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EFFECTS OF CHEMICAL POLLUTANTS ON SOIL MICROBIAL COMMUNITIES: MECHANISMS, ECOLOGICAL CONSEQUENCES, AND SUSTAINABLE MANAGEMENT

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ABSTRACT
Soil microorganisms regulate nutrient transformations that sustain plant productivity and ecosystem resilience. Chemical pollutants can disrupt these functions by altering microbial abundance, community composition, enzyme activity, functional gene expression, and interactions among microorganisms. This critical review examines the effects of pesticides, herbicides, heavy metals, antibiotics, petroleum hydrocarbons, and persistent organic pollutants (POPs) on soil microorganisms involved in nitrogen (N), phosphorus (P), and sulfur (S) cycling. Evidence indicates that pollutant effects are strongly context-dependent, varying with chemical structure, concentration, exposure duration, soil pH, organic matter content, nutrient status, and pre-existing microbial adaptation. Pesticides and herbicides can inhibit potential nitrification, N-acetylglucosaminidase activity, diazotrophic activity, and N-cycle functional genes, although some field studies report transient community shifts or recovery after dissipation. Heavy metals commonly constrain microbial biomass, enzyme activities, and nutrient mineralisation through toxicity, oxidative stress, membrane damage, and selection for resistant taxa. Antibiotics may alter microbial N transformations and promote communities carrying resistance determinants, whereas petroleum hydrocarbons and POPs can suppress sensitive nitrifiers and nutrient-cycling taxa while enriching pollutant-degrading organisms. Disrupted P cycling often manifests as altered phosphatase activity, phosphate-solubilising populations, and microbial P immobilisation; effects on S cycling, including arylsulfatase activity and sulfate reduction or oxidation, remain comparatively underexamined. These changes may reduce nutrient availability, destabilise soil organic matter turnover, impair plant growth, increase N losses, and compromise sustainable agriculture. Sustainable management should prioritise pollution prevention, integrated pest management, contaminant-specific risk assessment, organic amendments, biochar, phytoremediation, and microbiome-informed bioremediation. Future research should combine long-term field experiments with multi-omics, direct rate measurements, and assessments of pollutant mixtures to distinguish temporary compositional changes from persistent loss of soil function.

Keywords: Antibiotics; biogeochemical cycling; heavy metals; pesticides; soil microbiome

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1. Introduction

Soil microbial communities mediate decomposition, nutrient release and retention, and the transformation of inorganic and organic compounds. Therefore, their functions are central to soil fertility, crop production, and ecosystem stability. Chemical contamination threatens these functions because many pollutants affect not only intended targets, such as pests or pathogens, but also non-target bacteria, archaea, fungi, and protists.

Pollutant effects should not be inferred from changes in microbial diversity alone. Communities may retain taxonomic richness

while undergoing functional reorganisation, including the loss of sensitive nitrifiers, diazotrophs, phosphate-solubilising microorganisms, or sulphur-transforming taxa. Conversely, enrichment of tolerant or pollutant-degrading organisms may increase degradation capacity while reducing overall nutrient-cycling efficiency. The magnitude and direction of effects depend on pollutant bioavailability, dose, persistence, co-contaminants, and soil properties. This review evaluates how major chemical pollutants alter microbial N, P, and S cycling and considers the consequences for sustainable agriculture.

2. Major Chemical Pollutants Affecting Soil Microbes

Pesticides can affect non-target soil microorganisms through direct toxicity, altered substrate availability, and selective pressure on microbial populations. Fungicides may be particularly disruptive because fungi play a major role in organic matter decomposition, phosphorus mobilisation, and sulphur mineralisation. Herbicides can also indirectly affect microbial communities by altering root biomass, rhizodeposition, and plant species composition. In a comparative experiment with 20 commercial pesticides across three agricultural soils, pesticide effects on nitrogen-cycling processes varied substantially by soil type; nitrification and β-1,4-N-acetylglucosaminidase activity were most strongly reduced under conditions that favoured pesticide bioavailability. This finding indicates that the same active ingredient may have different ecological consequences across soils (Jxf et al., 2022).

