

Bioremediation Strategies for Herbicide Contaminated Soil: Techniques and The Role of Microbial Communities

*Arya Kuttan K¹ and Dr. Anu Rajan S.²

¹PhD Scholar (Plantation, Spices, Medicinal and Aromatic Crops), College of Agriculture, Vellayani, Thiruvananthapuram, Kerala Agricultural University, India
²Assistant Professor, Department of Agricultural Microbiology, College of Agriculture, Vellayani, Thiruvananthapuram, Kerala Agricultural University, India
 *Corresponding Author's email: arya-2025-22-005@student.kau.in

Herbicides keep modern farming productive by suppressing weeds and cutting down on labour. But when they are applied heavily and repeatedly, the downsides add up: they can leave behind toxic breakdown products, shift the makeup of soil microbial communities and cause long-term pollution of soils, waterways and groundwater. Many microorganisms can use herbicides as a source of carbon, nitrogen or phosphorus and in doing so they convert them to simpler and usually less harmful products. Bioremediation tries to put that natural capacity to work on purpose, either by encouraging the microbes already present in a contaminated site or by adding organisms with known degradative ability.

Bioremediation strategies and techniques

Bioremediation is defined as a biotechnological process that employs living organisms, predominantly microorganisms such as bacteria and fungi and in some cases plants (phytoremediation) and algae to degrade, detoxify or transform hazardous environmental contaminants into less toxic or nontoxic forms.

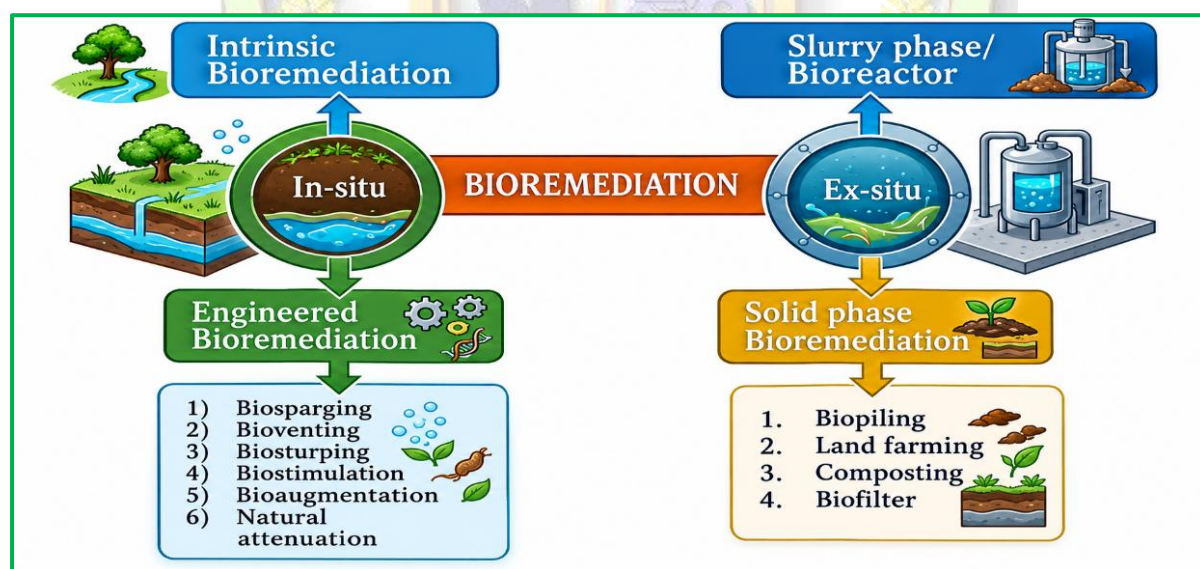


Figure 1. Bioremediation approaches for soil pollution

Bioremediation strategies are broadly classified into two categories based on the location where the treatment is carried out: in-situ bioremediation, in which contaminated soil is treated at the site of contamination without excavation and ex-situ bioremediation, in which contaminated soil is excavated and treated either onsite or at a different location. The choice between the two

depends on factors such as the type and depth of contamination, cost, site accessibility and regulatory requirements.

