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Review Article

Advanced Remediation of Heavy Metals, Microplastics, and Polycyclic Aromatic Hydrocarbons (PAHs) in Co-contaminated Agricultural Soils: A Review

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Abstract

Soil contamination by heavy metals, microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) poses a significant threat to agricultural productivity, environmental sustainability, and human health. The coexistence of these contaminants in agricultural soils creates complex remediation challenges because of their distinct physicochemical properties, environmental behavior, and persistence. This review has examined recent advances in remediation technologies for agricultural soils co-contaminated with heavy metals, MPs, and PAHs, covering physical, chemical, biological and integrated remediation approaches. Particular attention is given to emerging technologies, including nanomaterial-assisted remediation, electrokinetic systems, plant growth-promoting rhizobacteria (PGPR)-assisted remediation, biochar-supported microbial processes, and CRISPR-engineered microorganisms. Unlike previous reviews that primarily focused on individual contaminant classes or stand-alone remediation technologies, this review provides a comparative framework for evaluating remediation performance and a mechanistic framework linking contaminant characteristics, soil interactions, and remediation strategy selection. The analysis highlights the growing potential of integrated treatment-train approaches for managing multi-contaminant soils while identifying key challenges related to scalability, environmental safety, economic feasibility, and field implementation. Overall, the review provides insights into current research trends and future directions for developing sustainable and effective remediation strategies for co-contaminated agricultural soils.

Keywords: Soil remediation; Heavy metals; Microplastics; Polycyclic aromatic hydrocarbons (PAHs); Bioremediation

Introduction

Soil, as a foundational component of terrestrial ecosystems, is a critical and finite natural resource. It possesses intrinsic self-regulatory functions driven by microbial activity, sorption processes, and physicochemical buffering, which collectively contribute to the stabilization and partial detoxification of contaminants under environmental stress (Xia *et al.* 2024). However, the increasing and unabated discharge of anthropogenic pollutants has overwhelmed these natural processes, leading to widespread soil contamination (Yi *et al.* 2023). Soil degradation poses a direct threat to global food security, environmental integrity, and human health (Xia *et al.* 2024).

Among major soil contaminants, heavy metals, microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) are particularly persistent and problematic due to their long-term stability and adverse impacts on soil functioning and agricultural sustainability, often occurring in interconnected pollution scenarios (Chandel *et al.* 2025a; Mai *et al.* 2025). Agricultural soils worldwide are increasingly affected by heavy metal accumulation, with studies reporting elevated concentrations of Pb, Cd, and As in many intensively farmed regions. For example, global assessments estimate that a substantial proportion of agricultural soils exceed permissible limits for at least one toxic metal, reflecting widespread contamination linked to industrial emissions, agrochemicals, and wastewater irrigation (Tomczyk *et al.* 2023). These metals are non-degradable, highly persistent, and bioaccumulative, leading to long-term deterioration of soil quality, reduced crop

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productivity, and increased risks to human health through food chain transfer. Site-specific challenges, including pronounced spatial heterogeneity of contamination (Wang *et al.* 2022b), concurrent soil acidification (Sun *et al.* 2024), and weak correlations between total soil metal concentrations and plant uptake, further complicate risk assessment and management of contaminated farmlands (Islam *et al.* 2024). Collectively, these factors, combined with limited long-term effectiveness and high costs of existing remediation strategies, highlight the need for advanced and site-specific remediation and risk assessment frameworks (Zeng *et al.* 2023).

Simultaneously, microplastic (MP) pollution has emerged as a significant soil stressor. Global plastic production exceeds ~400 million metric tons annually (Ali *et al.* 2025), leading to widespread MP accumulation in agricultural soils through sewage sludge application, compost amendment, wastewater irrigation, and degradation of plastic mulches (Huang *et al.* 2020). Once in soil, MPs (≤5 mm) undergo fragmentation and weathering, altering key soil physical properties such as porosity, bulk density, and water-holding capacity, thereby affecting soil structure and root development (Qi *et al.* 2020). In addition, MPs disrupt soil biochemical functioning by interfering with enzyme activities involved in nutrient cycling (Fei *et al.* 2020). Importantly, MPs can act as carriers of co-contaminants due to their high hydrophobicity and large specific surface area, facilitating the adsorption of heavy metals, organic pollutants, and antibiotics, thereby enhancing their mobility, bioavailability, and combined toxicity (Dissanayake *et al.* 2022).

Polycyclic aromatic hydrocarbons (PAHs), a class of persistent organic pollutants composed of fused aromatic rings, further compound soil contamination issues. They are primarily generated through incomplete combustion of organic matter and persist in soils due to their strong hydrophobicity, high chemical stability, and strong affinity for soil organic matter, which results in low bioavailability but long-term environmental persistence. Consequently, PAHs accumulate in soils and can enter food chains, posing chronic ecological and human health risks. Their remediation remains challenging and often requires integrated approaches tailored to compound type, concentration, and site-specific soil conditions (Singh and Singh 2025a, b).

Soil contamination by MPs, PAHs, and heavy metals is addressed using a range of conventional and emerging remediation technologies depending on pollutant characteristics. Conventional physical and chemical approaches such as soil washing, thermal desorption, stabilization/solidification, and electrokinetic remediation have been widely applied for removing or immobilizing heavy metals and PAHs. However, these methods are often costly, energy-intensive, and potentially harmful to the environment (Chandel *et al.* 2025b). In contrast, biotechnological approaches such as phytoremediation and microbial remediation are gaining attention due to their cost-effectiveness and environmental compatibility, utilizing plants and microorganisms to absorb, transform, or degrade contaminants while preserving soil structure (Islam *et al.* 2024). For co-contaminated soils, biosurfactant-assisted soil washing has shown effectiveness in enhancing the removal of both heavy metals and organic pollutants (Zhang *et al.* 2022). Emerging strategies such as biochar-supported microbial systems integrate adsorption and biodegradation processes, while enzymatic degradation pathways are being explored for microplastic breakdown (Cheng *et al.* 2025). Additionally, nanotechnology-based amendments, including engineered nanoparticles, have demonstrated potential for enhancing adsorption capacity and catalytic degradation of pollutants such as PAHs in contaminated soils (Yang *et al.* 2024a). Despite substantial advances in soil remediation research, most published reviews have focused on individual contaminant groups, such as heavy metals, microplastics (MPs), or polycyclic aromatic hydrocarbons (PAHs), or have primarily discussed conventional remediation technologies. However, contaminated soils frequently contain multiple classes of pollutants simultaneously, resulting in complex interactions that influence contaminant mobility, bioavailability, toxicity, and remediation efficiency. Consequently, there is a growing need for a comprehensive review that critically evaluates advanced remediation technologies capable of addressing multi-contaminant soil systems.

The aim of this review is to provide a comprehensive and critical assessment of recent and emerging remediation strategies for soils contaminated with heavy metals, MPs, and PAHs. The review examines the mechanisms, effectiveness, advantages, limitations, and practical applicability of physical, chemical, biological, and integrated remediation approaches. Particular emphasis is placed on advanced technologies, including electrokinetic remediation, thermal desorption, nanoremediation, biochar-supported microbial systems, plant growth-promoting rhizobacteria (PGPR)-assisted remediation, and CRISPR-engineered microbial consortia. Unlike previous reviews that typically focus on a single contaminant class or remediation approach, this review provides an integrated perspective on the remediation of multiple co-existing soil contaminants and identifies current challenges, research gaps, and future directions for the development of sustainable, cost-effective, and field-applicable remediation strategies.