Heavy metals differ from degradable organic pollutants in that they persist and cannot be biologically degraded. Cadmium, copper, lead, zinc, chromium, and mercury can inhibit microbial growth, impair membrane integrity, bind to proteins, and reduce enzyme activity. However, moderate or chronic exposure can select for metal-tolerant communities. Such adaptation may preserve some microbial biomass while reducing the functional diversity and abundance of sensitive taxa responsible for nutrient transformations. The response is governed not only by the total metal concentration but also by pH, organic matter, texture, redox conditions, and metal speciation (Edaphic Factors Mediate the Response of Nitrogen Cycling ..., 2025).

Antibiotics enter agricultural soils via livestock manure, sewage sludge, reclaimed wastewater, and pharmaceutical waste. Their effects extend beyond suppressing susceptible microorganisms, as they can alter microbial interactions, select for antibiotic-resistance genes, and modify N_2O production and consumption pathways. Evidence synthesis suggests that the effects of antibiotics on N_2O emissions can be concentration-dependent: low concentrations may stimulate emissions under certain conditions, whereas higher concentrations may suppress microbial activity and N_2O fluxes. These contrasting outcomes highlight the need to distinguish among changes in denitrifier abundance, activity, and net gaseous-N loss (Yu et al., 2024).

Petroleum hydrocarbons cause a distinct form of disturbance. They provide an abundant carbon source for specialised degraders but often create nutrient limitations because hydrocarbon degradation requires substantial N and P inputs for microbial biomass production. Consequently, contaminated soils may show enrichment of hydrocarbon-degrading taxa alongside depletion of available inorganic N and P. Biostimulation with nutrients can improve degradation, but excessive fertilisation may increase nutrient leaching, shift microbial competition, or inhibit degradation activity (Koshlaf & Ball, 2017).

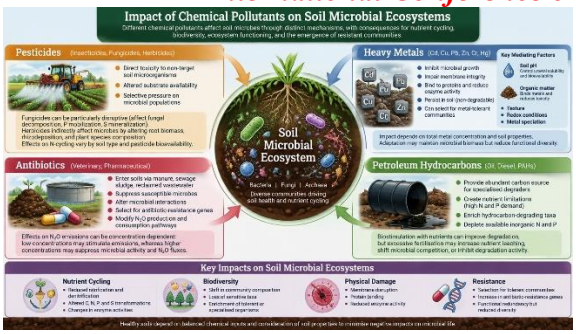


Figure 1: Impact of chemical Pollutants on Soil Microbial Ecosystem

3. Effects on Microbial Nitrogen Cycling

Nitrogen fixation is vulnerable to pollutants because the nitrogenase complex is energetically costly and sensitive to environmental stress. Metals may impair diazotrophs directly through cellular toxicity, whereas pesticides can alter rhizosphere conditions and reduce plant-associated nitrogen fixation. Reductions in nifH abundance or expression may indicate decreased diazotrophic potential; however, gene abundance alone cannot confirm reduced N-fixation rates. Direct isotope-based measurements are therefore needed to establish whether contaminant exposure decreases actual biological nitrogen fixation (Nandanwar et al., 2020; Stewart, 1976).

Ammonification and organic-N depolymerization can be constrained by reduced activities of proteases, urease, and N-acetylglucosaminidase. When pollutant stress suppresses these enzymes, organic N may remain unavailable to plants, even when soil total N is high. In pesticide-exposed soils, decreases in potential nitrification and N-acetylglucosaminidase activity have been documented, although effects varied among pesticides and soils (Jxf et al., 2022).

Nitrification is often sensitive because ammonia oxidisers have relatively specialised energy metabolisms. Pollutants may reduce the abundance or activity of ammonia-oxidising archaea, ammonia-oxidising bacteria, and nitrite oxidisers. However, the direction of change is not always uniform. For example, when one ammonia-oxidising group is inhibited, another may increase due to reduced competition or altered substrate availability. Therefore, apparent increases in amoA gene abundance do not necessarily indicate higher nitrification rates.

