International Journal of Plant & Soil Science

Volume 37, Issue 12, Page 290-317, 2025; Article no.IJPSS.148996
ISSN: 2320-7035

Soil Contamination by Heavy Metals and Pesticides: A Critical Review of Toxicological Mechanisms, Sustainable Remediation Strategies, and One Health Implications

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Authors' contributions

This work was carried out in collaboration among all authors. Authors IRS and PRS jointly evaluated the state of knowledge in the field and identified soil pollution as a critical and pervasive environmental issue with profound implications for ecosystem integrity and human health. Author IRS conceived the core research concept and conducted an extensive review of the scientific literature focusing on key soil contaminants, their toxicological profiles, plant stress physiology, and sustainable agricultural management. He also led the manuscript preparation and synthesis. Authors PRS and RRS contributed to the refinement of the manuscript and provided critical input on the analytical and interpretative aspects of the study. Author IRS designed the conceptual framework and directed the overall analysis, while author RRS conducted advanced SciFinder literature searches and assisted in the critical evaluation of remediation technologies. Drawing upon the authors' prior research experience and publications, Author MHN contributed expert perspectives on the health and biomedical dimensions of the review, thereby strengthening its interdisciplinary scope. All authors collaboratively aligned their efforts toward advancing sustainable agricultural practices within the

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Cite as: *Isak Rajjak Shaikh, Parveen Rajjak Shaikh, Majeed Hazzaa Nomaan, and Rafik Rajjak Shaikh. 2025. "Soil Contamination by Heavy Metals and Pesticides: A Critical Review of Toxicological Mechanisms, Sustainable Remediation Strategies, and One Health Implications". International Journal of Plant & Soil Science 37 (12):290–317. https://doi.org/10.9734/ijpss/2025/v37i125893.*

framework of the "One Health" paradigm, emphasizing the integration of environmental, plant, and human health perspectives, and read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i125893

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc. are available here: https://pr.sdiarticle5.com/review-history/148996

Review Article

Received: 06/10/2025
Published: 23/12/2025

ABSTRACT

Background: Soil contamination by heavy metals and pesticides remains a persistent global challenge with far-reaching consequences for agricultural productivity, ecosystem stability, and human health. Despite extensive research, existing studies remain fragmented across soil science, toxicology, and environmental health, limiting efforts to integrate soil nutrient status, contaminant dynamics, and their implications for plant stress, food-web integrity, and environmental well-being.

Objectives: The review aims to conceptualize and critically evaluate advancements in soil nutrient dynamics, pollutant toxicology, and remediation strategies, with emphasis on heavy metals and pesticides. It integrates soil ecological processes, plant stress responses, environmental toxicology, and human health within a unified "One Health" perspective.

Methodology: This review employs a focused yet transparent evidence-mapping approach – short of a holistic protocol but still structured and traceable under PRISMA – to integrate soil profiling, contaminant toxicology, and sustainable remediation within the One Health framework. Through a targeted literature search using defined inclusion criteria and multidisciplinary keywords, the review critically evaluates soil nutrient dynamics, toxicological pathways of heavy metals and pesticides, and emerging mitigation strategies while identifying key knowledge gaps relevant to sustainable agroecosystem management.

Results: Soil functions as a complex biogeochemical system whose fertility, nutrient cycling, and ecosystem services depend on the interplay between organic matter, microbial communities, and physicochemical properties across soil horizons. Anthropogenic pressures – industrial emissions, mining, waste disposal, agrochemicals, and excessive fertilization – introduce heavy metals and pesticides that disrupt nutrient dynamics, degrade soil structure, impair microbial processes, and trigger plant physiological stress. Evidence demonstrates that agrochemical overuse destabilizes soil microbial ecology and nutrient–microbe interactions, causing contamination, reduced biodiversity, nutrient imbalance, and increased risks to food security and environmental quality. Integrating these findings reveals that soil health is tightly linked to contaminant behaviour, plant–soil interactions, and ecosystem resilience, emphasizing the need for sustainable management and remediation strategies to preserve soil-based ecosystem services.

Conclusion: Heavy metal and pesticide contamination undermines soil functioning, plant productivity, ecosystem stability, and public health, reaffirming that soil integrity is a core component of the "One Health" continuum. Evidence indicates that while physicochemical remediation offers rapid mitigation, biologically driven and green-chemistry approaches – such as biochar, phytoremediation, and microbial degradation – provide more sustainable, scalable, and ecologically restorative solutions. Advancing soil health and sustainable agriculture requires interdisciplinary collaboration, long-term field research, integrated contaminant modeling, and globally harmonized regulatory frameworks to safeguard ecosystems, food security, and human well-being.

Keywords: Soil contamination; heavy metals; pesticides; toxicology; phyto(remediation); soil microbiome; one health; environmental sustainability.

1. INTRODUCTION

Soil is a foundational ecological resource supporting global food systems and terrestrial biodiversity. Its physical, chemical, and biological properties regulate nutrient cycling, plant productivity, and ecosystem stability, thereby positioning soil health at the core of the "One Health" paradigm linking plant, animal, environmental, and human well-being (Mumford et al., 2023; Hill et al., 2024; Banerjee & van der Heijden, 2023) through only sustained ecosystem services (Shaikh & Shaikh, 2025). Often regarded as the "skin of the Earth," soil is a dynamic matrix of minerals, organic matter, air, water, and microorganisms that regulate essential biogeochemical processes, with the rhizosphere microbiome particularly critical for nutrient cycling and biological nitrogen fixation (Philippot et al., 2024). Maintaining balanced interactions among soil physicochemical properties, microbial communities, and environmental factors is therefore vital for ecological resilience and human survival (Kalavathy, 2004). However, anthropogenic activities including industrial emissions, mining, waste disposal, and intensive agrochemical use have accelerated the accumulation of heavy metals and pesticides – the major contaminants – in agricultural soils. These pollutants threaten soil fertility, disrupt microbial communities, impair plant physiological processes, and pose increasing risks to environmental and human health.

Although micronutrients like Zn, Cu, and Fe are essential at trace levels, their accumulation beyond threshold concentrations leads to phytotoxicity and human health risks (Nieboer & Richardson, 1980). Their persistence, bioaccumulation, and biomagnification make understanding their environmental behaviour and toxic mechanisms crucial for risk assessment and remediation. Pesticides likewise represent a dominant contamination source, with herbicides comprising nearly half of global use (Atwood & Paisley, 2017). Varying chemical classes – organochlorines (OCPs), organophosphates (OPs), carbamates, and pyrethroids – exert distinct modes of action (Yadav & Devi, 2017; Raffa & Chiampo, 2021; Kim et al., 2017), yet all function as xenobiotics capable of disrupting soil microbiota, nutrient turnover, and biodiversity, raising concerns for ecological stability and food safety (Faruque Ahmad et al., 2024). Consequently, research and regulatory attention has intensified around pesticide fate, life cycles, and soil quality standards (Zhang & Li, 2023; Schwarz et al., 2022).

Global initiatives highlight the urgency of confronting soil degradation. The Global Status of Soil Pollution report, developed by the Food and Agriculture Organization (FAO) of the United Nations and the FAO's Intergovernmental Technical Panel on Soils (ITPS) with the United Nations Environment Programme (UNEP), calls for coordinated scientific action within the UN Decade on Ecosystem Restoration (2021–2030) (FAO & UNEP, 2021; UNGA Resolution 73/284, 2019), emphasizing soil organic matter conservation, microbial diversity preservation, and restoration of fertility through sustainable management. Yet current literature remains fragmented across soil science, toxicology, and environmental health, often addressing soil properties, nutrient profiles, or pollutants in isolation and giving limited attention to how soil contamination connects directly to the "One Health." This review responds to these gaps by integrating knowledge on soil profiling, nutrient dynamics, pollutant toxicity, and remediation strategies, underscoring links among soil processes, plant stress physiology, food safety, ecosystem stability, and human well-being.

The aims of this review are therefore to:

1. Consolidate current understanding of soil nutrient composition, contamination pathways, and implications for plant and ecosystem health;
2. Examine toxicological profiles of major pollutants – particularly heavy metals and pesticides – with emphasis on persistence, bioavailability, and ecological consequences; and
3. Evaluate recent advances in biological, chemical, and green chemistry-based remediation within the One Health framework, highlighting the need for integrative, sustainable approaches to soil restoration.

This review addresses existing fragmentation in the literature by integrating soil nutrient profiling, mechanistic toxicology, remediation science, and One Health concepts. It offers a consolidated framework for understanding how soil contamination affects plant, ecosystem, and human health, and evaluates sustainable remediation strategies that support long-term agricultural resilience.

2. STUDY DESIGN AND PRISMA-ALIGNED METHODOLOGY

Building upon the conceptual foundations introduced earlier – particularly the need to integrate soil profiling, toxicological assessment, and sustainable remediation within a One Health framework – this review adopts a structured, transparent methodology for identifying, screening, and synthesizing relevant scientific evidence. Although not a holistic review, the process follows PRISMA-aligned steps, including identification, screening, eligibility assessment, and inclusion (Fig. 1).

2.1 Objectives

The review aims to conceptualize and critically evaluate advancements in soil nutrient dynamics, pollutant toxicology, and remediation strategies, with particular emphasis on heavy metals and pesticides. It integrates soil ecological processes, plant stress responses, environmental toxicology, and human health into a unified One Health perspective. The specific objectives are to:

1. Synthesize physicochemical and biological foundations of soil fertility and contamination.
2. Assess toxicological pathways of heavy metals and pesticides and their ecological implications.
3. Evaluate sustainable mitigation strategies – including bioremediation, phytoremediation, biochar amendments, and green chemistry approaches.
4. Identify knowledge gaps to guide sustainable agricultural systems and One Health-oriented soil management.

2.2 Literature Search and Data Collection Strategy

A structured literature search was conducted across Scopus, Web of Science, PubMed, and Google Scholar, incorporating peer-reviewed articles, review papers, book chapters, technical documents, and international reports (FAO, UNEP, WHO). This approach ensured comprehensive coverage of soil science, toxicology, agricultural sustainability, and One Health domain.

2.2.1 Search terms

Keywords and Boolean combinations targeted soil profiling, contaminants, toxicology, remediation, and One Health, including:

- “soil contamination” AND “heavy metals”
- “pesticides” AND “soil microbiota”
- “soil profile” OR “nutrient dynamics”
- “toxicological profiling” AND “agricultural soils”
- “phytotoxicity” AND “heavy metals”
- “bioremediation” OR “phytoremediation”
- “biochar” AND “soil amendment”
- “One Health” AND “soil pollution”

2.2.2 Time frame

Studies published up to 2024 were prioritized, with select 2025 studies included to ensure relevant and up-to-date coverage. Foundational works such as Nieboer & Richardson (1980) and Jensen (1907) were included for their historical and conceptual significance.