Variety of soil contamination

Soil contamination arises from the accumulation of hazardous substances in soil matrices due to industrial emissions, agricultural inputs, waste disposal, and atmospheric deposition. These contaminants include both inorganic and organic pollutants that differ in origin, persistence, and environmental behavior. Natural processes such as volcanic activity, rock weathering, and wildfires may contribute background levels of certain elements; however, contemporary soil contamination is overwhelmingly driven by anthropogenic activities, including intensive agriculture, industrial production, mining, and improper waste management (Priya *et al.* 2022).

In real-world scenarios, contaminants rarely occur in isolation; instead, multiple contaminant classes frequently coexist within the same soil system. Heavy metals, persistent organic pollutants (such as polycyclic aromatic hydrocarbons and pesticides), and emerging contaminants (including pharmaceuticals and personal care products) are increasingly reported as co-contaminants in agricultural and peri-urban soils (Taghavi *et al.* 2022). This co-occurrence is largely driven by shared emission sources such as wastewater irrigation, industrial effluents, sewage sludge application, and agrochemical inputs, which simultaneously introduce chemically distinct pollutants into the soil environment (Sahithya *et al.* 2022). The simultaneous presence of these contaminants significantly complicates soil remediation because their transport, bioavailability, and toxicity are interdependent rather than independent. For instance, organic contaminants may alter soil organic matter interactions, thereby influencing the speciation and mobility of heavy metals, while certain inorganic ions can affect the sorption and degradation pathways of organic compounds. Such coupled behavior makes it difficult to predict contaminant fate using single-pollutant models and reduces the effectiveness of conventional remediation strategies designed for isolated pollutants (Priya *et al.* 2022).

Emerging contaminants represent an additional layer of complexity due to their diverse chemical nature and insufficient regulatory control. These compounds, including pharmaceuticals, personal care products, and industrial additives, are often continuously released into the environment at low concentrations but persist over time, leading to pseudo-persistent exposure conditions. Their co-existence with legacy pollutants further increases ecological risk through additive or synergistic effects, while also limiting remediation efficiency due to competitive sorption and altered microbial activity (Chaturvedi *et al.* 2021).

A key challenge associated with such mixed contamination is the lack of comprehensive understanding of long-term environmental fate and transformation pathways under multi-pollutant conditions (Akhbarizadeh *et al.* 2020). The interactions among organic pollutants, inorganic elements, and emerging contaminants create complex chemical and biological feedback mechanisms that hinder accurate risk assessment and remediation design (Priya *et al.* 2022). As a result, there is an increasing need to move beyond single-contaminant frameworks toward integrated, multi-pollutant remediation strategies that can effectively address co-contaminated soil systems (Rathi *et al.* 2021). The main categories of contaminants in soil have been illustrated in Fig. 1.

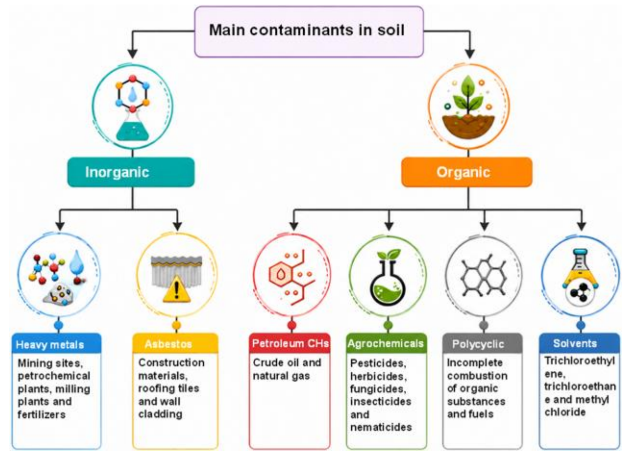

Fig. 1: Major categories and sources of soil contaminants. The figure illustrates the principal groups of contaminants commonly found in agricultural soils, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), microplastics (MPs), pesticides, pharmaceuticals and other emerging pollutants

Remediation technologies for soil contamination

Soil remediation aims to restore contaminated soils to a condition that is safe for human health and the environment by reducing contaminant concentrations or immobilizing their mobility. The selection of an appropriate remediation strategy depends on the nature and concentration of contaminants, site-specific soil characteristics, hydrogeological conditions, and the intended risk reduction goals. Effective remediation supports ecosystem recovery, sustainable land use, and long-term environmental management (Azuazu *et al.* 2023).

Recent advances in remediation technologies have increasingly focused on enhancing the efficiency of treating soils contaminated with single and multiple pollutants. In particular, bioremediation has gained attention due to its ability to utilize microorganisms to degrade, transform, or immobilize contaminants within soil matrices. Approaches such as bioaugmentation and biostimulation have demonstrated improved remediation performance compared to conventional methods, while also offering lower operational costs and greater environmental compatibility. In some studies, microbial remediation has also been associated with reduced secondary environmental impacts, including lower greenhouse gas emissions under optimized aerobic conditions, although this effect is strongly dependent on soil conditions, contaminant type, and oxygen availability (Song *et al.* 2022).

A major challenge in soil remediation is co-contamination, where multiple pollutant classes such as heavy metals, organic contaminants, and emerging pollutants coexist within the same soil system. This creates antagonistic treatment requirements, since remediation actions targeting one contaminant may negatively affect another. For example, chemical amendments used to mobilize heavy metals can inadvertently increase the mobility of co-existing organic pollutants, while organic amendments may enhance sorption of hydrophobic compounds but reduce metal bioavailability control. In addition, contaminant interactions with soil organic matter and microbial communities can alter degradation pathways and reduce the overall efficiency of remediation strategies (Lee *et al.* 2024).

To address these complexities, integrated remediation approaches—often referred to as treatment trains—are increasingly being applied. A treatment train combines multiple remediation technologies in a sequential or complementary manner to achieve more effective soil restoration. In a typical sequence, physical methods such as excavation or soil vapor extraction (SVE) are first applied to remove or extract volatile or accessible contaminants. This is followed by chemical treatments such as oxidation or reduction processes to transform or degrade residual pollutants, and finally biological methods, including bioremediation, are used to further degrade or stabilize remaining contaminants through microbial activity (Dadrasnia and Agamuthu 2014). A representative example of an integrated system is the combination of bioventing and soil vapor extraction, which has been shown to achieve high removal efficiencies under controlled conditions. Such integrated approaches demonstrate that combining physical and biological processes can significantly enhance remediation performance while reducing environmental disturbance. However, despite their effectiveness, treatment train systems often require high operational costs, complex process control, and careful optimization of individual stages to avoid inefficiencies or unintended contaminant redistribution (Amin *et al.* 2014; Michael-Igolima *et al.* 2022; Nwankwegu *et al.* 2022a).