Denitrification responses are similarly complex. Antibiotics, metals, and pesticides may suppress nitrate and N_2O reduction, potentially increasing incomplete denitrification and N_2O accumulation. Conversely, pollutant-tolerant denitrifiers can become dominant in chronically contaminated soils. Heavy-metal contamination has been associated with changes in N mineralisation, nitrification, denitrification, dissimilatory nitrate reduction to ammonium, and N immobilisation, with soil pH, organic carbon, and redox conditions modifying the response (Edaphic Factors Mediate the Response of Nitrogen Cycling ..., 2025).

4. Effects on Microbial Phosphorus Cycling

The effects of pollutants on P cycling are less extensively studied than those on N cycling. Nevertheless, microbial P transformations are essential because plants acquire only a small fraction of total soil P directly. Microorganisms release P through mineralisation of organic P, solubilise sparingly available mineral phosphates, and immobilise soluble P in biomass.

Metals can inhibit acid and alkaline phosphatases by binding to enzymes or by reducing the abundance of enzyme-producing microorganisms. In experimental metal-contaminated soils, alkaline phosphatase and arylsulfatase activities were among those affected, indicating that P and S cycling may be altered concurrently (Xian et al., 2015). Chemical fumigation can also modify soil P pools and the composition of microbial communities carrying the phoD gene, which

encodes an alkaline phosphatase relevant to organic-P mineralisation (Wang & Tang, 2024).

A contradictory pattern may arise in which microbial P immobilisation increases under contaminant stress. This may reflect microbial nutrient conservation rather than improved P fertility. In such cases, P retained in biomass may be temporarily unavailable to plants, particularly when microbial turnover is slow. Therefore, studies should measure phosphatase activity, microbial biomass P, available inorganic P, plant uptake, and P-solubilising capacity together.

5. Effects on Microbial Sulfur Cycling

Sulfur cycling remains a major evidence gap. Sulfur mineralisation depends on the microbial decomposition of organic S compounds, whereas sulfur oxidation and sulfate reduction are driven by specialised microorganisms under contrasting redox conditions. Arylsulfatase is widely used as an indicator of organic-S mineralisation potential and may be particularly sensitive to metal contamination. In a soil enzyme assessment, arylsulfatase showed greater sensitivity to heavy metal stress than several other tested enzymes, although soil organic matter moderated this response (Xian et al., 2015).

The consequences of disrupted S cycling may be important for crop nutrition and health. Reduced S mineralisation may limit sulfate availability, particularly in low-S soils or high-yield systems with substantial crop S demand. In waterlogged soils, pollutant effects on sulphate-reducing bacteria may also influence sulphide formation, metal precipitation, and the availability of redox-sensitive nutrients. However, few studies have simultaneously quantified sulphate-reduction rates, sulphur-oxidising populations, sulphur functional genes, and plant S uptake. This limitation prevents strong conclusions about the long-term influence of pollutants on S fertility.

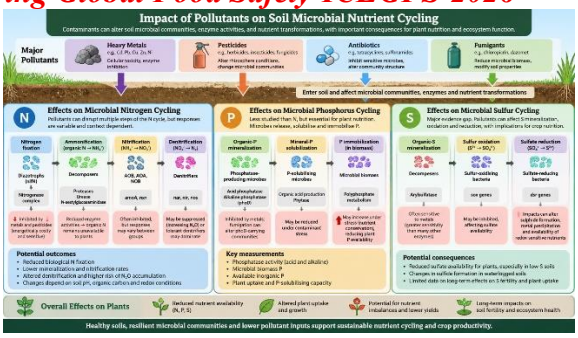


Figure 2: Impact of Pollutants on Soil Microbial Nutrient Cycling

6. Mechanisms of Microbial Disruption

Chemical pollutants disrupt soil microorganisms through several interconnected mechanisms.

Cellular toxicity.