2.3 Inclusion and Exclusion Criteria

Inclusion criteria encompassed:

- Peer-reviewed studies on heavy metals, pesticides, soil microbes, nutrient dynamics, or remediation
- Research describing mechanistic toxicology, ecological impacts, or sustainable agricultural practices
- Mechanistic or applied insights into soil–plant–microbe interactions
- International agency reports (FAO, UNEP, WHO)

Exclusion criteria included:

- Non-peer-reviewed or non-scientific material
- Studies unrelated to soil systems or lacking contaminant relevance
- Articles without adequate methodological transparency

2.4 Screening and Selection

The search yielded approximately 1,200 records. After title and abstract screening, 587 publications remained. Full-text evaluation narrowed this to 412 eligible studies, from which 123 thematically relevant papers were reviewed in depth. A final set of 65 high-quality studies was selected for comparative synthesis. This curated selection reflects the interdisciplinary scope of soil science, toxicology, ecological resilience, and environmental health.

2.5 Analytical Approach

A thematic analytical framework guided the synthesis of included studies, focusing on:

- Soil profiling, nutrient dynamics, and physicochemical properties
- Contaminant behaviour, including chemical characteristics, fate, mobility, and bioavailability
- Mechanistic toxicological pathways affecting plants, soil microbiota, animals, and humans
- Ecological disruptions such as plant stress, microbial dysfunction, and ecosystem impairment
- Remediation strategies, evaluated for efficiencies, constraints, scalability, ecological compatibility, and sustainability
- Alignment with the One Health framework, emphasizing interconnected plant, ecosystem, and human health outcomes

This integrated approach identifies converging scientific themes and persistent gaps, underscoring the central role of soil profiling (Fig. 2) in interpreting nutrient availability, soil fertility, contaminant dynamics, and the design of sustainable remediation strategies. Ultimately, the methodological framework supports a cross-sectoral understanding of how contaminated soils influence plant defenses, food safety, ecosystem services, and human health.

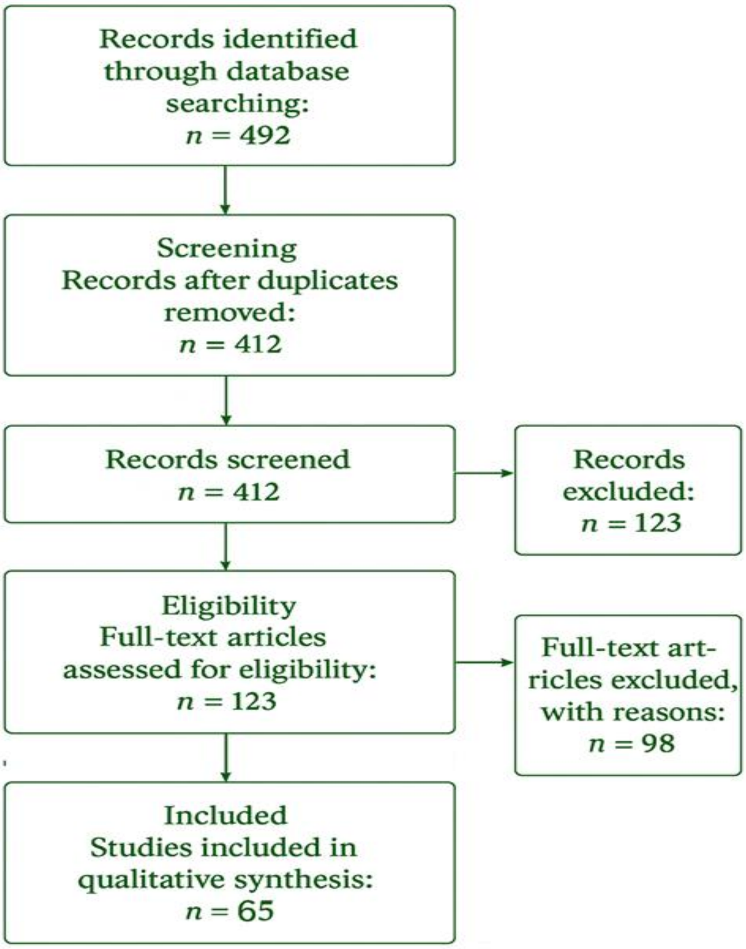


Fig. 1. PRISMA flowchart

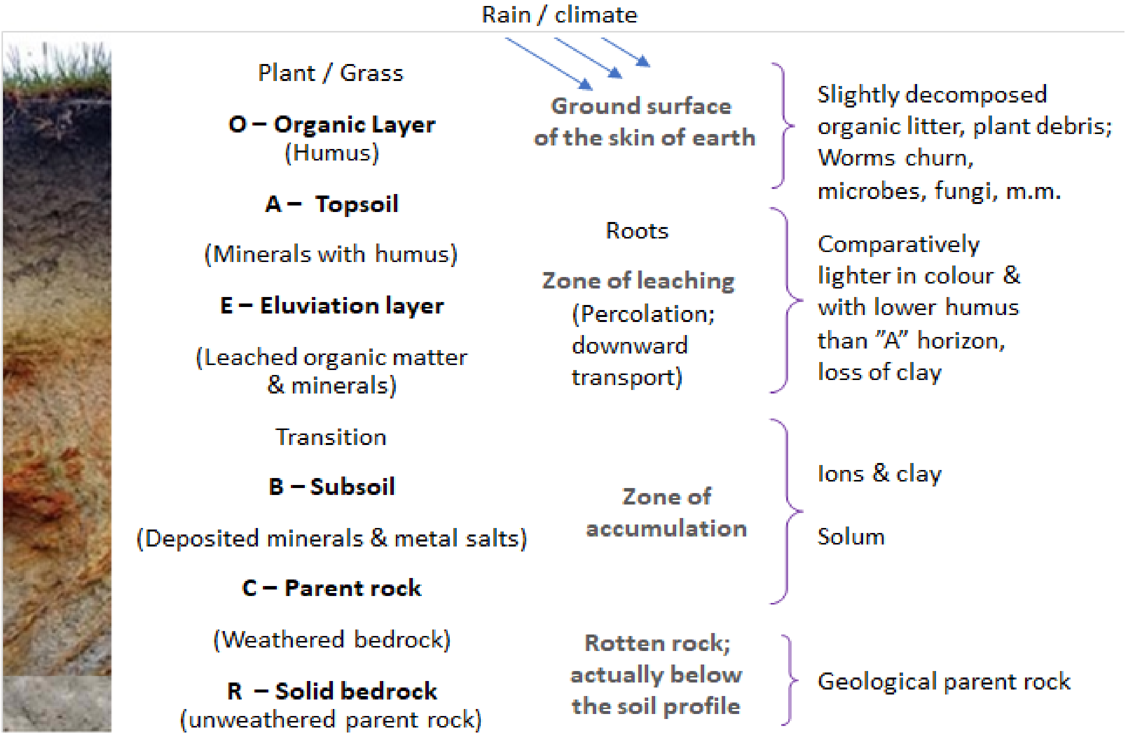


Fig. 2. A soil profile (shown on the wall of a gully) consisting of distinct soil horizons

3. RESULTS AND DISCUSSION

Building on the methodological foundations outlined in Section 2, this section presents a critical synthesis of the results, emphasizing that soil must be understood not merely as a physical substrate but as a multifunctional ecological system. Its physicochemical properties, biological components, and nutrient dynamics collectively sustain terrestrial life and underpin ecosystem services. Soil fertility – defined by its capacity to supply essential nutrients, support root development, and maintain microbial and biochemical functions – remains central to agricultural productivity and ecosystem stability. Accordingly, the soil profile provides the framework for interpreting nutrient availability, pollutant behaviour, and plant–soil interactions, forming the basis for the integrated analysis of heavy metal and pesticide contamination, their ecological impacts, and implications for sustainable remediation strategies.

3.1 Soil as a Biogeochemical and Ecological System

Agroecosystems comprise communities of plants and animals interacting with modified chemical and physical environments to produce food, fibre, and fuel (EC / Grizzetti et al., 2018). Within these systems, soil acts as a dynamic, heterogeneous matrix of minerals, organic matter, water, gases, and microorganisms. Pedology and edaphology highlight how soil classification and soil–organism interactions together shape nutrient distribution, pollutant mobility, and microbial ecology. Historical observations of soil horizons (Schelling, 1970) and assessments of intra-horizon variability (Hartemink et al., 2020) underscore the role of spatial heterogeneity. The soil microbiome – especially rhizosphere communities – plays a critical role in nitrogen cycling, carbon turnover, soil structure, and ecosystem resilience. Beneficial microbial networks, therefore, must remain intact when applying agricultural interventions or remediation strategies (Philippot et al., 2024).

3.2 Nutrient Cycling, Soil Organic Matter, and Microbial Function

Although nitrogen is abundant atmospherically, plants depend on biological nitrogen fixation mediated by Rhizobium, Azolla–cyanobacteria associations, and Azotobacter spp. (Shridhar, 2012). Soil organic matter (SOM), a small but essential fraction of the soil matrix, regulates microbial metabolism, nutrient retention, moisture capacity, and soil structure, making SOM maintenance fundamental to long-term productivity.