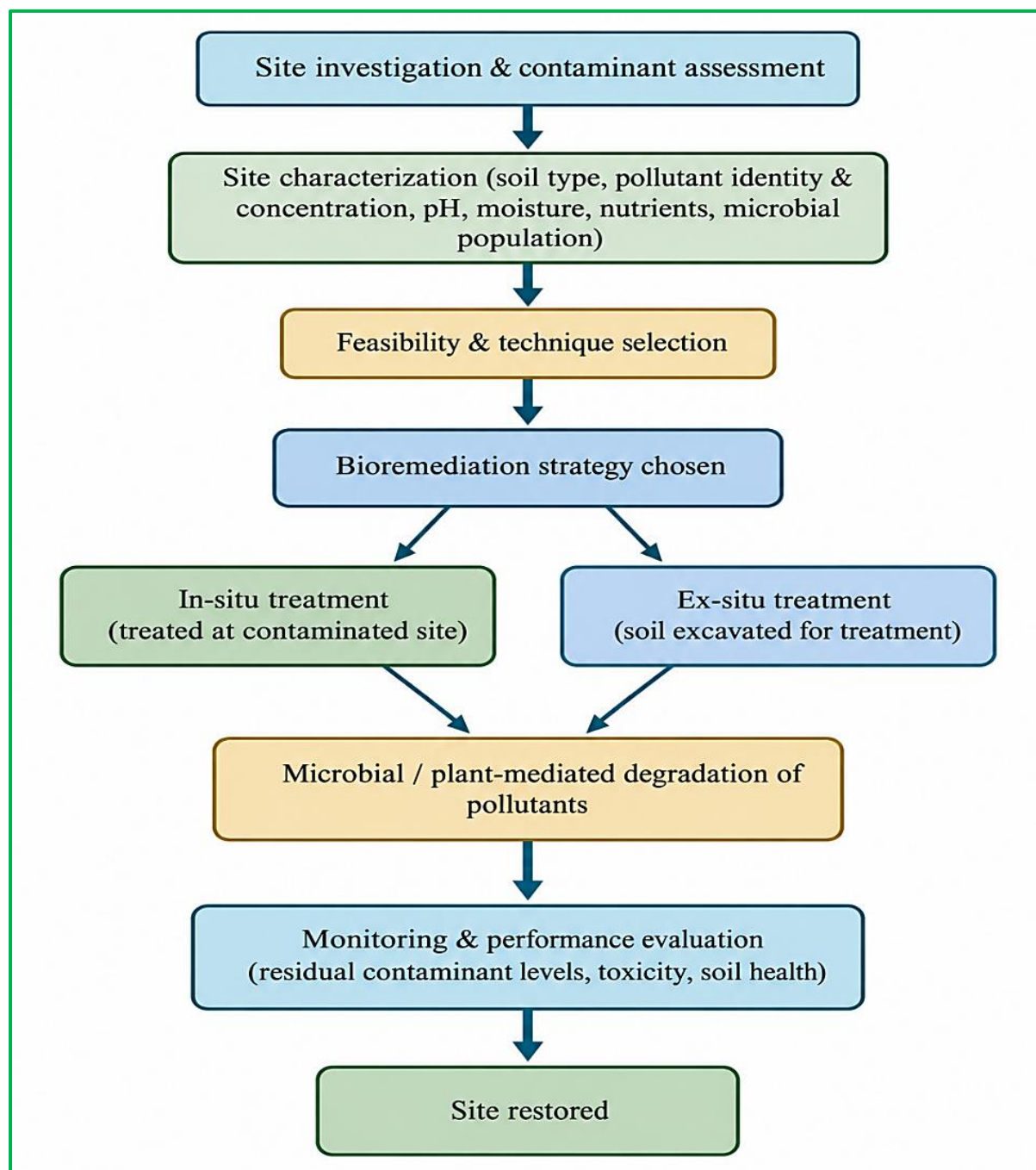


Figure 2. General process flow chart of soil bioremediation

A wide variety of specific techniques have been developed for the bioremediation of polluted soils, each suited to particular contaminant types, site conditions and remediation goals. Table 1 summarizes the major techniques along with their principle of operation and typical applications.