These toxic agents can induce oxidative stress by generating reactive oxygen species, leading to cellular damage and apoptosis. They may also disrupt ion homeostasis and signal transduction pathways, impairing normal cell function. The extent of toxicity often depends on the concentration, exposure duration, and the specific cellular targets affected.(Martindale & Holbrook, 2002)

Oxidative stress

Pollutants can induce oxidative stress in microbial communities by increasing reactive oxygen species (ROS) production, which can damage cellular components such as lipids, proteins, and DNA. This oxidative burden forces microbes to allocate more energy and resources toward detoxification processes, including the synthesis of antioxidant enzymes and repair mechanisms, to neutralise ROS and mitigate cellular damage. As a result, the metabolic investment in protective functions may reduce the resources available for other critical microbial activities, such as nutrient transformation and biogeochemical cycling.(Fasnacht & Polacek, 2021)

The shift in microbial resource allocation caused by oxidative stress can have broader ecological implications. When microbes prioritize detoxification over nutrient

processing, key ecosystem functions—such as decomposition, nitrogen fixation, and carbon cycling—may be impaired or slowed. This trade-off could ultimately affect soil fertility, water quality, and overall ecosystem productivity, especially in environments exposed to persistent or high levels of pollutants. Understanding how oxidative stress modulates microbial function is thus essential for assessing the environmental impact of pollution and developing strategies to maintain ecosystem resilience.(Singh et al., 2024; Zhan, 2024)

Enzyme inhibition.

Metals inhibit enzymes primarily by binding directly to active sites, blocking substrate access or altering enzyme conformation and reducing catalytic activity. These metals may interact with key amino acid residues or cofactors essential for enzymatic function, leading to reversible or irreversible inhibition depending on the metal type and concentration. This binding disrupts normal enzyme-substrate interactions and can impair critical biochemical pathways.(Medyantseva et al., 1998; Riordan, 1977)

In contrast, organic pollutants tend to affect enzymes more indirectly by altering membrane-associated processes. They can interfere with electron transport chains embedded in membranes, which are vital for energy production and metabolic reactions. Additionally, these pollutants may influence the production or secretion of extracellular enzymes by microorganisms, thereby impacting nutrient cycling and overall ecosystem functioning. Such disruptions can diminish enzymatic efficiency and microbial activity, with broader implications for environmental health and pollutant degradation.(Chaudhry & Paliwal, 2020; Magalhães et al., 2023)

Selection and community restructuring.

Environmental or anthropogenic pressures can drive selection and community restructuring, shifting microbial populations so tolerant taxa become more abundant. This proliferation of tolerant species often occurs at the expense of sensitive specialists that perform critical ecosystem functions such as nitrification, nitrogen fixation, phosphorus solubilization, and sulfur oxidation. These sensitive microbes play essential roles in nutrient cycling, maintaining soil fertility, and supporting plant growth. Their decline can disrupt these biogeochemical processes, potentially reducing ecosystem productivity and altering nutrient availability.

Moreover, losing these specialist taxa may reduce the functional diversity and resilience of microbial communities, making ecosystems more vulnerable to further disturbances. As tolerant taxa dominate, the overall efficiency and balance of nutrient transformations may decline, with cascading effects on ecosystem health and sustainability. Understanding these community dynamics is crucial for managing stressed ecosystems and developing strategies to preserve or restore the functions provided by sensitive microbial specialists.

Altered soil physicochemical properties.

Pollutants and remediation additives can significantly influence soil physicochemical properties, which in turn affect the soil's biological and chemical processes. Changes in pH, for example, can alter the solubility and mobility of contaminants and nutrients, thereby impacting microbial communities and their metabolic activities. Similarly, shifts in redox potential affect the oxidation-reduction reactions within the soil matrix, influencing the availability of electron acceptors and donors essential for microbial respiration and biogeochemical cycling. These modifications can either inhibit or stimulate specific

microbial functions, depending on the nature and extent of the changes.

Furthermore, pollutant- or additive-induced changes in sorption processes can alter the retention and release patterns of organic and inorganic compounds in soil. This, in turn, affects nutrient and contaminant bioavailability, both of which are critical for microbial growth and activity. Nutrient imbalances or toxic accumulations resulting from these physicochemical shifts can disrupt microbial diversity and ecosystem functioning. Consequently, understanding how these soil property changes indirectly regulate microbial functions is essential for optimising remediation strategies and maintaining soil health.