Traditional remediation technologies are often resource-intensive, requiring substantial inputs of water, energy, and chemical reagents, which increases overall project costs and limits large-scale applicability (Lu *et al.* 2020). Consequently, there is growing interest in developing more sustainable and efficient remediation strategies. Advances in metagenomics have enabled the identification of microbial degradation pathways, improving the design of targeted bioremediation systems (Azuazu *et al.* 2023). Furthermore, microbial approaches have shown potential for degrading persistent contaminants, including emerging pollutants such as microplastics and per- and polyfluoroalkyl substances (PFAS), thereby expanding the scope of bioremediation applications. Enhancement strategies such as bioaugmentation, involving the introduction of specialized pollutant-degrading microbial strains, have been shown to improve degradation efficiency under specific conditions (Muter 2023). Similarly, biostimulation—through the addition of nutrients or electron donors—can enhance indigenous microbial activity and has been reported as a cost-effective and efficient strategy for promoting contaminant degradation (Mayakaduwage *et al.* 2022). The use of sustainable amendments such as biochar further

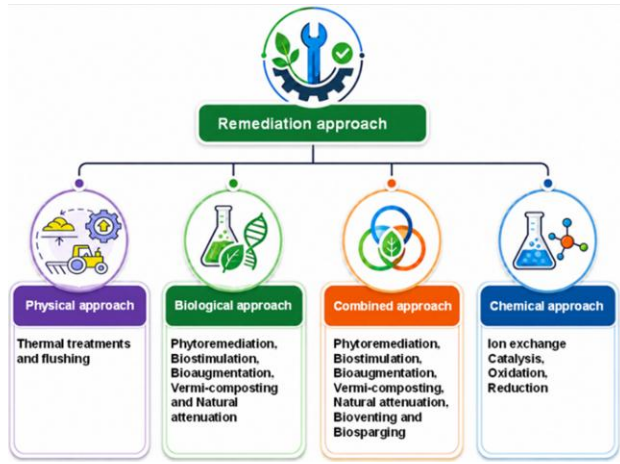

Fig. 2: Evolution of conventional and emerging soil remediation technologies. The figure summarizes the progression of soil remediation approaches from traditional physical and chemical technologies (*e.g.*, soil replacement, soil washing, thermal desorption and stabilization) to advanced biological and integrated remediation strategies

improves bioremediation performance by enhancing nutrient retention, microbial habitat stability, and contaminant sorption, thereby contributing to more efficient and environmentally friendly remediation systems (Nwankwegu *et al.* 2022b). The revolution and development of remediation practices of soil are being driven by various approaches, and innovative ways of employing the current technological approaches have been shown in Fig. 2.

Remediation of heavy metal pollution

Wan *et al.* (2020) evaluated the effectiveness of five different methods of treating a planting area of wheat, and while remediating the soils with a physical method yielded the greatest overall risk reduction, using phytoextraction also resulted in the highest level of environmental performance. Another investigation suggested that the repetitive nature of risk assessments and evaluations of remediation performances is a necessary component of the overall management of heavy metal contamination in soils; thus, developing both a scientific approach and a long-term approach to the use of effective technologies is essential (Saxena *et al.* 2020).

There are three main remediation strategies for heavy metal pollution in agricultural soils: removal of the total concentration of metals from the soil, control of bioavailability of the metals, and control of movement of metals within biological systems, as outlined by Hu *et al.* (2018). The primary methods currently being used to remediate heavy metal-contaminated agricultural soils include physical, chemical, biological, and combined remediation methods. Cost evaluation of each type of remediation technology must include both direct costs (equipment purchase, operation/maintenance, material costs, and labour costs) and indirect costs (monitoring, management of secondary pollution created by remediation, and disposal of equipment) in addition to time cost factors. Additionally, it is important to assess the practical viability of remediation technologies as well as the amount of time required to complete remediation using those technologies. Over the last few years, combined remediation methods have advanced the fastest among methods of remediating heavy metal-contaminated agricultural soils, with increased rates of success for the removal of heavy metals from contaminated soils (Mai *et al.* 2025). The transport of heavy metals between soil and environment has been shown in Fig. 3.

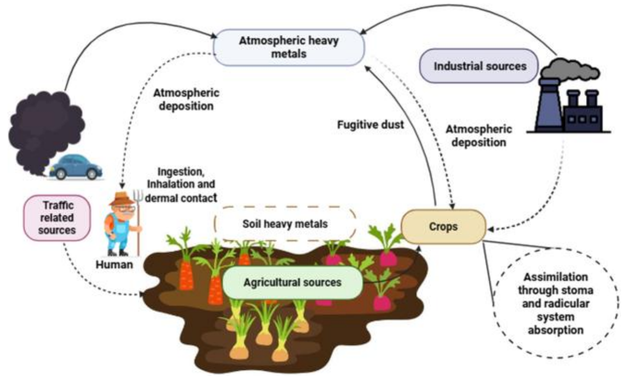

Fig. 3: Pathways of heavy metal transport and accumulation in the soil–plant–environment system. The figure illustrates the major routes through which heavy metals enter, migrate, and accumulate within agricultural ecosystems. Sources include industrial emissions, mining activities, wastewater irrigation, fertilizers, and atmospheric deposition

Physical remediation technologies

Engineering measures: Engineering approaches for remediating contaminated soils include soil blending, soil replacement, and soil turning (also referred to as soil mixing or inversion). Soil blending involves the uniform mixing of contaminated soil with clean soil or clean topsoil to dilute the concentration of contaminants, particularly heavy metals, thereby reducing their overall environmental risk. Soil replacement refers to the complete excavation of contaminated soil followed by its replacement with clean soil or suitable backfill material, while the excavated contaminated material is subjected to separate treatment or disposal. Soil turning involves the mechanical inversion of soil layers, bringing less contaminated subsurface soil to the surface and mixing it with more contaminated upper layers to redistribute and reduce contaminant concentrations in the root zone (Liu *et al.* 2021). These three approaches are quite simple, yet they can dramatically reduce the contaminant levels in soils. Each of these methods has the potential to alter the soils' physical structures, thus reducing the amount of nutrients available to plant root systems, causing a reduction in crop production. The expense associated with these soil remediation techniques also limits their application to smaller contaminated locations (Mai *et al.* 2025).

Electrokinetic remediation: Electrokinetic (EK) remediation is an in situ soil decontamination technology that relies on the application of a low-intensity direct electric field to induce the movement of charged species within the soil matrix. The primary transport mechanisms include electromigration of ionic contaminants, electroosmosis of pore water, and electrophoresis of colloidal particles, enabling the mobilization of metals and other charged pollutants toward oppositely charged electrodes. As contaminants migrate, they accumulate in electrode zones where they can be extracted and subsequently treated. Despite its applicability to low-permeability soils and fine-grained matrices, the efficiency of EK remediation is strongly influenced by several operational constraints. These include the development of pH gradients near the electrodes due to electrolysis reactions, which can affect contaminant speciation and mobility; relatively high energy consumption during prolonged operation; and electrode fouling or scaling, which can reduce system efficiency over time. In addition, soil buffering capacity and heterogeneity can further limit contaminant transport and overall remediation performance (Mai *et al.* 2025).

Yang *et al.* (2024b) conducted a comparison of the capacity to extract cadmium in contaminated soils through stainless steel, titanium, and graphite electrodes, and concluded that the application of graphite achieved a significantly higher removal efficiency (73.0% removal efficiency) than titanium (40.0%) and stainless steel (44.0%). The superior performance of graphite electrodes can be explained by their greater capability to create an electrochemical interface for the transfer of electrons, resulting in a greater formation of H^{+} ions that assist in cadmium desorption and migration. Longer (120 h) and stronger electric fields (increasing from 2.5 to 3.0 V/cm) resulted in improved efficiencies (10.6%) for cadmium removal. Remediation efficiencies will vary with soil types and will typically be more favorable when applied to low-permeability, clay-type, and/or silty soils (Peng 2019). The addition of chemical agents, such as inorganic and/or organic acids or chelating agents, keeps heavy metals in solution and enhances the overall effectiveness of EK remediation (Tsui *et al.* 2022).

