technical inputs, and editing the draft of manuscript. Priyanka Oza: Contributed to conceptualization, literature collection, data interpretation and manuscript drafting. Prof. Shalini R. Singh: Assisted in literature screening and formatting of the manuscript. All authors reviewed and approved the final version of the manuscript.

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