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FROM HERBICIDE POLLUTION TO SOIL RECOVERY: MICROBIAL BIODEGRADATION AND COST-EFFECTIVE CONSORTIA FOR RESTORING AGRICULTURAL SOIL HEALTH

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ABSTRACT

Herbicides support reliable crop production, but repeated applications can leave residues and transformation products in the soil and water. These compounds may disrupt microorganisms that decompose organic matter, cycle nutrients, form soil aggregates, and support plant growth. This review examines microbial biodegradation as a practical and potentially affordable method for reducing herbicide residues while aiding in the recovery of agricultural soils. The discussion focuses on bacteria, fungi, indigenous microbial communities, and microbial consortia, with examples of atrazine, 2,4-dichlorophenoxyacetic acid, and glyphosate. Microbial processes include hydrolysis, oxidation, dehalogenation, phosphonate cleavage, and aromatic ring breakdown. Biostimulation, bioaugmentation, compost-assisted treatment, biopiling, slurry bioreactors, and rhizosphere-assisted remediation were compared. Particular attention is given to the cost advantages of using locally adapted microorganisms, low-cost organic amendments, in situ treatment, and consortia in which different members complete different steps in a degradation pathway. Important limitations include the poor bioavailability of aged residues, variable soil conditions, metabolite accumulation, weak survival of introduced strains, and difficulty in transferring laboratory

results to working farms. Metagenomics, functional omics, synthetic biology, and controlled genome editing may improve treatment design; however, their use must remain subject to ecological and regulatory safeguards. Therefore, successful remediation should be measured by both chemical reduction and the recovery of microbial activity, nutrient cycling, plant–microbe partnerships, soil structure, and crop productivity.

KEYWORDS: Agricultural soil; bioaugmentation; biodegradation; biostimulation; herbicide residues; microbial consortia; soil health.

1. INTRODUCTION

Herbicides have become central to modern weed management; however, repeated applications can leave residues and transformation products in soil and water. The concern is not only where the parent compound goes, but also how long it remains, what it becomes, and how it affects the living soil community. The fate of herbicides is shaped by their molecular structure, application history, soil texture, organic matter, pH, moisture, temperature, microbial activity, and drainage conditions. Glyphosate and its metabolite aminomethylphosphonic acid have been reported in agricultural soils, water, groundwater, precipitation, and other related environmental compartments. Atrazine has also been detected in agricultural watersheds and stream (Battaglin et al., 2014; Mahler et al., 2017).

Soil health is more than just the absence of contamination. Soil health is the ability of soil to support productive plants, biological diversity, and the environmental services on which agriculture depends. These physical, chemical, and biological functions are closely associated with microbial activity. Soil microorganisms decompose organic matter, mineralize nutrients, form aggregates, establish plant symbioses, and contribute to contaminant transformation (Food and Agriculture Organization of the United Nations [FAO], 2020).

Bioremediation works with biology rather than against it. Bioremediation employs microorganisms, plants, or their enzymes to transform, immobilize, or detoxify contaminants while preserving the original soil structure and life as much as possible. When treatment occurs in place, the costs associated with excavation, transport, energy use, and disposal may be reduced. This review examines how microbes can make herbicide cleanup more practical and affordable, while helping the soil regain its biological functions.

2. Herbicide Pollution and Soil Health

After application, herbicides may attach to soil particles, move with runoff, leach through the soil profile, change through abiotic reactions, or be transformed by microorganisms. Sorption can reduce immediate movement but may also hide residues from the microbial cells. Desorption during rainfall or irrigation can increase the transport of pesticides. Therefore, environmental risk depends not only on the total concentration but also on the chemical form, location, accessibility, and transformation products.

Herbicides can alter microbial biomass, community composition, functional genes, respiration, enzyme activity, and root-associated interactions. The effect depends on the active ingredient, formulation, concentration, exposure time, soil conditions, and sensitivity of the resident organisms. Soils may temporarily retain some functions because different organisms can perform similar jobs, but prolonged disturbance can reduce resilience to drought, nutrient stress, and further chemical exposure (Pileggi et al., 2020).

Excavation, soil washing, thermal treatment, chemical oxidation, and disposal can quickly remove contaminants, but they may be costly and disruptive across agricultural landscapes. They can also remove organic matter, damage soil structures, and eliminate resident microbial communities. Bioremediation is usually less invasive, although it can be slower and more dependent on local conditions than other remediation methods.

3. Microbial Mechanisms of Herbicide Biodegradation

Microbial degradation can occur in two broad ways: some organisms use a herbicide or its breakdown products as a source of nutrients or energy, while others incidentally transform the compound while growing on a different food source. Hydrolases, oxygenases, dehalogenases, phosphatases, peroxidases, and laccases can initiate or support these reactions.

A decrease in the concentration of the original herbicide is encouraging, but it is not proof of successful remediation. The products formed during degradation must also be tracked because some may be persistent, mobile, or toxic. Chemical results should be interpreted in conjunction with toxicity, microbial activity, and plant response measurements.