Thermal desorption technology: Thermal desorption is an ex situ soil remediation technique that removes volatile and semi-volatile contaminants by applying controlled heat to contaminated soils. The heating process increases the vapor pressure of contaminants, enabling their volatilization and subsequent capture through off-gas treatment systems. While this technology is most commonly applied for organic pollutants such as petroleum hydrocarbons, it can also be used for certain volatile metal(loid) species, including mercury (Hg), arsenic (As), and selenium (Se), depending on their chemical form and soil conditions. The efficiency of thermal desorption depends strongly on operational parameters such as temperature, residence time, and soil properties, which influence contaminant volatilization and mass transfer. In some experimental studies, additives such as iron-based compounds (*e.g.*, $FeCl_3$) have been explored to enhance the removal of specific metal species by promoting their conversion into more volatile or extractable forms under controlled conditions. However, the effectiveness of such amendments is highly system-specific and depends on soil type, contaminant speciation, and treatment conditions. Although thermal desorption can achieve high removal efficiencies under optimized conditions, its application at field scale is limited by high energy requirements, operational costs, and the need for efficient off-gas treatment systems to prevent secondary air pollution (Zhu *et al.* 2024).

In a study, a drum-style, electric thermal desorption apparatus with built-in controls was used to perform thermal desorption on agricultural soils surrounding a mercury-based processing plant. The maximum removal of mercury was 96.2% when the temperature of the desorbed material was set at 400°C, the time of treatment was set at 30 min and the ratio of $FeCl_3$ to the concentration of mercury in the soils was set to 150. The optimal conditions for the removal of cadmium were determined to be a ratio of $FeCl_3$ to cadmium of 150, a temperature of 450°C, and a treatment duration of 20 min (Mai *et al.* 2025).

Chemical remediation technologies

In-situ chemical stabilization method: In-situ chemical stabilization is a targeted remediation approach that involves the application of passivating amendments to contaminated soils to reduce the mobility and bioavailability of heavy metals. These amendments promote transformation of metal species into less soluble, less mobile, or more strongly sorbed forms, thereby decreasing their uptake by plants and entry into the food chain. A wide range of materials has been used for this purpose, including waste-derived amendments such as biochar and biomass-based functionalized materials, industrial by-products such as calcium carbide slag, steel slag, and fly ash, as well as mineral-based materials including dolomite, hydrotalcite, zeolite, and gypsum-based products. In addition, nanomaterials such as nanoscale zero-valent iron (nZVI) have demonstrated strong potential for immobilizing heavy metals through reduction, adsorption, and co-precipitation mechanisms. Although in-situ stabilization can significantly reduce the immediate bioavailability of heavy metals, the immobilized forms are not always permanently stable. The long-term effectiveness of this approach depends on soil aging processes, during which stabilized metals may undergo gradual changes in speciation and binding strength. Remobilization can occur under changing environmental conditions such as soil acidification, redox fluctuations (*e.g.*, waterlogging or drying–wetting cycles), and the presence of plant root exudates that can complex or mobilize bound metals. Therefore, while stabilization reduces short-term risk, its long-term reliability requires careful site monitoring and consideration of potential reactivation pathways under dynamic soil conditions (Mai *et al.* 2025).

In a study, it has been evaluated how to use lime and phosphate fertilizer (calcium superphosphate) as individual passivators to stabilize lead, copper, cadmium, and zinc in soil. The addition of lime at 2% (w/w) to the soil raised the pH of the soil from 3.95 to 6.15, allowing lead and copper in the soil to be stabilized at a rate of 99.8%. The stabilization of cadmium in the soil was complete at a rate of 98.5% and zinc was stabilized to a rate of 99.4%. The use of phosphate fertilizer at the molar ratio of phosphorus: lead = 0.6 without lime was able to stabilize lead at a rate of 95.7%, but had little or no effect on stabilization of copper, cadmium, or zinc. While phosphate fertilizer is useful to reduce the availability of heavy metals, this method will not physically remove heavy metals from the soil, only change the chemical form of the heavy metals and make them temporarily unavailable to plants. Therefore, long-term monitoring must be conducted so that the stability of the immobilized heavy metals can be determined, thus increasing energy needs and costs of remediation (Wu *et al.* 2022a).

Chemical leaching method: In the chemical leaching method, contaminated soil is flushed with a leaching agent that mobilizes heavy metals from the solid phase into the liquid phase through dissolution, complexation, or ion exchange reactions. The mobilized contaminants are subsequently collected from the effluent and treated in a controlled system. Common leaching agents include ferric chloride ($FeCl_3$), ethylenediaminetetraacetic acid (EDTA), citric acid, nitric acid, and acetic acid. Among these, citric acid and ferric chloride are generally considered more environmentally compatible due to their relatively lower persistence and reduced long-term impact on soil properties. However, the use of strong synthetic chelating agents such as EDTA raises environmental concerns. EDTA is highly persistent in soils and natural waters, and its strong complexation capacity can lead to the formation of stable metal–EDTA complexes that are highly mobile in the subsurface environment. This increases the risk of metal leaching into groundwater and may extend contaminant transport beyond the treatment zone. In addition, the spent leachate generated during chemical leaching requires careful collection and treatment to prevent secondary pollution, as it contains concentrated metal–chelate complexes and residual reagents that can pose environmental hazards if improperly managed (Wang *et al.* 2022c).

A study has been conducted on oscillatory leaching tests utilizing EDTA at different concentrations at a 15:1 liquid-to-soil ratio. Based on the results, as the concentration of EDTA increases, the cadmium removal efficiencies also increase to a maximum of 83.6% at an EDTA concentration of 0.1 mol/L and subsequently decrease in removal efficiency with increasing concentrations, indicating that inhibitory effects occur at concentrations greater than 0.1 mol/L EDTA (Wu *et al.* 2022b). Another study evaluated the chemical leaching process and estimated, taking into account the cost of leaching agents, reducing agents, and the waste treatment process, that the total cost would be approximately $121.92 per ton (USD). This cost is significantly less than that of electrochemical flushing and reduction, which would be approximately $206.88 per ton (USD). Chemical leaching is easy to implement, but it adversely affects the soil structure and plant nutrient levels (Wang *et al.* 2021).

Bioremediation technologies

Phytoremediation: Phytoremediation is a sustainable remediation technique that utilizes plants to absorb, transform, or immobilize soil pollutants. The main phytoremediation mechanisms include phytoextraction, phytostabilization (phytofixation), and phytovolatilization. Phytoextraction refers to the uptake of contaminants, particularly heavy metals, from soil through plant root systems and their subsequent translocation and accumulation in above-ground plant tissues. Once absorbed, metals are stored in cellular compartments such as vacuoles, cell walls, or complexed with ligands to reduce their toxicity. The contaminated plant biomass is then harvested and subjected to appropriate disposal or metal recovery processes. Despite its environmental advantages, phytoremediation has several inherent limitations. The process is generally slow and may require multiple growing seasons to achieve significant contaminant reduction, particularly in soils with high pollution loads. In addition, the disposal or treatment of contaminated biomass presents a major challenge, as improper handling may lead to secondary environmental contamination. There is also a potential risk of entry of accumulated contaminants into the food chain if non-target or edible plant species are used or if site management is inadequate. These factors limit large-scale applicability and necessitate careful selection of plant species and site-specific management strategies (Luo *et al.* 2025).