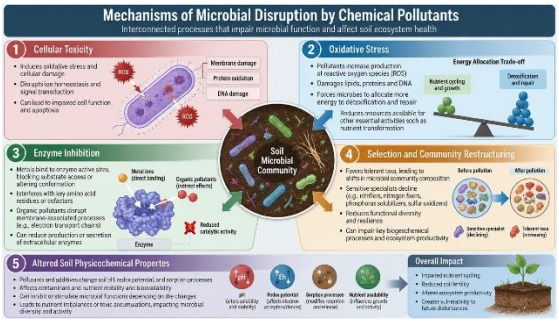


Figure 3: Mechanisms of Microbial Disruption by Chemical Pollutants

7. Ecological and Agricultural Consequences

Disrupted microbial nutrient cycling can reduce soil fertility, even when total nutrient concentrations remain high. Reduced mineralisation limits the release of plant-available N, P, and S from organic matter. Inhibited nitrification may restrict nitrate supply, whereas altered denitrification may increase gaseous N losses or incomplete denitrification products. Declining phosphatase activity can constrain P acquisition in low-input systems, whereas disrupted sulfur mineralisation may limit sulfur nutrition in crops with high S demand.

Pollutant exposure may also weaken soil multifunctionality, including decomposition, aggregate stabilisation, disease suppression, and resilience to drought or fertilisation. In agricultural systems, these effects can increase dependence on external fertilisers, reduce nutrient-use efficiency, and undermine long-term sustainability. Nonetheless, the outcomes are not universally negative; pollutant-degrading populations can support natural attenuation, and some communities exhibit functional redundancy or recover after exposure. The critical issue is whether recovery restores process rates and nutrient availability, rather than merely taxonomic diversity.

8. Sustainable Management and Remediation.

Evaluate remediation based on ecological recovery rather than contaminant reduction alone. A decrease in extractable metal or hydrocarbon concentrations is insufficient if nitrification, phosphatase activity, microbial biomass, or plant nutrient uptake remain impaired. Monitoring should therefore include contaminant bioavailability, enzyme activities, nutrient pools, microbial functional indicators, crop performance, and greenhouse gas emissions.

Biochar can reduce the bioavailability of certain metals and organic contaminants through sorption, surface complexation, pH modification, and changes in soil carbon dynamics. However, its effects depend on feedstock, pyrolysis temperature, application rate, ageing, and soil properties. Biochar should not be treated as universally beneficial; excessive rates may alter pH, nutrient balance, and microbial habitat in undesirable ways (Nguyen et al., 2023).

Phytoremediation can restore vegetation cover, stabilise contaminated soil, and create rhizosphere conditions that support pollutant-transforming microorganisms. Plant-associated

bacteria and fungi can enhance metal immobilisation, phytoextraction, biosorption, or degradation of organic contaminants. The effectiveness of these approaches depends on selecting plant–microbe combinations suited to the contaminant type, climate, soil chemistry, and intended land use (Khatoon et al., 2024).

9. Research Gaps and Future Perspectives

Major gaps include a scarcity of long-term field experiments, inconsistent pollutant doses, and inadequate measurement of actual nutrient fluxes. Many studies rely on microbial diversity or functional gene abundance, which alone cannot establish process rates. Future studies should integrate metagenomics, transcriptomics, enzyme assays, stable-isotope tracing, and direct measurements of nitrogen, phosphorus, and sulfur transformations.

Research should also address realistic mixtures of pesticides, metals, antibiotics, and hydrocarbons; repeated low-dose exposure; interactions with climate stress; and recovery trajectories after remediation. Sulfur cycling and microbial P immobilisation require particular attention in this context. Finally, remediation success should be evaluated using soil multifunctionality, plant performance, nutrient-use efficiency, and contaminant bioavailability, rather than contaminant removal alone.

10. Conclusion

Chemical pollutants can impair microbial nutrient cycling by suppressing sensitive taxa, inhibiting enzymes, altering functional gene distributions, and modifying soil physicochemical conditions. Nitrogen cycling has attracted the most attention, whereas the effects of pollutants on phosphorus and sulfur cycling remain insufficiently resolved. Because responses vary across pollutants, soils, and exposure histories, sustainable management requires contaminant-specific, function-oriented assessment. Pollution prevention, integrated pest management, organic amendments, carefully designed biochar applications, phytoremediation, and microbiome-assisted restoration offer complementary pathways to protect soil fertility and agricultural sustainability.

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