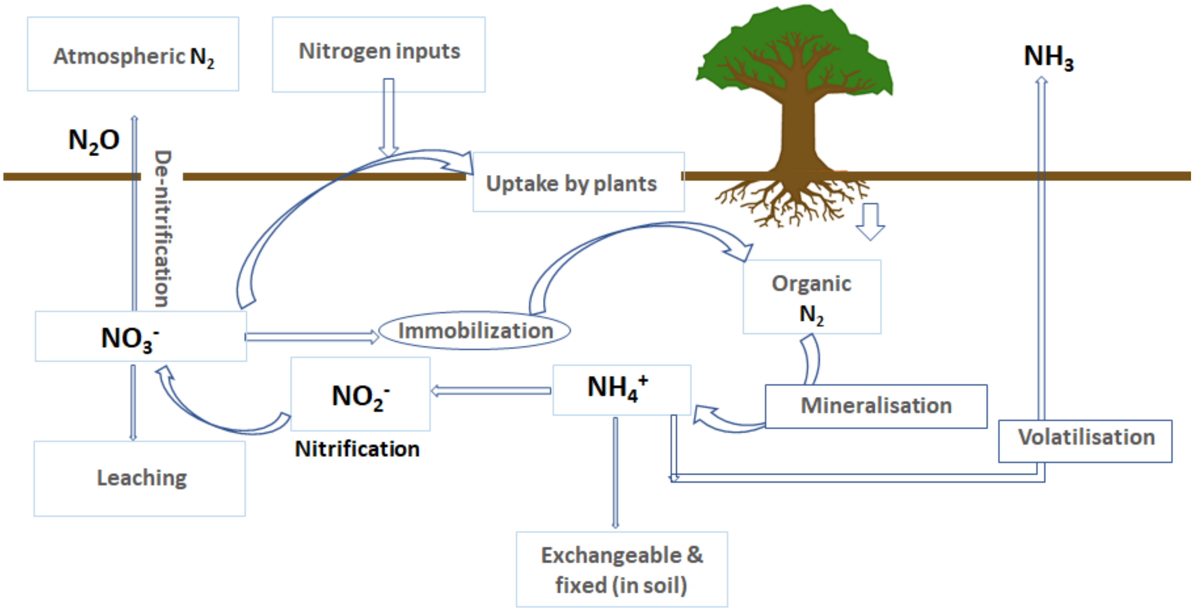


Fig. 3 Nutrients and nitrogen cycle

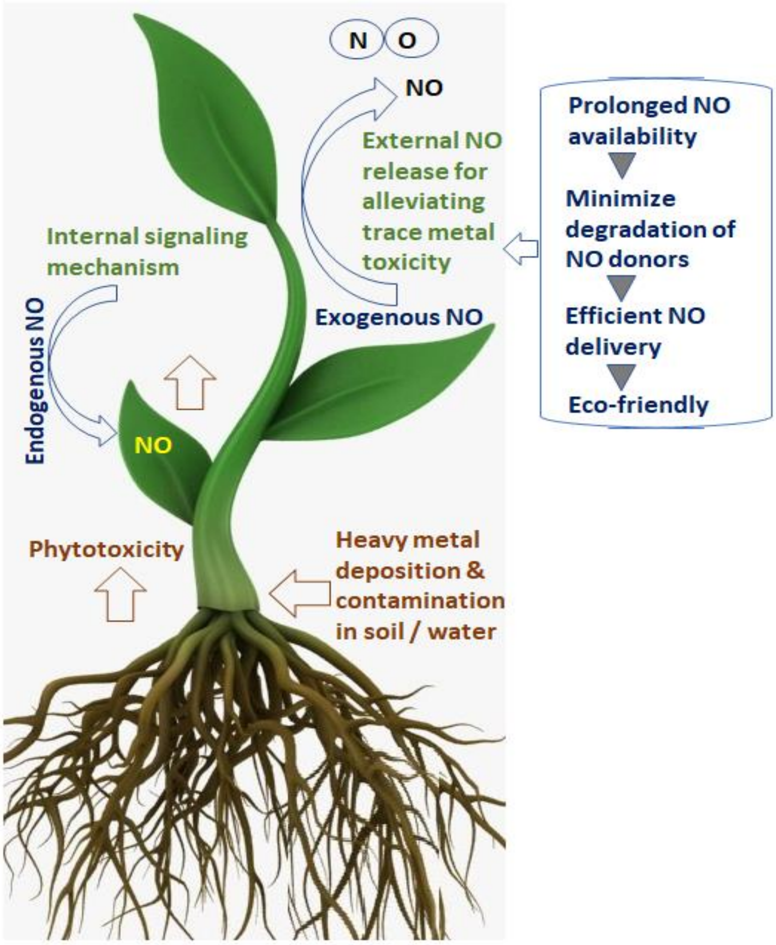


Fig. 4. Nitric oxide and the alleviation of HM phytotoxicity

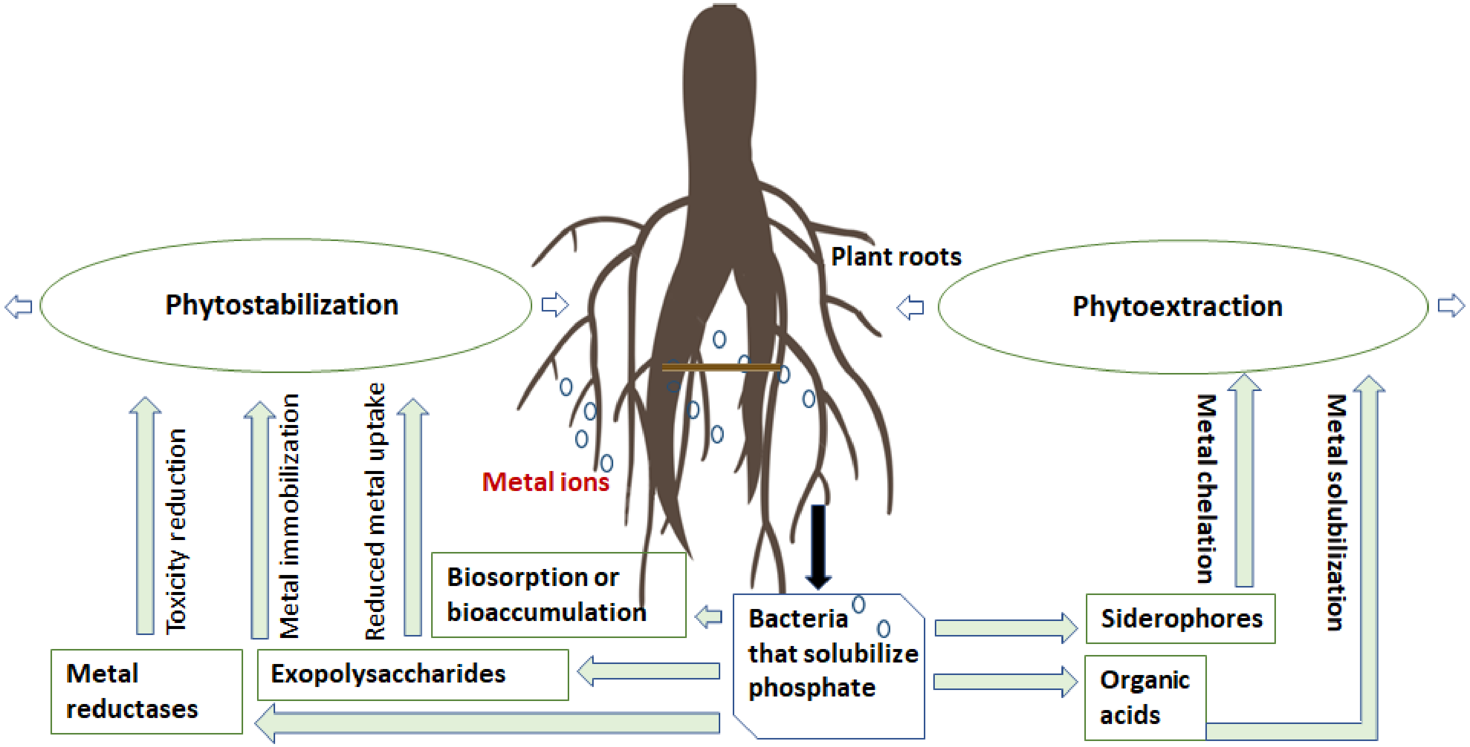


Fig. 5. Phosphate solubilizing bacteria (Ahmad, M. 2015)

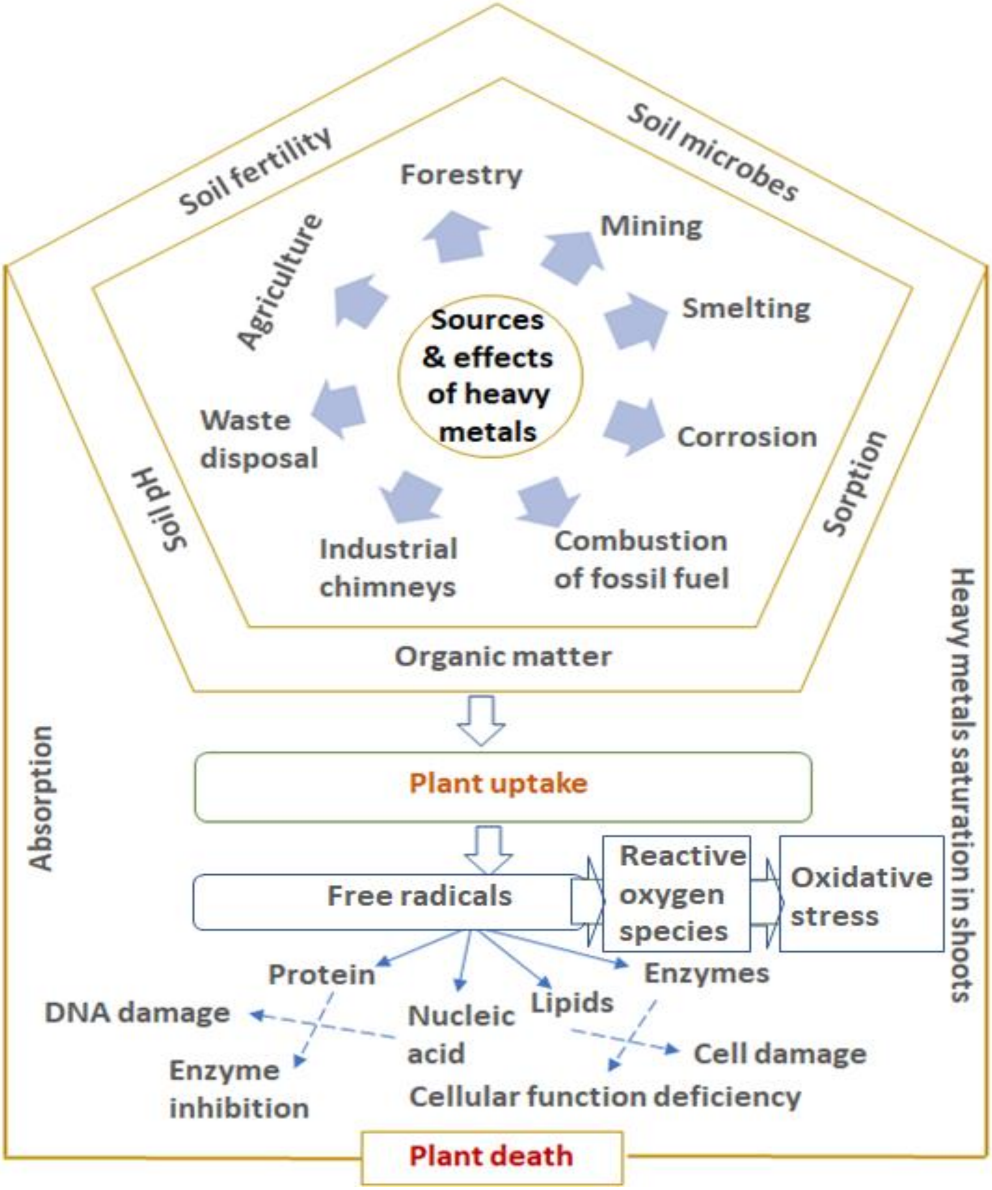


Fig. 6 Sources, mechanism and effects of heavy metal toxicity in plants

Anthropogenic pressures – including unsustainable land use, mining, industrial emissions, and waste disposal – introduce heavy metals and metalloids into agricultural soils (Alloway, 1995), altering nutrient dynamics, impairing microbial processes, and disrupting soil physicochemical properties. Fertilizers are routinely applied to correct nutrient deficiencies (Fig. 3) yet Soil Organic Carbon (SOC) depletion due to improper fertilization remains problematic. Moderate fertilizer application enhances yields, whereas excessive inputs reduce fertility and long-term productivity (Allam et al., 2022).