Phytoextraction depends on finding hyperaccumulator plants that will thrive under heavy metal conditions. The commonly used hyperaccumulator plants are *Solanum nigrum* L., *Bidens bipinnata* L. and *Pteris vittata* L. (Mai *et al.* 2025). Among those, *Solanum nigrum L.* has shown a high resistance to cadmium even when it is grown in a single contaminated soil, demonstrating concentrations of cadmium of 31.8 mg/kg in the aerial parts of the plant and 27.8 mg/kg in the root. The cadmium enrichment coefficient in the shoots was reported as 3.17 with minimal effects on the plant's growth. Instead of lowering the overall concentrations of heavy metals, phytostabilization aims to decrease their mobility and bioavailability through processes like root uptake, oxidation, and precipitation. Willow species, such as *Salix viminalis* L. and *Salix purpurea* L. have a high tolerance to heavy metal ions and can effectively immobilize contaminants. Phytovolatilization is the process by which plants absorb volatile heavy metals, transform them biochemically into less hazardous forms, and then release them into the atmosphere (Zhao *et al.* 2023).

Microbial remediation: Microbial remediation is the use of metabolically active microorganisms in order to decrease heavy metal concentrations within soils by transforming them into less toxic forms *via* adsorption and transformation mechanisms. Microbial adsorption occurs by accumulating heavy metals in soils based upon the contributions of both living and nonliving (inactive) metal-metabolizing organisms (*e.g*., fungi, bacteria, archaea, yeasts, *etc*.). Several types of microalgae, fungi, and yeasts have demonstrated a strong ability to absorb heavy metals from contaminated soils (Yan *et al.* 2021).

Microbial transformation involves the biochemical conversion of heavy metals into less toxic or non-toxic species *via* mechanisms such as oxidation-reduction, complexation, methylation, and demethylation. Microbial-based cleanup strategies are highly effective for the biotransformation of soils contaminated by heavy metals. For example, a study demonstrated that the *Aspergillus niger* strain SY1 was capable of removing 75.0% Cr (VI) from soils at an initial concentration of 250 mg/kg after 15 days. Analogously, the leaching efficiency of *Aspergillus niger* for soils simultaneously contaminated by a mixture of heavy metals demonstrated that the optimal conditions (substrate concentration of 20 g/L, sugar concentration of 100 g/L, and spores concentration of 2×10^7 individuals/mL) resulted, after 8 days, in leaching efficiencies of 93.5% for Cd, 11.4% for Pb, 62.3% for Cu, and 68.2% for Zn. This information shows that the *Aspergillus niger* strain SY1 represents a promising bio-alternative for the cleanup of dredged sediments contaminated by heavy metals (Diao *et al.* 2019). Furthermore, it has been demonstrated that *Rhodobacter sphaeroides* can convert Cd into the less toxic compound CdS through intracellular chemical reactions, *Bacillus sphaericus* can remove about 60.0% of Pb from soil, and *Citrobacter* species can adsorb about 40.0% of Cr (Mai *et al.* 2025).

Bacteria, fungi, and algae have wide distribution, high growth rates, and easy cultivation. Therefore, microbial remediation has cost benefits (Yin *et al.* 2019). Microbial remediation is another important field of research in the study of soil remediation due to the benefits in the process, which include: easy operational procedures, small secondary pollution, minimal disturbance of soil structural properties, and high purification efficiency. As a rule, this method demands a significant purification period and the impact of microorganisms on the plant development in agricultural fields has not been investigated.

Animal remediation: The primary animal-based remediation involves the use of particular organisms which live in the soil and which digest the heavy metal contaminants into their bodies, and which help in cleaning up the soil. For this reason, earthworms that are one of the most common detritivore organisms in soil ecosystems are commonly studied.

Earthworm can tolerate heavy metals and daily activities of earthworms could consume soil up to five to thirty times their body weight. They have special chloragogen tissues in their bodies which enable heavy metals to be stored and retained. There exist profound limitations of animal-based remediation methods along with these advantages, and a lack of research in this area is also still a problem (Mai *et al.* 2025).

Combined remediation technologies

Electrokinetic-permeable reaction barrier (EK-PRB) technology: Nowadays, there is a focus on the integrated technology of electrokinetic permeable reactive barriers (EK-PRBs) due to its extremely efficient separation of the heavy metals in polluted soil. This technique is based on two steps; the first is electrokinetic remediation, which involves the extraction of contaminants out of soil using an electric field; and the second one is the use of permeable reactive barriers (PRBs) that can be used to extract or destroy chemicals by adsorption, precipitation, redox reaction, or biodegradation. The contaminants that move towards the PRB under the influence of an electric field get immobilised or degraded at the PRB. The moisture level of the soil and permeable reactive barrier, remediation duration, choice of electrode and electrolyte, pH and voltage gradient are considered as the factors that have a significant influence on the effectiveness of an EK-PRB remediation system (Neshati *et al.* 2023). The use of PRBs has many cost-effective alternatives that have been investigated to be used as PRBs materials such as activated carbon, fly ash, and attapulgite-nano iron bimetallic composite. As an example of remediating heavy metals *via* EK-PRB technology, Li *et al*. (2024) have shown that an increase in voltage gradient causes higher removal rates of cadmium. Fly ash/yeast pellets achieved a Cd removal rate of 53.7% at 2.50 V/cm compared to only fly ash used as a PRB. Therefore, PRB's operating parameters need to be optimised based on interacting parameters (*i.e*., effective remediation *vs*. chemical, material, and energy costs), especially for farmland remediation. Overall, EK-PRB technology offers significant advantages over conventional electro-kinetic methods in terms of better in-situ removal of heavy metals through the interception or transformation of the metals, and thus presents a viable technology for remediation of contaminated sites.

Electric-microbial combined remediation technology: During the conventional EK treatment of heavy metal-contaminated soil, precipitation may commonly take place in the cathodic zone; thus, the migration efficiency of the metals may be impeded. To overcome the above limitations, a new technology called combined electric-microbial treatment has been proposed and practiced in recent years. During combined electric-microbial treatment, contaminants can be removed through electromigration, electroosmosis, and electrophoresis based on an externally applied electric field; moreover, metal reduction *via* the cathodic reduction mechanism may be accelerated due to microbial action (Yan *et al.* 2021).

In a study, a voltage gradient of 1 V/cm for soils contaminated with cadmium-resistant bacteria (*Escherichia coli*, *Bacillus* spp. and *Bacillus cereus*) has been used for a period of 10 days in EK experiments to remove cadmium. The results indicate that the efficiency of cadmium removal was raised by 7.63%, 17.2% and 19.5% for *Bacillus* spp., *Bacillus cereus* and *Escherichia coli*, respectively, than that in normal EK process for cadmium pollution removal, in addition to lowering the power cost by 64.8, 109.5 and 116.5 kW·min/mg, respectively (Mai *et al.* 2025). The comparative overview of remediation technologies for heavy metal pollution in agricultural soils is given in Table 1.

Remediation of microplastic pollution

In terrestrial ecosystems, the breakdown of microplastics (MP) is a cooperative process that involves both biotic (such as microbial enzymatic depolymerization, mineralization, and assimilation) and abiotic (such as thermal oxidation, photo-oxidation and polymer hydrolysis). Biotic degradation, especially microbial-mediated processes, offers more potential for further plastic mass reduction through biochemical mineralization and surface adsorption than abiotic pathways. MP depolymerization is accelerated by some enzymes, including laccase, manganese peroxidase, lignin peroxidase, and hydrolases like lipases, esterase, and cutinases. Microbial strains that can use plastics as a carbon source have been reported in a growing number of studies in recent years. These results show that microbioremediation shows promising potential for removing MP from soils, but research in this field is still in its infancy (Hou *et al.* 2022). The process of microbioremediation of microplastics is shown in Fig. 4.