Atrazine degradation is commonly associated with the Atz pathways. In Pseudomonas sp. strain ADP, atrazine chlorohydrolase, encoded by atzA, replaces chlorine with a hydroxyl group and produces hydroxyatrazine (HA). AtzB and AtzC then remove the amino substituents and generate cyanuric acid. Further reactions can convert cyanuric acid into carbon dioxide and ammonia (Mandelbaum et al., 1995; Sadowsky et al., 1998).

The degradation of 2,4-dichlorophenoxyacetic acid is associated with the tfd pathway in bacteria, such as Cupriavidus necator JMP134. TfdA initiates the oxidative cleavage of the ether linkage, producing 2,4-dichlorophenol and glyoxylate. Subsequent reactions transform chlorinated intermediates through dechlorination and ring cleavage.

Glyphosate can be transformed through the C–P lyase system, which produces sarcosine and inorganic phosphate, or through glyphosate oxidoreductase, which produces AMPA and glyoxylate, respectively. AMPA may persist under certain soil conditions; therefore, it should be included in monitoring.

Bacteria and fungi can work together to degrade herbicides. Fungi produce extracellular oxidative enzymes that modify complex aromatic structures, while bacteria may use the resulting products. Therefore, mixed communities can complete pathways that are difficult for a single isolate to perform.

4. Microbes in Cost-Effective Bioremediation

The economic appeal of microbial bioremediation stems from its ability to function in the field with relatively little infrastructure. When treatment can occur in place, the costs associated with excavation, transport, energy use, and disposal may be reduced. The greatest savings are usually possible when indigenous microorganisms are activated with locally available materials, and treatment is combined with ordinary soil and crop management.

Biostimulation activates resident degraders by managing carbon, nutrients, moisture, aeration, pH, and electron acceptors. Compost, crop residues, and other biomass can provide carbon and improve moisture retention in soil. Nitrogen or phosphorus may be added when nutrient limitations restrict growth. However, excessive amendments can cause nutrient loss, oxygen depletion, or contaminant mobilization (Kanissery & Sims, 2011).

Bioaugmentation involves the addition of selected bacteria or fungi with demonstrated degradation capacity. Strains isolated from contaminated sites may survive better than organisms from unrelated environments. Immobilization in compost, biochar, alginate, or other carriers can protect cells and improve their distribution. However, introduced strains may be outcompeted, consumed by protozoa, or unable to reach strongly sorbed residues.

Microbial consortia contain organisms with complementary function. One member may transform the parent herbicide, another may consume toxic intermediates, and yet another may support biofilm formation or plant growth. This division of labor can make a consortium more robust than a single strain (Pileggi et al. 2020).

Plant roots release sugars, amino acids, and organic acids that support the growth of rhizosphere microbes. Rhizosphere-assisted remediation combines plants with microbial degraders, potentially improving contaminant contact while restoring soil structure and organic matter inputs. This is most suitable when residues do not prevent plant establishment or create a food chain risk.

5. Comparative Treatment Technologies

In situ treatment is performed within contaminated soil and can minimize excavation and transport. Natural attenuation relies on existing biological and abiotic processes, whereas biostimulation and bioaugmentation actively increase microbial degradation. These methods are best suited for sites where concentrations are manageable, soil conditions can be monitored, and groundwater protection is maintained.

Ex situ methods include composting, landfarming, biopiling, and slurry bioreactors. Excavated soil can be mixed, aerated, amended, and monitored closely. Slurry systems provide excellent mass transfer but require energy and disrupt soil matrices. Composting and biopiling can use local organic materials, although space, leachate, odors, and emissions must be managed accordingly.

6. Recovery of Soil Health

Successful remediation should be judged by more than just the removal of chemicals. The important question is whether the soil begins to function normally again, whether microbes become active, nutrients cycle, plants establish, and beneficial root partnerships return. Recovery can be assessed through microbial biomass, respiration, community composition, functional genes, enzyme activity, nutrient cycling, plant growth and soil structure.

Rhizobium and Bradyrhizobium support nitrogen fixation in leguminous crops. Herbicide stress can affect bacterial survival, root colonization, signaling, and nodule formation. Arbuscular mycorrhizal fungi improve phosphorus acquisition, water uptake, and stress tolerance in plants. Their recovery can be monitored through root colonization, hyphal development, spore abundance, and plant nutrient status.

Soil enzymes are useful functional indicators. Dehydrogenase reflects general microbial respiration, urease reflects nitrogen transformation, phosphatase reflects organic phosphorus cycling, and beta-glucosidase reflects carbon decomposition. Enzyme results should be interpreted alongside chemical and microbial measurements because an amendment can temporarily increase enzyme activity without indicating complete ecological recovery.