Nitrate, the primary assimilated form of nitrogen, is highly soluble and prone to leaching and runoff (Fig. 4). Phosphorus, the second most limiting nutrient for crops (Shen et al., 2011), enters soils via fertilizers, organic manure, and sewage sludge (Fig. 5). Under certain conditions, it becomes mobile, contributing to eutrophication of freshwater and marine systems (Schroder et al., 2010; Shaikh et al., 2013).

Industrial emissions, mining, waste disposal, and agrochemical use have substantially increased Cr, Cd, Zn, Cu, Pb, Al, As, and Hg concentrations in soils, imposing severe environmental, ecological, and economic consequences (Fig. 6).

3.3 Agrochemical Inputs, Soil Pollution, and Microbial Disruption

Modern agriculture's reliance on pesticides and fertilizers often neglects long-term ecological effects. Pesticides, inherently xenobiotic, disrupt beneficial soil microbiota, diminish pollinators, and raise food safety concerns (Faruque Ahmad et al., 2024). These impacts have encouraged researchers to support regulatory agencies in defining pesticide life cycles, soil quality standards, and environmental thresholds (Zhang & Li, 2023; Schwarz et al., 2022).

While pesticides remain essential for crop protection, their excessive use causes soil contamination, nutrient imbalance, and structural degradation. Global assessments by the FAO and UNEP emphasize the need for sustainable soil management, microbial conservation, and restoration of SOM (FAO & UNEP, 2021). The Global Status of Soil Pollution report reinforces the importance of prevention and remediation under the UN Decade on Ecosystem Restoration (2021–2030) (UNGA Resolution 73/284, 2019).

3.4 Integrative Understanding of Soil Function and Contamination

Collectively, these observations highlight soil as a complex biogeochemical system whose ecological services depend on nutrient balance, organic matter, and microbial communities. Heavy metals, pesticides, industrial wastes, and inappropriate fertilizer use disrupt soil fertility, plant stress physiology, biodiversity, and food security. Understanding these dynamics is essential for designing integrated remediation strategies that restore soil function while preserving ecosystem services.

This integrative perspective underpins the subsequent sections, which analyse nutrient dynamics, contaminant toxicology, and remediation strategies, emphasizing their relevance to agricultural sustainability, environmental health, and the One Health framework.

4. SOIL PROFILE AND NUTRIENT–SOIL INTERACTIONS

Building on the integrative understanding of soil structure and ecosystem services discussed in Section 3, a focused examination of the soil profile is essential for contextualizing nutrient availability, contaminant mobility, microbial activity, and plant–soil interactions. The vertical arrangement of soil horizons, shaped by pedogenic processes, governs cation exchange capacity, metal sorption, organic matter turnover, and root distribution – factors that directly determine how heavy metals and pesticides behave within the soil matrix.

4.1 Structure of the Soil Profile and Its Functional Importance

The classical horizons O, A, E, B, C, and R represent layers with distinct physical, chemical, and biological properties. Early soil cartography (Schelling, 1970) and contemporary analyses (Hartemink et al., 2020) illustrate substantial intra- and inter-horizon variability, emphasizing that soil is not a uniform medium.

The A horizon, rich in organic matter, underpins nutrient uptake, microbial colonization, and contaminant interactions, whereas the B horizon often serves as a zone of accumulation for metals, clay, and humic substances. This heterogeneity influences water infiltration, root penetration, redox gradients, and sorption–desorption processes. Understanding these horizon-specific dynamics is therefore critical for predicting pollutant transport, assessing bioavailability, and selecting remediation strategies.

4.2 Nutrient Dynamics and Soil Fertility

Soil fertility results from interactions among organic matter, minerals, microbial communities, and nutrient transformations. Although nitrogen is abundant in the atmosphere, plants rely on biological nitrogen fixation by rhizobacteria, cyanobacteria, and diazotrophs such as Azotobacter (Shridhar, 2012). SOM, though a small portion of total soil mass, regulates nutrient retention, water-holding capacity, and aggregation, while its decomposition products – including humic and fulvic acids – bind heavy metals, reducing toxicity and controlling bioavailability.

4.3 Factors Regulating Nutrient Availability and Soil Quality

Nutrient mobility is shaped by soil pH, redox potential, clay mineralogy, ionic strength, microbial biomass, and competing contaminants. Excessive or imbalanced fertilization alters microbial structure, disrupts nutrient cycling, and may induce soil acidification or salinization.

Anthropogenic inputs – including industrial emissions, mining residues, sewage sludge, and agrochemicals – introduce heavy metals and synthetic pollutants into agricultural soils (Alloway, 1995). These contaminants compete with essential nutrients, inhibit microbial nitrogen fixation, impair root enzymatic activity, and induce oxidative stress in plants.

4.4 Agrochemicals and the Disruption of Soil Nutrient–Microbe Balance

Although fertilizers and pesticides remain integral to modern agriculture, their misuse can destabilize soil nutrient–microbe interactions. Pesticides, being xenobiotic, suppress beneficial microbes, reduce enzymatic activity, and interfere with nutrient cycling (Faruque Ahmad et al., 2024). Their persistence – well documented across organochlorines, organophosphates, carbamates, and pyrethroids (Yadav & Devi, 2017; Raffa & Chiampo, 2021; Kim et al., 2017) – modifies soil chemistry and cation exchange behaviour, also influencing heavy-metal sorption. Growing concerns have prompted refinement of pesticide guidelines and soil quality standards (Zhang & Li, 2023; Schwarz et al., 2022).

4.5 Implications for Soil Contaminant Behaviour

The physicochemical properties of each horizon determine pollutant partitioning, transformation, and movement. Clay-rich B horizon promotes metal adsorption; SOM-rich A horizon enhances pesticide sorption while enabling biodegradation; fluctuating redox conditions can mobilize Fe, Mn, and As; and soil moisture and microbial activity control agrochemical degradation pathways. Thus, nutrient–soil interactions are inseparable from contaminant dynamics, as the soil profile ultimately dictates pollutant persistence, root and microbial exposure, and pathways into the food chain.

5. HEAVY METALS, PESTICIDES, AND THEIR TOXICOLOGICAL MECHANISMS

Building on the nutrient–soil interactions described in Section 4, heavy metals and pesticides represent two dominant contaminant classes that disrupt soil biochemical processes, plant physiology, microbial communities, and broader ecological and human health pathways. Their persistence, bioavailability, and capacity for food-chain accumulation make them among the most consequential pollutants. Although widely reported in soils, their mechanistic toxicological effects require integrated interpretation to understand how contamination impairs soil function, agricultural productivity, and One Health outcomes.

5.1 Heavy Metals: Sources, Persistence, and Environmental Behaviour

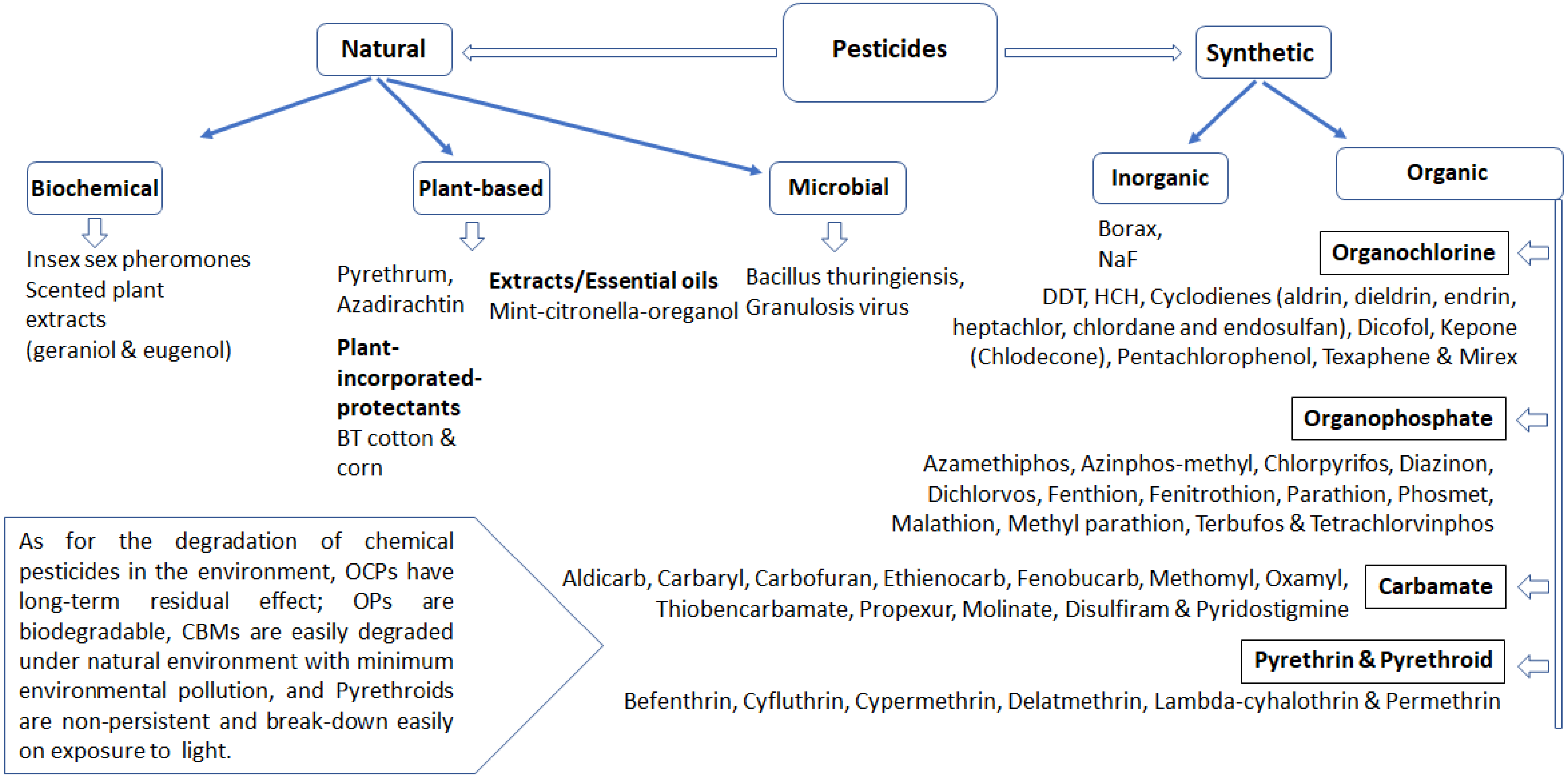
Heavy metals enter agricultural soils through multiple pathways, including mining effluents, industrial emissions, sewage sludge, agrochemical residues, and atmospheric deposition (Alloway, 1995). Their persistence in soils reflects their non-degradable nature, with environmental fate and bioavailability strongly influenced by soil pH, redox potential, clay mineralogy, organic matter content, and the presence of competing ions. While essential micronutrients such as Zn, Cu, and Fe are required for plant and microbial metabolism, they become toxic when concentrations exceed critical thresholds (Nieboer & Richardson, 1980). In contrast, non-essential metals, including Cd, Pb, and Hg, exhibit toxicity even at trace levels, posing significant risks to soil health, plant productivity, and food chain safety. The accumulation of heavy metals in plants thus poses potential human health risks through contaminated soils (Ibrahim & Selim, 2018) and also through vegetables (Kaushik et al., 2025).