Table 1. Major bioremediation techniques, principles and applications

Technique	Principle	Typical Application
Bioaugmentation	Addition of specialized pollutant-degrading microbial strains	Sites lacking sufficient indigenous degraders; recalcitrant pollutants
Biostimulation	Addition of nutrients (N, P, K) and electron acceptors to boost indigenous microbes	Oil spills, hydrocarbon contaminated soils
Bioventing	Forced aeration of vadose zone to stimulate aerobic degradation	Petroleum hydrocarbon contamination

Technique	Principle	Typical Application
Biosparging	Air injection below water table	Saturated zone hydrocarbon contamination
Landfarming	Periodic tilling of excavated soil spread in thin layers	Refinery waste, petroleum sludge
Composting	Mixing with organic bulking agents; thermophilic degradation	Explosives-contaminated soil, pesticides
Biopiles	Aerated static piles with leachate collection	Volatile & semi-volatile hydrocarbons
Slurry-phase bioreactor	Soil mixed with water in a controlled reactor vessel	Highly contaminated, recalcitrant soils requiring rapid treatment
Phytoremediation	Use of plants to extract, degrade, or stabilize pollutants	Heavy metals, moderately contaminated large areas
Mycoremediation	Use of fungi (especially white-rot fungi) and their enzymes	PAHs, dyes, pesticides, lignin-like pollutants

Bioremediation of herbicides

Bioremediation of herbicides is a promising approach to mitigate the environmental impact of herbicide contamination in soils. This process involves using microorganisms to degrade or transform herbicides into less harmful compounds, offering a sustainable alternative to traditional methods like containment and disposal. Recent studies have demonstrated the potential of microbial communities and specific strains in effectively degrading herbicides, thereby reducing environmental contamination and improving soil health.

Microbial degradation of herbicides

Microbial taxa utilize herbicides as sources of carbon, nitrogen, phosphorus, or energy through specialized catabolic pathways. The table below summarizes microbial strains, their enzyme systems, target herbicides and experimentally validated removal efficiencies across diverse matrices.

Table 2. Microbial biodegradation performance across representative herbicide classes and experimental matrices

Herbicide Class	Target Compound	Microbial Agent	Matrix / System	Efficiency & Outcomes	Reference
Phenoxy-carboxylic acids	2,4-D	<i>Enterobacter cloacae</i>	Agricultural leachate	90.4% removal in 24 h at pH 3.5	Debebe <i>et al.</i> , 2025
Organophosphonates	Glyphosate	<i>Paenibacillus ottowii</i> NPDY10	Liquid culture & paddy trial	100% removal (400 mg/L) in 4 days	Deng <i>et al.</i> , 2026
Phenylureas	Diuron	Immobilized <i>A. globiformis</i> D47	Nanocellulose fiber network	Accelerated degradation and survival	Li <i>et al.</i> , 2021
Triazines	Atrazine	Enriched anaerobic consortium	Factory soil enrichment	Six metabolites identified	Bao <i>et al.</i> , 2024
Triazines	Metribuzin	<i>Streptomyces heliomyces</i> C1	In vitro culture (50 mg/L)	83.12% degradation at pH 7.2	Rebai <i>et al.</i> , 2024
Pyridinecarboxamides	Diffenican	Quadruple bacterial SynCom	Agricultural soil & Mineral salt medium	82.2% soil removal over 35 days	Książek-Trela <i>et al.</i> , 2025
Diphenyl ethers	Oxyfluorfen	<i>Micrococcus</i> sp. F3Y	Unsterilized soil (50 mg/kg)	98.2% mineralized within 25 days	Yao <i>et al.</i> , 2025
Dinitroanilines	Trifluralin	<i>Arthrobacter aurescens</i> CTFL7	Soil amended with RAMEB (randomly methylated-β-CD)	88% clearance (DT50 = 19 days)	Lara-Moreno <i>et al.</i> , 2022

Fungal bioremediation of herbicides

Saprophytic fungi like *Corioloropsis rigida* and *Fusarium lateritium* have been effective in degrading pendimethalin, a common herbicide. These fungi not only reduced herbicide levels but also improved the symbiotic abilities of *Phaseolus vulgaris*, enhancing plant growth and soil microbial activity (Paniagua-López *et al.*, 2025).