Fungal bioremediation of microplastics: Fungi are among the most promising microbial agents for microplastic (MP) degradation due to their high species diversity and versatile enzymatic systems capable of acting on complex polymeric structures. Their filamentous growth form allows efficient surface colonization of plastic particles, enabling close physical interaction that facilitates biodegradation. The degradation process is generally initiated by the secretion of extracellular enzymes that induce surface modification and oxidation of polymer chains, weakening the structural integrity of microplastics such as polyethylene (PE) and polystyrene. Following initial surface oxidation, fungal enzymes, including oxidases, peroxidases, and hydrolases, contribute to depolymerization by breaking long polymer chains into lower-molecular-weight fragments. These smaller intermediates can then be further metabolized through intracellular pathways, ultimately leading to partial or complete mineralization under favorable conditions, producing end products such as carbon dioxide, water, and trace gases (Jesus and Alkendi 2022).

Table 1: Comparative overview of remediation technologies for heavy metal pollution in agricultural soils

Technology / Approach	Primary Mechanism(s)	Advantages	Limitations	Field Applicability and Scalability	Estimated Relative Cost	Future Prospects / Research Needs
Soil Replacement / Blending / Turning	Dilution, excavation, redistribution	Rapid, straightforward	Alters soil structure & fertility; high disturbance	High for small sites; low for large fields	High	Precision techniques with minimal disturbance (Liu *et al.* 2021; Mai *et al.* 2025)
Electrokinetic (EK) Remediation	Electromigration, electroosmosis	Effective in low-permeability soils; in-situ	pH gradients, high energy use, electrode fouling	Moderate; graphite electrodes achieve 73.0% Cd removal *vs.* titanium (40.0%)	Medium to High	Hybrid systems with real-time control (Yang *et al.* 2024b; Mai *et al.* 2025)
Thermal Desorption	Volatilization *via* heating	High removal for volatile metals (Hg, As)	Energy-intensive; secondary air pollution	Low–Moderate; ex-situ preferred	High	Additive-enhanced and renewable energy integration (Zhu *et al.* 2024; Mai *et al.* 2025)
In-situ Chemical Stabilization	Precipitation, adsorption (lime, phosphate, nZVI, biochar)	Low disturbance; rapid bioavailability reduction	Long-term stability uncertain; possible remobilization	High; 2% lime stabilizes Pb/Cu up to 99.8% and Cd up to 98.5%.	Low–Medium	Stable long-term amendments and monitoring (Wu *et al.* 2022a; Mai *et al.* 2025)
Chemical Leaching / Soil Washing	Dissolution & complexation (EDTA, citric acid)	High removal efficiency	Wastewater generation; soil damage	Moderate; requires effluent treatment setups. Achieves 83.6% Cd removal at 0.1 mol/L EDTA	Medium	Greener chelants and closed-loop recovery (Wu *et al.* 2022b; Wang *et al.* 2022c)
Phytoremediation	Phytoextraction, phytostabilization	Eco-friendly, low cost, soil health improvement	Slow process; biomass disposal issues	High for large areas; hyperaccumulators like *Solanum nigrum L.* store 31.8 mg/kg Cd in shoots	Low	Hyperaccumulator breeding + PGPR synergy (Luo *et al.* 2025; Mai *et al.* 2025)
Microbial Remediation	Biosorption, biotransformation	Sustainable, low secondary pollution	Slow; variable efficacy	Moderate to High; *Aspergillus niger* SY1 removes 75.0% Cr(VI) within 15 days.	Low	Engineered consortia & metagenomics (Diao *et al.* 2019; Mai et al. 2025)
EK-PRB	EK transport + reactive barrier	Synergistic removal; in situ	Operational complexity	Promising; fly ash/yeast pellet barriers hit a 53.7% Cd removal rate at 2.50 V/cm.	Medium	Optimized low-cost PRB materials (Li *et al.* 2024; Yang *et al.* 2024b)
Electric-Microbial Combined	EK + microbial acceleration	Higher efficiency than EK alone	Scaling & microbe compatibility	Emerging; *E. coli* and *Bacillus cereus* boost Cd removal by 19.5% and 17.2%.	Medium	Field trials in multi-contaminant soils (Yan *et al.* 2021; Mai *et al.* 2025)

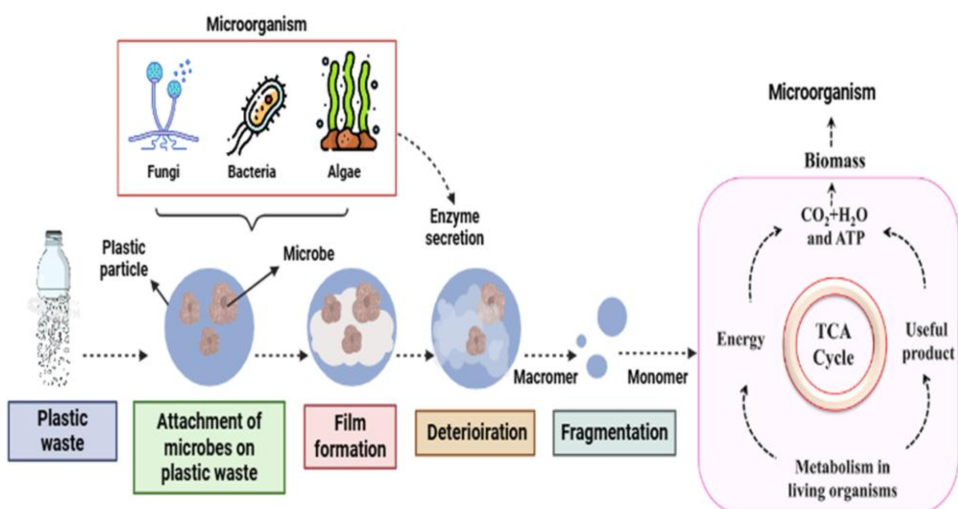

Fig. 4: Mechanisms of microbioremediation of microplastics (MPs) in soil environments. The figure depicts the major stages involved in microbial degradation of microplastics, including microbial colonization, biofilm formation, extracellular enzyme secretion, polymer depolymerization, formation of low-molecular-weight intermediates, microbial assimilation, and final mineralization

A study conducted by Paço *et al.* (2017) showed that hyphal (vegetative) growth of the fungus *Zalerion maritimum* could metabolize polyethylene microplastics by utilizing extracellular enzymes, including hydroxylases, as well as intracellular enzymes that function through a proteolytic enzyme mechanism. Additionally, studies conducted by Zhang *et al.* (2020) demonstrated that the filamentous fungus *Aspergillus flavus* PEDX3 was also capable of degrading high-density polyethylene (HDPE) and low-density polyethylene (LDPE) by secreting extracellular enzymes that hydrolyzed hydrolysable alkanoates, resulting in the release of carbon dioxide, water, and molecular hydrogen. Although there are several studies that have shown that fungi can metabolize MP material, there remains an analytical gap in terms of understanding how exactly fungi degrade MP material. Also, although a number of studies have shown that these fungi are able to metabolize polymeric material (PE), there are extremely limited studies that can prove that polymers can be fully decomposed. This implies that this knowledge gap needs to be filled through further studies and the entire topic of how fungi break down MP material should be investigated (Chandel *et al.* 2025a).