5.1.1 Mechanisms of heavy metal toxicity in plants

Heavy metals interfere with plant processes through:

- Oxidative stress, with Cd, Pb, and Cr (VI) promoting Reactive Oxygen Species (ROS) accumulation and damaging cellular components.
- Photosynthetic impairment, disrupting chlorophyll synthesis and electron transport.
- Root growth inhibition, disturbing cell division, elongation, and nutrient uptake.
- Nutrient imbalances, limiting Ca, Mg, Fe, and Zn uptake.
- Microbial disruption, inhibiting enzymes, nitrogen fixation, and beneficial microbial populations.

These mechanisms underpin the ecological and food-chain consequences of metal contamination.



As for the degradation of chemical pesticides in the environment, OCPs have long-term residual effect; OPs are biodegradable, CBMs are easily degraded under natural environment with minimum environmental pollution, and Pyrethroids are non-persistent and break-down easily on exposure to light.

Fig. 7. Classification and examples of pesticides

Table 1. Application of fungicides: Classification based on mode of action and mechanism

Name	Mode of action	Mechanism	Target diseases
Tebuconazole	Systemic	Inhibits sterol biosynthesis (C14-demethylation)	Leaf spots, Rusts
Propiconazole		Inhibits sterol biosynthesis	Leaf spots, Powdery mildew
Hexaconazole		Inhibits sterol biosynthesis	Sheath blight, Rusts
Difenoconazole		Inhibits sterol biosynthesis	Anthracnose, Powdery mildew
Azoxystrobin	Systemic, Translaminar	Inhibits sterol biosynthesis	Blast, Downy mildew
Trifloxystrobin	Systemic, Contact	Inhibits mitochondrial electron transport (cytochrome b)	Rusts, Powdery mildew
Kresoxim-methyl	Systemic	Inhibits mitochondrial respiration	Powdery mildew, Rusts
Boscalid	Systemic	Inhibits mitochondrial respiration	Botrytis, Alternaria
Fluxapyroxad		Inhibits succinate dehydrogenase	Powdery mildew, Leaf spots
Penthiopyrad		Inhibits succinate dehydrogenase	Leaf spots, Blights
Mancozeb	Contact	Inhibits succinate dehydrogenase	Leaf spots, Blights
Zineb	Contact	Multi-site activity affecting enzyme systems	Downy mildew, Leaf spots
Thiram	Contact	Multi-site activity affecting enzyme systems	Seed-borne diseases
Captan	Contact	Multi-site activity affecting enzyme systems	Fruit rots, Leaf spots
Myclobutanil	Systemic	Multi-site activity affecting enzyme systems	Powdery mildew, Leaf spots
Triadimefon	Systemic	Inhibits sterol biosynthesis	Rusts, Powdery mildew
Cymoxanil	Translaminar	Inhibits sterol biosynthesis	Downy mildew, Late blight
Metalaxyl	Systemic	Inhibits RNA synthesis	Downy mildew, Late blight
Mefenoxam	Systemic	Inhibits RNA synthesis	Pythium, Downy mildew
Chlorothalonil	Contact	Inhibits RNA synthesis	Leaf spots, Blights
Fosetyl-Al	Systemic	Multi-site activity affecting fungal enzymes	Downy mildew, Phytophthora
Carbendazim	Systemic	Disrupts fungal metabolism	Leaf spots, Blights
Thiophanate-methyl	Systemic	Inhibits microtubule assembly	Powdery mildew, Leaf spots
Pyrimethanil	Systemic	Inhibits methionine biosynthesis	Botrytis, Anthracnose
Neem oil	Contact	Disrupts fungal reproduction	Powdery mildew, Leaf spots

5.2 Pesticides: Classification, Environmental Persistence, and Soil Interactions

Pesticides vary widely in chemical structures and modes of action, with fate determined by adsorption–desorption processes, pH, organic matter, and microbial degradation. Major groups include organochlorines, organophosphates, carbamates, and pyrethroids (Yadav & Devi, 2017; Raffa & Chiampo, 2021; Kim et al., 2017). Dichloro-Diphenyl-Trichloroethane (DDT) remains a classic example of environmental persistence and bioaccumulation (Fig. 7).

Carbamates, derived from organic carbamic acid structures, include widely used compounds such as carbaryl (Fig. 8) (Zacharia & Tano, 2011). Mechanistically, carbamates and organophosphates share toxicity patterns through acetylcholinesterase inhibition (Silberman & Taylor, 2023).

5.2.1 Mechanisms of pesticide toxicity in plants and soil microbes

Key toxicological effects include:

- Acetylcholinesterase inhibition, affecting soil fauna and non-target insects.
- Membrane damage, altering cellular ion exchange.
- Oxidative imbalance, with ROS-induced lipid and protein damage.
- Soil microbial dysbiosis, reducing abundance, diversity, and nutrient-cycling capacity (Faruque Ahmad et al., 2024).
- Altered nutrient cycling, disrupting nitrification, phosphate solubilization, and carbon turnover.

These mechanisms compromise soil fertility, plant health, and food safety.

5.3 Interactions between Heavy Metals and Pesticides in Soil

Co-contamination is common and produces synergistic effects:

- Competitive sorption on clay and organic matter.
- Altered bioavailability, with pesticides modifying soil pH/redox conditions and metals inhibiting pesticide degradation.
- Synergistic toxicity, exacerbating oxidative stress and impairing detoxification.
- Microbial impacts, reducing richness and inhibiting nutrient-cycling enzymes.

Such interactions highlight the need for mitigation strategies addressing multiple pollutants.

5.4 Food Chain Transfer and One Health Implications

Heavy metals and pesticides affect One Health by linking soil pollution to plant, animal, and human outcomes:

- Bioaccumulation of Cd, Pb, and as in edible plant tissues.
- Pesticide residue persistence in food crops and animal feed.
- Microbiome disruption, compromising rhizosphere health and plant resilience (Philippot et al., 2024).
- Human health impacts, including neurological damage, endocrine disruption, renal injury, carcinogenicity, and immunotoxicity.
- Ecosystem effects, impairing soil fauna, pollinators, and decomposers.

These pathways demonstrate that soil contamination is both an environmental and public health concern.

5.5 Toward Sustainable Mitigation: The Need for Mechanistic Understanding

Mechanistic insights into toxicity are essential for designing effective remediation. The persistence of heavy metals, stability of many pesticides, and synergistic effects of co-contamination necessitate scalable, ecologically compatible remediation solutions. The next section examines biological, physico-chemical, and green chemistry-based remediation approaches, assessing their efficiencies, limitations, and relevance to restoring soil function within a One Health framework.

6. REMEDIATION TECHNOLOGIES – COMPARATIVE CRITICAL EVALUATION

Remediating contaminated agricultural soils requires understanding the scientific basis of each technology alongside their advantages, limitations, scalability, and environmental trade-offs. Because heavy metals and many pesticides persist in soils, remediation must reduce contaminant loads while restoring soil ecological functioning, sustaining crop productivity, and aligning with One Health principles.

6.1 Scientific Principles of Major Remediation Technologies

6.1.1 Physico-chemical approaches

Physico-chemical methods – soil washing, immobilization/stabilization, solidification, electrokinetic remediation, and thermal vitrification – primarily rely on desorption, solubilization, or structural transformation of pollutants. Soil washing uses surfactants, chelators, or acidic agents to extract metals and organics, while stabilization binds contaminants within mineral matrices to reduce mobility. Electrokinetic remediation, effective in fine-textured soils, mobilizes metals such as Cd, Pb, Zn, Cr (VI), and as under applied electric fields.

Although efficient, these approaches can substantially alter soil chemistry and disturb microbial equilibria.

6.1.2 Biological approaches

Biological remediation – including microbial degradation, phytoremediation, rhizofiltration, bioaugmentation, and biostimulation – leverages natural ecological processes. Microorganisms transform pesticides via oxidative, reductive, or hydrolytic pathways (Kumari et al., 2022), while hyperaccumulator plants extract or immobilize metals over successive growth cycles. Amendments such as compost, organic matter, or biosurfactants enhance native microbial activity and pollutant degradation.