7. Field-Scale Constraints

Aged residues may bind to humic substances, clay minerals, and micropores, thereby reducing contact with microbial cells. This often creates a rapid initial degradation phase, followed by a slower period. Surfactants, biosurfactants, organic amendments, and moisture management can improve accessibility, but they can also increase leaching.

The pH affects herbicide ionization, sorption, microbial growth, and enzyme activity. Temperature and water content influence the reaction rates, oxygen diffusion, and microbial physiology. Agricultural soils fluctuate more widely than laboratory cultures; therefore, field protocols should be based on seasonal measurements rather than laboratory optima.

Introduced strains may decline because of competition, predation, desiccation, nutrient limitation, or poor soil movement. Locally isolated strains, carrier materials, biofilms, root targeting, and compatible organic amendments may improve the establishment. Genetically modified or genome-edited organisms require additional assessments of persistence, gene transfer, ecological displacement, and regulatory compliance.

8. Molecular Innovations

Metagenomics can be used to identify degradation genes and uncultured organisms in contaminated soils. Metatranscriptomics, proteomics, metabolomics, and stable isotope probing can determine whether pathways are active and whether herbicide-derived elements enter the microbial biomass. These tools can guide the selection of indigenous degraders and the design of site-specific biostimulation strategies.

Synthetic consortia can be designed based on the division of labor. A primary degrader may transform the parent herbicide, a second organism may consume the toxic intermediates, and a biofilm-forming partner may improve persistence. Metabolic engineering may expand the substrate range or stress tolerance; however, engineered systems require stability testing and ecological safeguards.

CRISPR-based editing may support pathway characterization, activation of silent catabolic genes, and improvement of tolerance to desiccation or to oxidative stress. Laboratory or reactor applications are currently easier to control than unrestricted field releases.

9. Monitoring and Economic Evaluation

A practical remediation program must combine chemical removal with biological recovery. Useful measurements include parent herbicide and metabolite concentrations, toxicity, microbial biomass, respiration, functional genes, soil enzymes, nutrient cycling, plant establishment and yield. Sampling before, during, and after treatment helps distinguish real recovery from short-term effects.

Economic evaluations should report the treatment cost per unit mass of herbicide removed, treatment duration, amendment and inoculum costs, labor, monitoring, infrastructure, water, energy, and secondary waste management. A treatment that appears inexpensive but leaves toxic metabolites or mobilizes residues may not be the most economical option in the long term.

10. CONCLUSIONS

Microbial biodegradation offers a realistic route for soil recovery from herbicide pollution. Bacteria and fungi can transform herbicides through several biochemical pathways, whereas indigenous communities and microbial consortia can share the work of degradation. Locally adapted microorganisms, low-cost organic amendments, biostimulation, bioaugmentation, rhizosphere management, and consortium-based treatments can reduce the need for excavation and intensive physicochemical processing.

No single treatment is suitable for every type of agricultural soil. Biostimulation is appropriate when indigenous degraders are present, whereas bioaugmentation may help when the required pathway is absent or weak. Consortia can improve performance through metabolic complementarity; however, their stability and ecological effects must be tested. Complete remediation requires parent compound and metabolite analysis, toxicity reduction, and evidence that soil functions are returning.

Further progress will require microbial ecology, environmental chemistry, soil management, and economic planning to be considered together. A treatment that works in a flask but fails in dry, heterogeneous fields is not a practical solution. Therefore, the strongest programs will combine careful site diagnosis, locally appropriate microbes, affordable amendments, realistic monitoring, and long-term evaluation of soil health.

Table 1: Microbial approaches for cost-effective herbicide biodegradation.

Approach	Microbial role	Cost advantage	Main limitation
Biostimulation	Activates indigenous degraders with nutrients, organic matter, moisture, or redox management	Low inoculum and infrastructure costs	Native degraders must be present
Bioaugmentation	Introduces selected bacterial or fungal degraders	May shorten treatment time for a target herbicide	Poor survival and repeated application costs
Microbial consortium	Combines complementary pathways	Improved robustness and less intermediate accumulation	Stability and quality control required
Rhizosphere treatment	Uses plant exudates and root-associated microbes	Combines remediation with soil restoration	Requires tolerant plants
Compost or biopile	Uses organic amendments and managed aeration	Can use agricultural residues	Requires space and leachate control
Slurry bioreactor	Provides intensive mixing and controlled conditions	High reaction rates	Excavation and energy demand

Table 2: Soil enzymes are useful for monitoring biological recovery.

Enzyme	Functional role	Recovery interpretation
Dehydrogenase	General oxidative activity of viable microbial cells	Increasing activity suggests recovery of respiration
Urease	Hydrolysis of urea to ammonia and carbon dioxide	Recovery suggests improved nitrogen transformation
Phosphatase	Release of inorganic phosphate	Recovery suggests improved phosphorus cycling
Beta-glucosidase	Decomposition of carbon compounds	Recovery suggests improved carbon turnover

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