Bacterial bioremediation of microplastics: The idea of bacterial remediation of the polluted soil with microplastic is a developing topic that has recently demonstrated capabilities as an intervention strategy to plastic pollution. Like fungi, bacterial cells are also able to decompose plastic into monomeric units to produce methane under anaerobic conditions and carbon dioxide and water under aerobic conditions (Chandel *et al.* 2025a). Different bacterial communities have been reported to be efficiently involved in plastic pollution degradation. These are the *Bacillus* spp. and *Paenibacillus* spp. of the phylum *Firmicutes, Streptomyces* spp. of the phylum *Actinobacteria* and *Pseudomonas* spp. of the phylum *Proteobacteria*. Other than the established *Firmicutes* and *Proteobacteria* groups of bacteria, actinomycetes have been emphasized as a promising agents in the elimination of MPs (Zhang *et al.* 2021). *Actinomycetes* are filamentous bacteria that have been known to synthesize a wide variety of extracellular hydrolytic enzymes whose activity has the capacity to break down complex polymeric materials. The actinomycete bacterial groups have had a lot of potential in degrading various MPs among them *Streptomyces* spp. This was demonstrated by Ameen *et al.* (2025), who reported the degradation of Polyvinyl chloride (PVC) MPs by *Streptomyces gobiticini*. *Streptomyces gobiticini*-derived biofilms were observed to enhance the physical degradation of MPs. This occurred primarily because of the generation of the different bacterial hydrolytic enzymes.

Further evidence of bacterial MP degradation is also provided by Auta *et al.* (2017) who tested two types of bacteria, namely *Bacillus cereus* and *Bacillus gottheilii. B. cereus* resulted in 1.6, 6.6, and 7.4 percent of MP weight losses in polyethylene (PE), polystyrene (PS) and polyethylene terephthalate (PET). On the other hand, a degradation of PE, PET, polypropylene (PP), and PS was reported by *Bacillus gottheilii* as 6.2, 3.0, 3.6 and 5.8 percent, respectively. Moreover, the enhanced degradation efficiencies have been demonstrated in the mixed communities of the bacteria. As an example, the *Pseudomonas putida* that was isolated in the agricultural soil could degrade 92 percent of polyurethane (PU), in the form of Impranil DLNTM, after four days through the activity of a 45 kDa esterase (Lin *et al.* 2022). Moreover, the PET and the monomers were effectively hydrolyzed by a bacterial culture of *Ideonella sakaiensis* through the joint activity of two enzymes: the ISF6 4831, an alleged PET-hydrolyzing lipase, and ISF6 0224, a tannase, which breaks down mono (2-hydroxyethyl) terephthalic acid (Yoshida *et al.* 2016).

Plant growth-promoting rhizobacterial (PGPRs) bioremediation of microplastics

Microplastics (MPs) can only be biologically depolymerized by different and specialized microbial communities that have adapted to select ecological niches. Plant growth-promoting rhizobacteria (PGPRs) are some of these microorganisms that have received growing interest not only due to their proven ability to increase plant growth, but also due to their newfound interest in the cleansing of MP-contaminated soils. This is a new approach of bioremediation that takes advantage of the multifunctional nature of PGPRs to mitigate the environmental effects of MPs (Khan *et al.* 2024).

Plant growth-promoting rhizobacteria develop symbiotic relationships with plants, especially in the rhizosphere, where they control nutrient absorption and regulate the rhizosphere (Sushila and Sanya 2023). Besides the growth-promoting functions, some strains of the PGPR have enzymatic functionalities directly involved in the degradation of MPs. Enzymes produced by the PGPRs, including esterases and lipases, can break down complex polymer structures, converting the MPs to less toxic degradation products. In addition, the polymer degradation may involve the use of intermediate compounds that are detoxified with the help of PGPRs (Olabemiwo *et al.* 2024).

PGPRs also control the root exudate composition, which subsequently defines rhizosphere communities. These modifications can activate microbial activity linked to the breakdown of MP. In addition to remediation, the interactions between PGPR and plants promote the health of plants, including their resistance to diseases, and their tolerance to stress, useful especially in conditions of MP-pollution (Behera and Das 2023). Since the use of PGPRs in agriculture is already well established in the form of biofertilizers and biopesticides, their use in bioremediation of soil is an environmental friendly and combined approach to the control of the MP contamination (Sharma *et al.* 2023). Indicatively, *Bacillus spizizenii* has been documented to serve as a PGPR by producing indole-3-acetic acid, solubilizing phosphate, and improving the nitrogen metabolism, and at the same time degrading polystyrene MPs. Even though most of the existing evidence is founded on *in vitro* research, more studies are needed in order to determine its efficacy in the field in various crop systems. On the same note, the *Bacillus amyloliquefaciens* strain, L381, has been shown to degrade phthalates and promote stress resistance in *Oryza meridionalis* in a period of five days (Liu *et al.* 2022).

Table 2: Comparative overview of bioremediation technologies for microplastics (MPs) in agricultural soils

Technology / Approach	Primary Mechanism(s)	Advantages	Limitations	Field Applicability and Scalability	Estimated Relative Cost	Future Prospects/Research Needs
Fungal Bioremediation	Hyphal colonization + extracellular enzymes (peroxidases, hydrolases) for polymer chain breakdown	Versatile enzymatic systems; strong surface colonization of hydrophobic MPs (PE, HDPE)	Slow rates; limited evidence of complete mineralization; mechanisms not fully understood	Low to Moderate (mostly lab/pilot scale)	Low	Clarify degradation pathways and confirm full mineralization (Paço *et al.* 2017; Zhang *et al.* 2020; Chandel *et al.* 2025a)
Bacterial Bioremediation	Biofilm formation + enzymatic hydrolysis (esterases, lipases); metabolic assimilation of monomers	High metabolic diversity; mixed consortia show significantly higher efficiency	Low weight loss with single strains; strain- and MP-type specific	Moderate (better when isolated from contaminated soil)	Low	Develop stable mixed bacterial consortia for synergistic degradation (Yoshida *et al.* 2016; Auta *et al.* 2017; Ameen *et al.* 2025)
PGPR-Assisted Bioremediation	Rhizosphere colonization + secretion of esterases/lipases + plant growth promotion	Dual benefit (MP degradation + enhanced plant health and stress tolerance)	Mostly *in vitro* data; uncertain field survival due to competition	Promising but Emerging	Low	Extensive multi-crop field trials and long-term performance validation (Liu *et al*. 2022; Khan *et al.* 2024; Chandel *et al.* 2025a)
Enzymatic (Cell-Free) Degradation	Direct action of purified enzymes (cutinases, lipases, esterases)	Targeted action; no need to maintain live microbes in toxic environments	High production cost, enzyme instability and short activity in soil	Low (lab-scale mainly)	Medium–High	Enzyme engineering and immobilization on carriers for soil use (Hou *et al.* 2022; Jesus and Alkendi 2022)
Integrated Microbial Consortia	Synergistic fungal–bacterial–PGPR interactions	Higher overall efficiency; better adaptation and stress resistance	Complex dynamics and risk of competitive exclusion	Moderate (emerging)	Low–Medium	Development of stable synthetic consortia and long-term field monitoring (Lin *et al*. 2022; Chandel *et al*. 2025a)

In general, the synergistic interactions among PGPRs, plants, and rhizosphere microorganisms provide potential solutions to reduce the negative impacts of MP contamination on the health of the soil and the growth of plants. However, there are still a number of challenges to the maximization of this method, and subsequent research ought to strive to rectify these gaps so that the potential of microbioremediation can be fully achieved. In line with this, the challenges that are currently present as well as the prospects of future developments in promoting MP bioremediation strategies are discussed in the further sections (Chandel *et al.* 2025a). The comparative overview of bioremediation technologies for microplastics (MPs) in agricultural soils is given in Table 2.