6.1.3 Green chemistry and integrated approaches

Green chemistry approaches incorporate biochar amendments, nanomaterials, engineered enzymes, and hydrogel systems. Biochar improves cation exchange capacity, immobilizes metals, and enhances soil structure, while nano-enabled phytoremediation increases root uptake and detoxification potential (Gomes, 2025). These strategies are valued for low energy requirements, reduced secondary pollution, and suitability for long-term soil health restoration.

6.2 Advantages and Limitations

6.2.1 Physico-chemical methods

Advantages:

- Rapid and efficient, particularly at high contamination levels.
- Applicable to both organic and inorganic pollutants.
- Suitable for industrial hotspots and acute contamination events.

Limitations:

- High operational and energy costs.
- Generation of secondary waste requiring safe disposal.
- Potential alteration of soil physicochemical properties.
- Limited feasibility in large-scale agricultural contexts.

6.2.2 Biological methods

Advantages:

- Environmentally sustainable and cost-effective.
- Enhance SOM and microbial biodiversity.
- Support long-term ecological restoration.
- Integrate well with agroecological and organic systems.

Limitations:

- Slower than physico-chemical techniques.
- Sensitive to climate, soil properties, and plant traits.
- Low biomass of hyperaccumulators constrains extraction efficiency.
- Less effective in severely contaminated soils.

6.2.3 Biochar and green chemistry approaches

Advantages:

- Improve soil structure, pH regulation, and carbon sequestration.
- Facilitate metal immobilization while supporting crops.
- Promote microbial-mediated remediation.
- Align with circular bioeconomy, converting waste to value.

Limitations:

- Efficacy depends on feedstock type and pyrolysis temperature.
- Over-application may disrupt nutrient balance.
- Limited long-term field validation.

Previous studies from Iraq show that absence of early monitoring has escalated public health risks in polluted sites, as Pollution Load Index (PLI) values were not assessed in time (Al-Mashhadi & Alabadi, 2023). Another study by Alain, T. K., et al. (2025) and Derra, M., et al. (2024) significantly advance understanding of environmental metal contamination in Korsimoro, Burkina Faso. Alain et al. (2025) demonstrate that agricultural soils in market gardening sites exhibit notable heavy metal accumulation, with quantified health risks for exposed populations. Derra et al. (2024) specifically shows that trace metal concentrations in the Korsimoro dam exceed recommended thresholds, indicating potential ecological and human health hazards. Together, these works highlight the need for continuous environmental monitoring and mitigation strategies to protect water and soil resources in the region. Thus, the findings suggest that due to long-term accumulation and persistence of heavy metals, affected areas require urgent intervention (Fig. 9) to prevent further ecological degradation, reduced agricultural productivity, diminished crop quality, and increased human health disorders.

6.3 Scalability and Cost Considerations

- **Large-scale agriculture:** Biological and biochar-based methods are most feasible, offering low cost and minimal disruption.
- **Localized hotspots:** Soil washing, thermal treatments, and electrokinetics provide high efficiency but require significant capital.
- **Low-resource regions:** Phytoremediation and organic amendments (manure, compost, crop residues) remain accessible and affordable.
- **Industrial–agricultural interfaces:** Hybrid approaches – physico-chemical remediation for hotspots combined with phytoremediation for surrounding areas - optimize recovery.

Cost-effectiveness varies by contaminant: metals require long-term immobilization, whereas pesticides benefit from microbial and enzymatic degradation pathways.

6.4 Environmental Trade-Offs

A comprehensive evaluation includes potential ecological side effects:

- Physico-chemical treatments may induce soil acidification, organic matter loss, and microbial decline.
- Phytoremediation risks contaminant concentration in plant biomass, requiring secure disposal.
- Nanomaterial use necessitates monitoring of nano-toxicity and trophic impacts.
- Improperly produced biochar may contain polyaromatic hydrocarbons.
- Microbial remediation may generate by-products with uncertain long-term ecological effects.

These considerations emphasize the need for integrated, ecosystem-aligned remediation strategies that maintain soil functionality, biodiversity, and agricultural resilience.

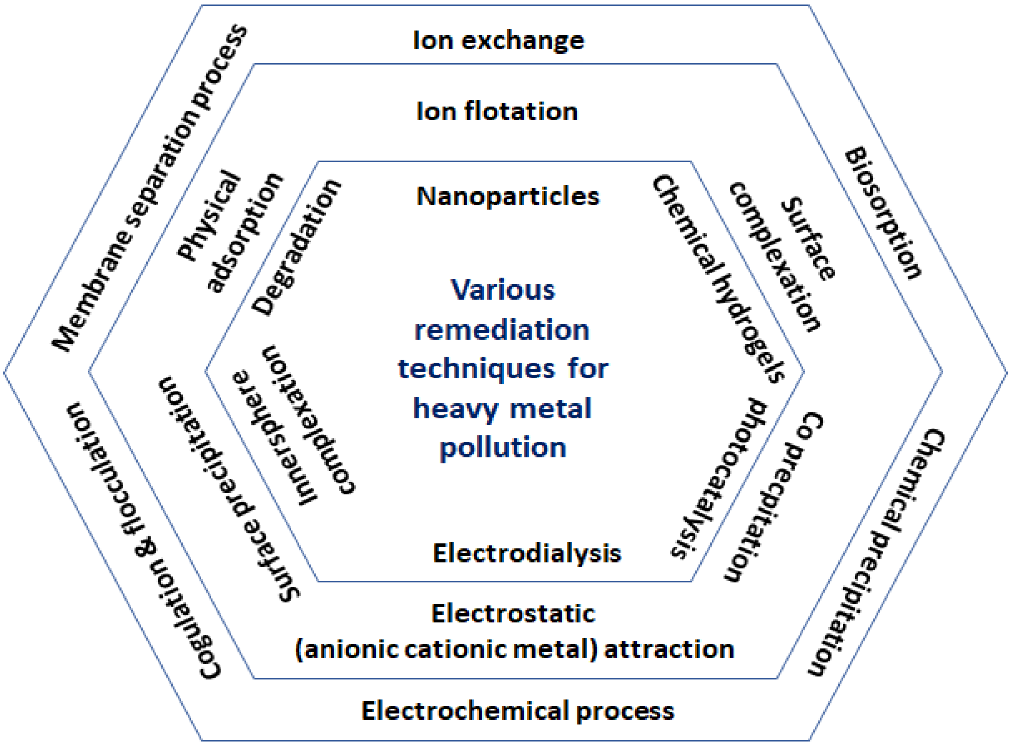


Fig. 8. Various different remediation techniques for heavy metal pollution

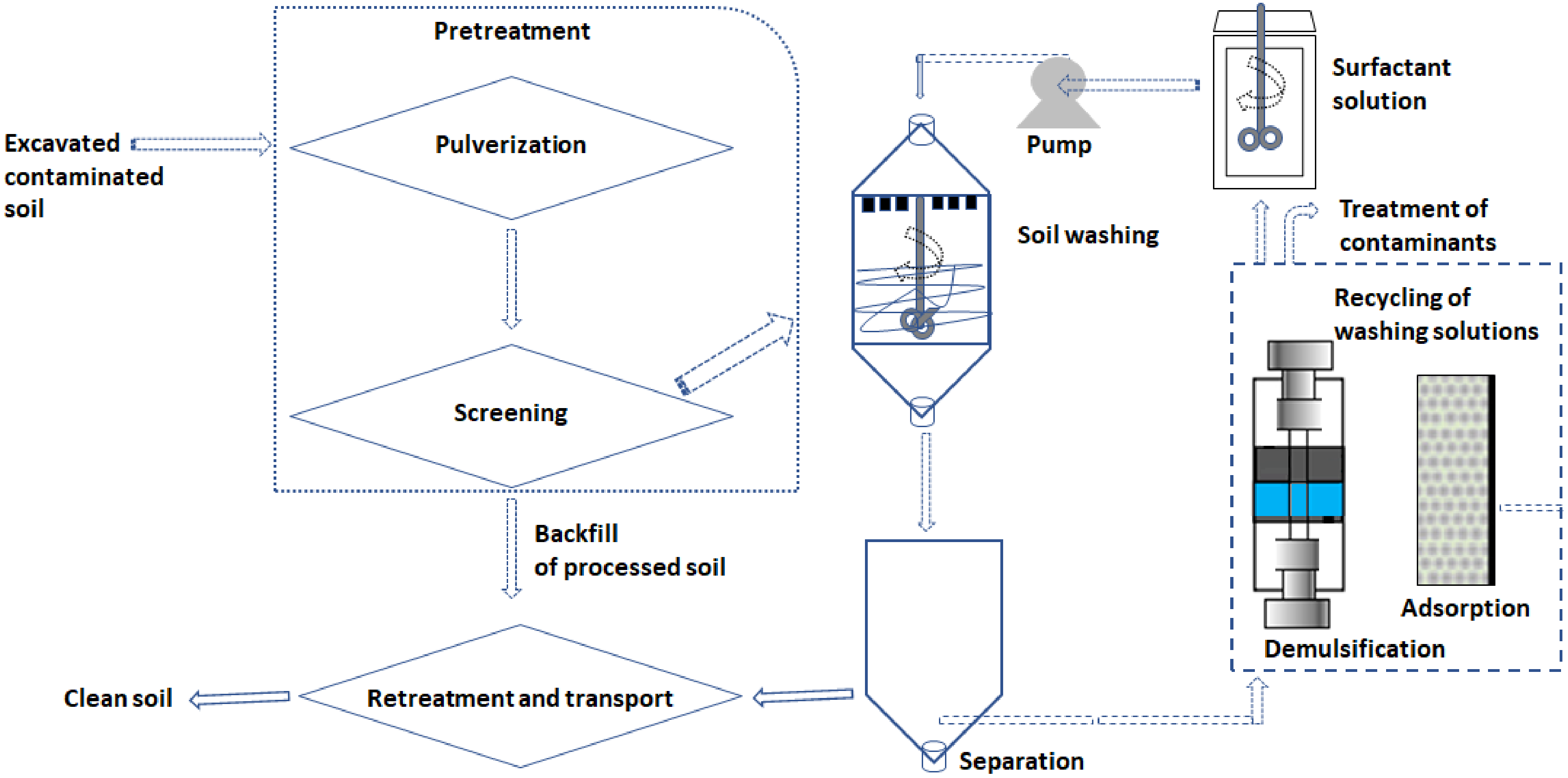


Fig. 9. Schematic design of soil washing (including the remediation example using surfactants, bioreports, etc. (RoyChowdhury et al., 2018 and Arfasa et al. 2022)