Microbial communities and herbicide degradation

Microbial consortia have emerged as a powerful tool for bioremediation, leveraging the synergistic interactions among diverse microbial species to enhance the degradation of pollutants. These consortia can effectively address various contaminants, including heavy metals, hydrocarbons and synthetic dyes, through collaborative metabolic processes. The strongest direct evidence comes from recent synthetic communities. A four-member SynCom degraded eight herbicides by more than 60% within 48 hours in laboratory tests and achieved 60% to 99% removal of endogenous herbicides over 35 days in black soil microcosms while maintaining biomass above 10^4 cfu/g soil. This same SynCom increased carbohydrate-active enzymes, microbial necromass-associated carbon and genes linked to the tricarboxylic acid cycle, pyruvate metabolism and glycolysis, suggesting that remediation can also reactivate soil carbon metabolism (Zhang *et al.*, 2025). Consortium logic also appears in specific herbicide systems. The diflufenican study found that a quadruple community outperformed the best single strain in both mineral medium and soil (Książek-Trela *et al.*, 2025). Earlier work on linuron showed that biofilm cooperation among *Comamonas testosteroni*, *Hyphomicrobium sulfonivorans* and *Variovorax* was necessary because no single member could degrade the herbicide alone (Pileggi *et al.*, 2020).

Factors Influencing Bioremediation

The success of microbial bioremediation depends on microbial activity, environmental conditions, herbicide properties and soil characteristics, which together determine herbicide bioavailability and degradation rate. Bioavailability is often the first limiting factor, because strong sorption of herbicides to clay and organic matter makes them less accessible to microbes and slows degradation. Environmental conditions such as pH, temperature, moisture, oxygen and nutrient supply regulate microbial growth and enzyme activity, so even well-adapted degraders perform poorly outside their optimal range. Co-contaminants such as heavy metals or very high herbicide concentrations can be toxic to degrading microorganisms and suppress their activity. The nature of the degradation products also matters, since some intermediates, such as the glyphosate metabolite AMPA and the atrazine metabolite hydroxyatrazine, can be as toxic as or more mobile than the parent compound. Complete mineralization should therefore be verified rather than assumed.

Future prospects

Moving from successful pilot studies to large-scale environmental restoration will require addressing the limitations posed by environmental variability and nutrient availability and several research directions are likely to improve the reliability and efficiency of microbial bioremediation. Genomic and metabolic engineering approaches can improve degradation pathways, enhance the survival of introduced strains under field conditions and help identify the less obvious community members that make a consortium effective. Rather than treating contamination after the fact, preventive bioremediation could seed or stimulate herbicide-degrading communities in agricultural soils to reduce residues before they reach water bodies. Combining microbial degradation with constructed biobeds and other engineered systems can further buffer fluctuations in temperature, pH, nutrients and manage toxic intermediates more reliably than inoculation alone. Finally, long term field trials are needed to confirm that laboratory performance holds under real conditions, with particular attention to inoculant survival, nutrient regulation and the fate of degradation intermediates.

Conclusion

Microbial bioremediation is a robust, eco-friendly and sustainable technology for managing herbicide pollution. By harnessing the metabolic pathways of diverse bacteria, fungi and actinobacteria, high removal efficiencies can be achieved for a wide range of compounds, including atrazine, 2,4-D and sulfonylureas. Strategies such as bioaugmentation and biostimulation, particularly when using microbial consortia, have proven effective in both laboratory and field settings. The evidence suggests that single strains tend to be less robust than communities and that the members of a good consortium are not always the obvious degraders. Survival, nutrient regulation and toxic intermediates decide field outcomes more than raw degradation rate does. Ultimately, microbial bioremediation is a key tool for ensuring the ecological sustainability of modern agricultural practices and protecting global water and soil resources.

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