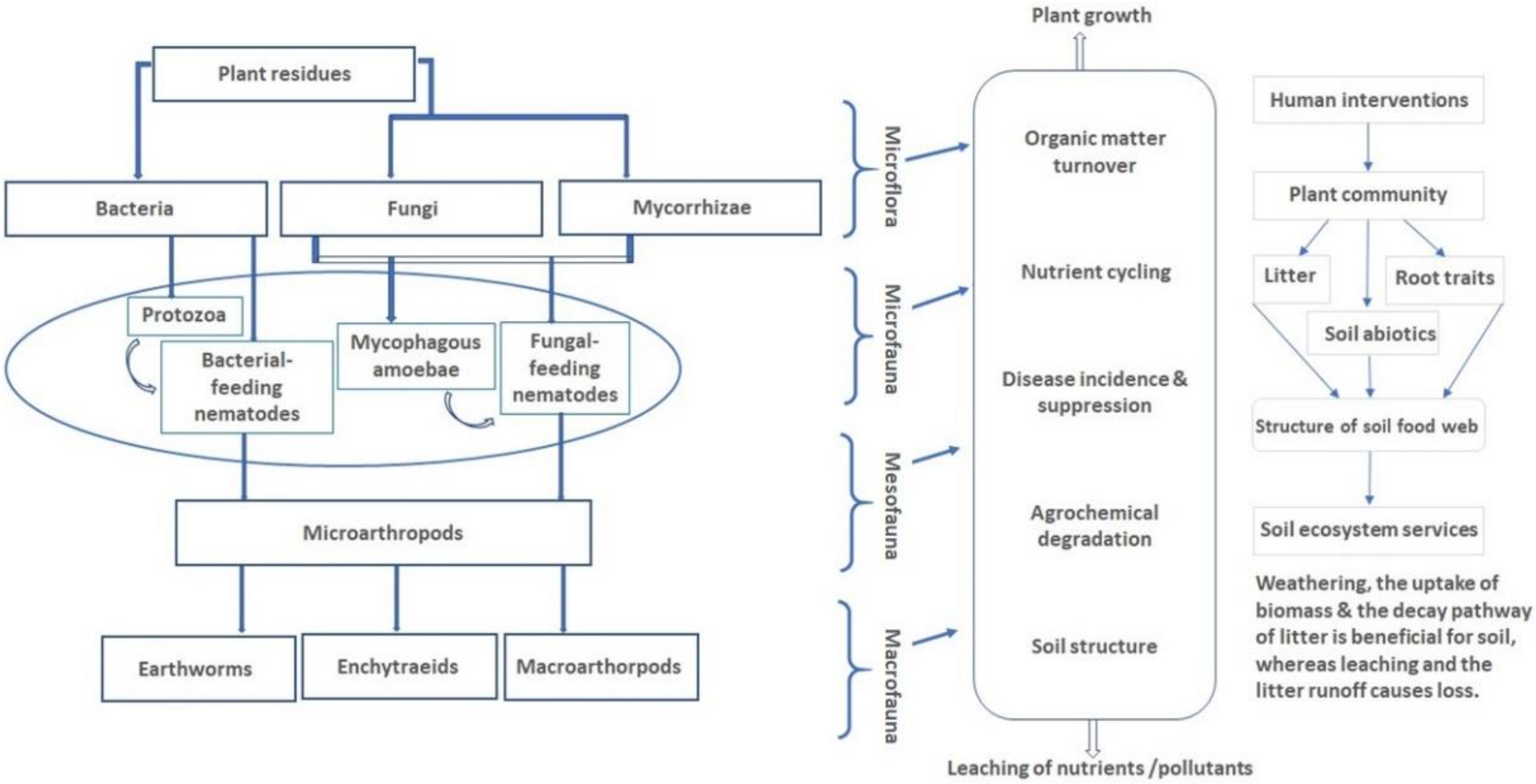


Fig. 10. Soil food web: structure and pathways for nutrients

7. INTEGRATING SOIL POLLUTION WITH THE ONE HEALTH FRAMEWORK

7.1 Mechanistic Exposure Pathways Linking Soil to Human and Environmental Health

The One Health framework provides a mechanistic lens linking soil contamination with plant dysfunction, ecosystem disruption, and human disease.

7.1.1 Soil–plant–food chain transfer

Heavy metals such as Cd, Pb, and as readily enter roots, accumulate in edible tissues, and persist through trophic levels. Persistent pesticides, including OCPs and certain herbicides, follow similar bioaccumulation trajectories.

7.1.2 Impacts on the soil microbiome and rhizosphere health

Microbiome dysbiosis induced by metals or xenobiotic pesticides suppresses nitrogen fixation, disrupts beneficial microbes and enzyme systems, and heightens plant vulnerability to stress.

7.1.3 Ecotoxicological feedback loops

Contaminants affect soil fauna, pollinators, and decomposers, weakening nutrient cycling and organic matter turnover.

7.1.4 Human exposure pathways

Exposure occurs via contaminated food, inhalation of dust, polluted groundwater, and occupational handling. These pathways contribute to carcinogenicity, neurotoxicity, endocrine disruption, and cardiometabolic disorders (Rusin et al., 2021; Popescu et al., 2024).

7.2 Planetary Health and Sustainable Agriculture Alignment

Integrating remediation with One Health emphasizes soil as a regulator of nutrient cycles, biodiversity, and food security, and positions soil contamination as a planetary boundary threat. Climate change intensifies contaminant mobility, redox shifts, and pesticide volatilization. Consequently, remediation must align with climate adaptation, biodiversity conservation, and sustainable food-system transitions. This interdependence underscores soils as foundational to ecosystem integrity and human well-being.

8. FUTURE DIRECTIONS AND KNOWLEDGE GAPS

8.1 Multicontaminant and Co-Exposure Models

Most remediation studies examine pollutants individually, although agricultural soils often contain metals, pesticides, microplastics, and pharmaceuticals. Integrated models are required to predict synergistic and antagonistic effects.

8.2 Long-Term Field Validation

Key technologies – biochar, nanomaterials, enzymatic remediation – lack long-term field trials assessing durability, safety, and agronomic performance across diverse climates.

8.3 Soil Microbiome–Centered Remediation

The soil microbiome remains under integrated in remediation design. Metagenomic, metabolomic, and systems-level tools are needed to harness microbiome-driven detoxification.

8.4 Harmonized Regulatory Frameworks

Inconsistent residue limits and monitoring protocols across nations hinder effective soil and food safety governance. Harmonized standards and integrated risk assessments are essential.

8.5 Scalable Green Chemistry Approaches

Biochar, biodegradable nanopolymers, biosurfactants, and enzyme biocatalysts require further development to increase scalability, affordability, and agricultural compatibility.

8.6 Climate–Pollution Interactions

Shifts in rainfall, temperature, and soil moisture will influence contaminant mobility and degradation. Improved predictive models are needed for future climate scenarios.

Fig. 11. Photograph of eutrophicated canal (called nala in the local language) which was later abandoned after the Purna dam was modified (Shaikh et al., 2013)

8.7 Research Enterprise, Policy, and Practice

Jacquet et al. (2022) advocate a paradigm shift toward pesticide-free agriculture. The European Commission (2023) provides a comprehensive IPM “toolbox” with ~1,300 examples aligned with eight Integrated Pest Management (IPM) principles. Given persistent risks from hazardous fungicides (Table 1), remediation must remain agronomically viable and environmentally sustainable (Ball et al., 2018; Jacobson et al., 2024). The One Health framework is therefore central, linking ecosystems, healthy soils, crops, food, and consequently human well-being (Fig. 10).

Our earlier work demonstrated that excessive nutrient inputs trigger eutrophication via runoff into irrigation canal systems (Shaikh et al., 2013) (Figs. 11 and 12) and influences the ecosystem.

8.8 The Science of the One Health Approach

The One Health (OH) framework recognizes the interdependence of environmental, plant, animal, and human health (Kahn, 2017). Established conceptually after the 2003 SARS pandemic, OH fosters collaboration among medical, veterinary, ecological, and agricultural sciences to address zoonoses, pollution, climate change, and plant disease. Sustainable agriculture operationalizes OH by reducing biodiversity loss, improving environmental quality, and enhancing food safety (Shen & Schwarz, 2023).

Advancing OH requires interdisciplinary collaboration. Seminal work on zoonotic transmission (Mackenzie & Jeggo, 2019; Mackenzie et al., 2014; Mubareka et al., 2023) and the COVID-19 pandemic illustrate the urgency of this integrative approach. Plant diseases can also influence human well-being (Al-Sadi & Abdullah, 2017), with evidence showing cross-kingdom pathogen transfer (Kim, 2020) and human-mediated plant viral dispersal (Ranawaka et al., 2020). Microbiomes further connect plant, animal, and human health (Kahn, 2017; Trinh et al., 2018), and soil pollution remains a major global driver of environmental degradation (Steffan et al., 2020). Climate-related stressors, such as extreme heat in the Arabian Peninsula, further destabilize OH balances (The Lancet Series on One Health and Global Health Security, 2023).

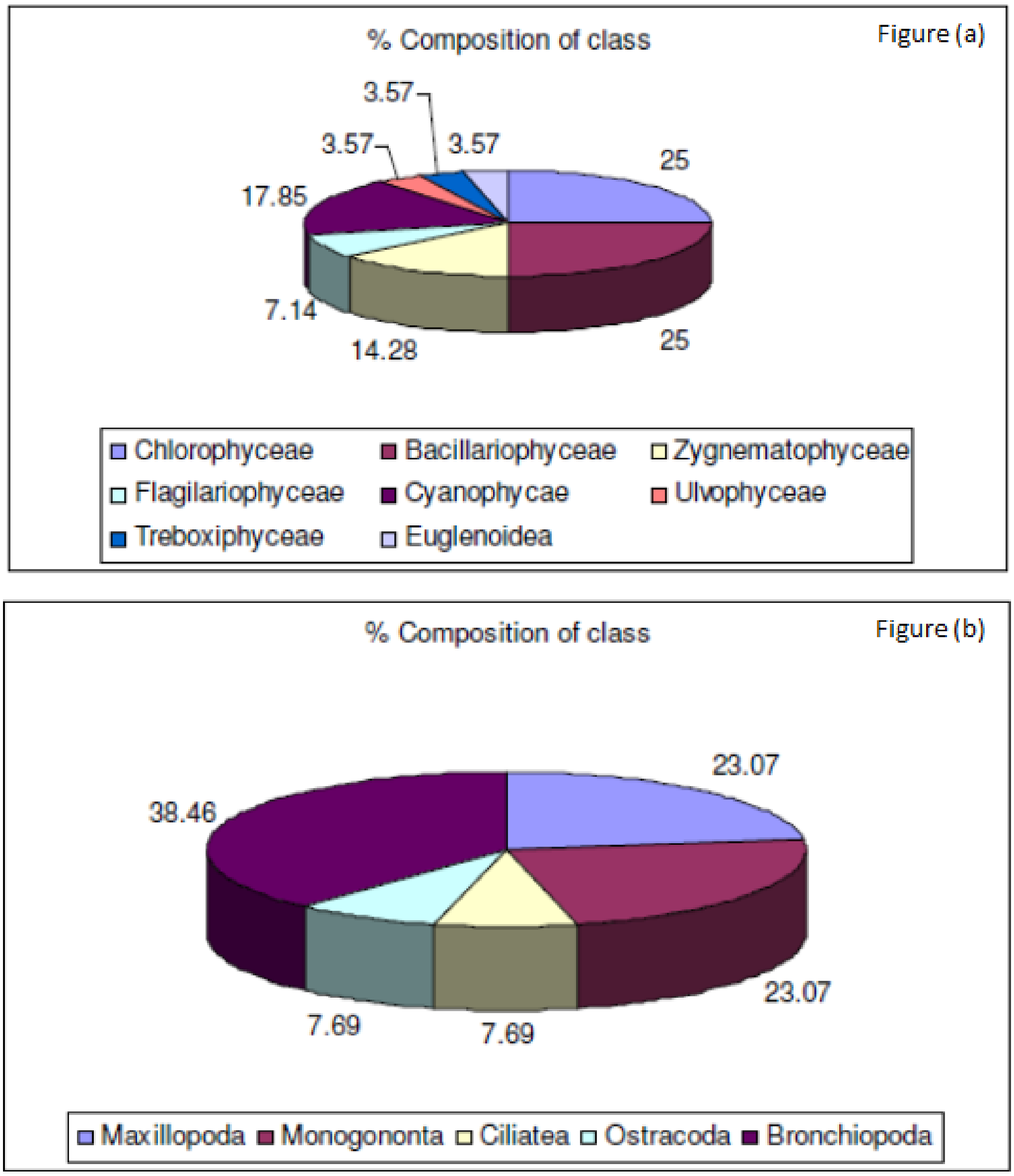


Fig. 12. (a) Percentage composition of phytoplankton in the eutrophicated study area, (b) Percentage composition of zooplankton in the study area (Shaikh et al., 2013 Author copyright: isca.in)

Global momentum for OH continues to grow (Brown et al., 2024; Gibbs, 2014; Destoumieux-Garzón et al., 2018). The OH paradigm now features prominently in major scientific journals (Nature Communications, 2023; Nature, 2025), and a dedicated OH journal has recently been launched (Zhou & Tanner, 2022). International institutions WOAH, FAO, UNEP, WHO are increasingly integrating OH into ecosystem and public-health policy (WOAH, 2023; FAO/UNEP/WHO/WOAH, 2024). Banerjee and van der Heijden (2023) further highlight soil microbiomes as central to OH, affirming soil as a core pillar of ecological and human well-being.

Building on the mechanistic and comparative analyses presented throughout this review, the OH relevance of our work lies in framing agricultural soil contamination not as an isolated environmental problem but as the initiating compartment in a cascading health continuum. By integrating soil nutrient profiling with toxicological pathways of heavy metals and pesticides, the study clarifies how subtle alterations in soil chemistry and microbiome structure translate into plant stress responses, impaired ecosystem services, and downstream human exposure risks. Rather than reiterating established links between pollutants and health outcomes, this synthesis demonstrates that soil acts as a long-term reservoir and amplifier of chemical stressors, governing their bioavailability, persistence, and transfer across biological boundaries. The originality of our contribution resides in coupling this systems-level understanding with sustainability-oriented remediation strategies – particularly green chemistry and biochar-based interventions – that are evaluated not only for contaminant reduction but for their capacity to restore soil functionality within real farm-field contexts. In doing so, the review reinforces soil health as a foundational but under-recognized pillar of the "One Health," where preventive remediation at the soil level emerges as a critical leverage point for protecting ecosystem resilience, food safety, and human well-being.

9. CONCLUSION

Soil contamination by heavy metals and pesticides is a multidimensional environmental challenge with critical consequences for plant productivity, ecosystem stability, food-chain integrity, and human health. This review shows that soil health is inseparable from the broader One Health domain. Mechanistic evidence demonstrates that contaminants disrupt plant physiology, alter microbial ecology, and threaten biodiversity and public health through multiple exposure pathways.

A synthesis of remediation technologies indicates that sustainable, scalable, and biologically compatible strategies are urgently needed. While physico-chemical methods offer rapid decontamination, biological and green chemistry approaches – biochar amendments, phytoremediation, microbial degradation, and nano-enabled methods – provide longer-term ecological restoration aligned with sustainable agriculture.

Addressing current gaps demands interdisciplinary collaboration, integrated multi-contaminant models, long-term field research, and harmonized global regulatory frameworks. Safeguarding soil health is therefore central to food security, environmental sustainability, and public health. Framed within One Health, soil remediation becomes a transformative pathway for strengthening ecosystem resilience and protecting the well-being of current and future generations.

10. FUTURE SCOPE

Addressing heavy metal contamination and excessive pesticide use is essential for ensuring food security in a growing global population. Although plants possess innate stress-response mechanisms, farmers must understand the environmental and physiological impacts of pollutants from agrochemicals, industry, and unsustainable land use. Awareness at the grassroots level remains essential for reducing environmental and health risks.

Scientific research continues to inform policy on permissible pollutant thresholds and risk assessment, ensuring that soil toxicology, remediation, and sustainable agriculture remain central to environmental management. Prevention remains preferable to remediation, yet innovation in field-applicable mitigation strategies is vital for achieving sustainability goals consistent with One Health principles.

This manuscript serves as a comprehensive resource for environmental and agricultural researchers, synthesizing evidence on soil nutrient dynamics, contamination, plant stress responses, and mitigation strategies through a One Health lens. Multidisciplinary collaboration remains crucial for advancing sustainable agricultural practices (Kahn, 2017; Mackenzie & Jeggo, 2019; Mackenzie et al., 2014).

Among remediation strategies, biochar is a cost-effective amendment for alleviating environmental stress (Foyer et al., 2016). It mitigates abiotic stressors (salinity, UV radiation, temperature extremes, heavy metals) and biotic pressures (pathogens, pests, fungi, nematodes), while enhancing soil fertility, microbial activity, cation exchange capacity, and reducing contaminant bioavailability through adsorption, ion exchange, co-precipitation, and surface complexation (Hasnain et al., 2023). Empirical studies demonstrate its ability to improve soil quality and reduce trace metal accumulation in cadmium-contaminated rice paddies (Xia et al., 2024; Priya et al., 2023; Xu et al., 2019; Tian et al., 2025), and to immobilize Zn, Pb, and Cd in switchgrass and poultry litter-derived biochar, lowering accumulation in ryegrass (Antonangelo et al., 2023). Biochar also enhances carbon sequestration and modulates greenhouse gas emissions (Zhang, 2015; Qi, 2023), while microbial bioremediation continues to show high efficacy.

Established remediation methods – soil washing, solidification, electrokinetic treatment, chemical stabilization, and phytoremediation – remain important, though biological and plant-based approaches offer sustainable long-term potential (Liu et al., 2018; Xu et al., 2019; Kim et al., 2022; Selvi et al., 2019). Prioritizing phytoremediation with responsible plant disposal is essential to prevent secondary pollution (Hu et al., 2023).

This review highlights the need to identify contamination sources, evaluate toxicological impacts, and link them to ecosystem and human health. Soil serves as a cornerstone of the One Health paradigm, reinforcing that human well-being is fundamentally tied to the health of plants, animals, and the environment (Banerjee & van der Heijden, 2023). Ultimately, healthy soils underpin ecological stability, agricultural productivity, and human health (Emikpe et al., 2024).

Future research must advance sustainable agriculture as a multidimensional framework integrating environmental protection, biodiversity conservation, plant and animal health, and human well-being. One Health offers the scientific foundation for evaluating risks posed by agrochemicals, microorganisms, plant pathogens, and infectious diseases, supported by comprehensive monitoring, life-cycle assessments, and strong environmental–health risk analyses.

Responding to the consequences of anthropogenic activities – especially soil pollution – requires production-appropriate agricultural practices that protect soil, water, and air, particularly under climate change, land degradation, and declining fertility. Green chemistry provides a unifying discipline for bridging agricultural innovation with sustainability (Shaikh et al., 2013; Shaikh & Shaikh, 2018; Shaikh, 2014). Innovations in green chemistry and sustainable engineering will be central to restoring degraded soils, minimizing pollution, and enhancing resource efficiency.

Although the present study provides scientific insights, its broader impact extends to societal transformation. Building resilient, knowledge-based communities and equitable food systems will require holistic approaches grounded in environmental stewardship, social justice, and sustainable livelihoods.

11. THE SIGNIFICANCE OF THE STUDY

11.1 The Environmental Significance

The idea is to conceptualize the agricultural soil profile for its nutrient content as well as contaminants, implications on plant stress management, food web or the health of humans and the environment and highlight through a critical review the importance of research into remediation of pollutants, with a special focus on nexus approaches in soil, sustainable agriculture practices and the “one-health.”

11.2 The Scientific Novelty

The novelty lies in its integrated and multidisciplinary approach to understanding soil pollution, toxicological profiling, and remediation of heavy metal and pesticide contamination within the framework of sustainable agriculture and the “One Health” concept. Unlike conventional reviews focusing narrowly on either contaminants or remediation techniques, this work holistically connects soil nutrient profiling, phytotoxicity mechanisms, ecosystem services, and human-environmental health interlinkages. It uniquely emphasizes cross-sectional roles of green chemistry and biochar-based strategies, advancing practical farm-field applications. By synthesizing chemical, biological, and ecological insights, the study pioneers a unified conceptual model for soil restoration and sustainability-driven remediation.

This review offers an integrated One Health assessment of heavy metal and pesticide contamination in agricultural soils, combining mechanistic toxicology, a comparative critical evaluation of remediation technologies, and a planetary health perspective to identify cross-sectoral knowledge gaps and sustainability priorities.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The authors affirm that all content and interpretations presented in this manuscript are original and solely the work of the authors. No generative artificial intelligence tools were employed at any stage of manuscript preparation, including writing or editing.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here:
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