Remediation of polycyclic aromatic hydrocarbons (PAHs) from soil

Polycyclic aromatic hydrocarbons (PAHs), also known as aromatic polycycles, are organic compounds that contain at least two fused aromatic rings. They are generated through industrial activities, which include fossil fuels and compound organic matter that has not been thoroughly burned. Because of toxicity, persistence, and a characteristic of accumulating in an organism, which makes them particularly detrimental to environments and human life, these organic compounds are considered priority ones by human health and safety regulators. Their non-degradable nature also contributes to making their cleanup in soils a rather complicated process (Guo *et al.* 2025).

Bioremediation of Polycyclic Aromatic Hydrocarbons (PAHs)

Fungi: PAHs can be used as an energy source by the mechanisms of co-oxidation by yeasts and molds, and the material is converted into their less toxic and simpler forms (Vijayanand *et al.* 2023). Fungi are generally more adaptable to diverse soil conditions than bacteria and possess broad enzymatic capabilities that enable them to degrade a wide range of organic contaminants, including high-molecular-weight PAHs that are often more resistant to bacterial degradation (Dai *et al.* 2023). Degradation of PAHs by fungi mostly takes place in the form of extracellular enzyme secretion. The enzymes involved in the breakdown of lignin, such as manganese peroxidase, lignin peroxidase, laccase, and cytochrome P450 synthesized by the wood-rot fungi, are important in the breakdown of PAH (Imam *et al.* 2022).

Furthermore, the non-wood-rot fungi can also degrade PAHs *via* cytochrome P450-mediated routes. These enzymes are highly stable and promote oxidation and adsorption of PAHs, decrease hydrophobicity, enhance desorption of soil particles, and transform PAHs to more accessible forms of carbon. Conversely, when using non-ligninolytic fungi, *i.e*., those that produce cytochrome P450 enzyme, the PAHs are oxidized to produce epoxide intermediates and water (Wójcik *et al.* 2022). The fungi that are commonly associated with plants in the soil impact the movement and transformation of PAHs in the soil. Furthermore, fungal mycelia have the potential to adsorb and translocate PAH molecules, which serve as carriers of bacteria and phages, increasing the bioavailability of PAH as well as promoting the microbial degradation mechanisms (You *et al.* 2022).

Bacteria: Bacteria can degrade PAHs both in anaerobic and aerobic conditions. In the aerobic process, molecular oxygen is the ultimate electron acceptor, and it promotes the breaking of PAH molecular bonds throughout the degradation process (Srivastava and Kumar 2019). Conversely, in an anaerobic environment, oxygen is substituted by other electron acceptors, which include iron and manganese ions, sulfur- and nitrogen-based compounds, perchlorate, chlorate, carbon dioxide, fumarate, and trimethylamine oxide. Streptomyces, *Pseudomonas*, and *Mycobacterium* are some examples of soil-dwelling bacterial genera that are widely distributed and are important in the degradation of PAH (Lara-Moreno *et al.* 2021). These bacteria either directly or indirectly stimulate the breakdown of PAH by enzymatic processes into less toxic metabolites. As an example, *Sphingomonas* sp. PJ1 and *Mycobacterium* sp. WY10 recorded 74.3 percent and 70.2 percent phenanthrene degradation efficiency after 30 days of incubation, respectively. In natural soil, bacteria tend to work synergistically with other microbes, including the algae and fungi, and this community of microorganisms greatly increases the degradation of PAHs (Hu *et al.* 2025).

Algae: Algae can co-exist with a variety of microbial communities in soil environments and have demonstrated the ability to degrade even the most toxic PAHs, including benzo[a]pyrene, to less toxic intermediates, including diols and quinones. Nonetheless, the effectiveness of algal-mediated degradation of PAH is determined by a number of factors such as the species of algae, light intensity and duration of exposure, concentration of PAH, toxicity and degradation by-products (Touliabah *et al.* 2022).

Recent investigations have shown that removal of PAH by algae is initiated with electrostatic adsorption of PAHs onto algal cell walls through functional groups like hydroxyl, carboxyl, phosphate, and amino groups, and then enzymatic redox reactions occur, leading to the mineralization of PAHs into CO_2 and H_2O (Satpati *et al.* 2023). At low concentrations of PAHs, algal growth can be stimulated, thereby enhancing PAH degradation. Removal efficiencies of fluoranthene (FLT) of up to 58% have been reported under such conditions (Wiśniewska *et al.* 2023). On the contrary, high concentrations of PAH decrease chlorophyll contents and prevent the growth of algae, thereby lowering degradation efficiency. Therefore, microalgae have the potential to help in the remediation of PAH in a direct and indirect way, especially in synergistic relationships with PAH-degrading bacteria (Ghanbarzadeh *et al.* 2022).

Soil animal: Earthworms can contribute to PAH remediation by absorbing pore water and ingesting soil organic matter containing PAHs. Through their feeding and burrowing activities, earthworms enhance the bioavailability of PAHs and stimulate microbial degradation processes within the soil (Esmaeili *et al.* 2022). PAHs are also degraded by the action of bacteria (*e.g.*, *Pseudomonas* and *Acidobacterium*) and fungi (*e.g.*, *Penicillium*, *Mucor* and *Aspergillus*) that can be found in the gut of earthworms. Likewise, other microorganisms enhance the faster elimination of PAHs in the soil (Rajadurai *et al.* 2022). The extent of degradation of PYR was also increased 2.1-2.8 times compared to the degradation of PYR in the control, 45.5-91%. Besides, earthworm activities also improve the soil structure and aeration, the mobility of PAHs and its OM, the contact of soil particles and PAHs, and the decomposing activity of microorganisms on PAHs (Luo *et al.* 2022).

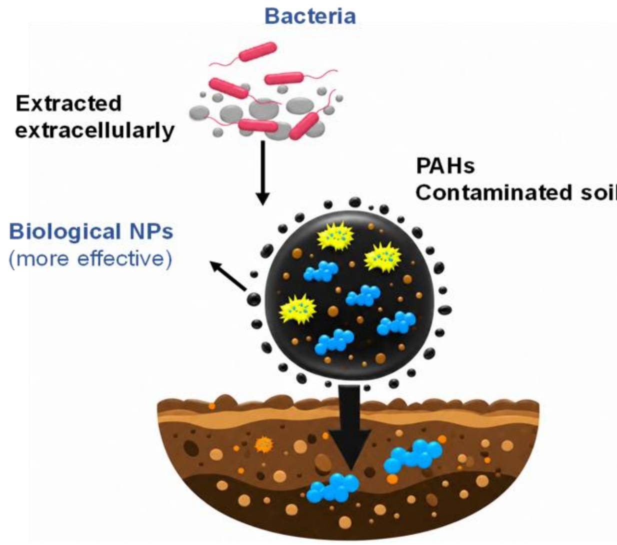

Fig. 5: Mechanistic pathways of nanoremediation for polycyclic aromatic hydrocarbons (PAHs) in contaminated soils. The figure illustrates the roles of nano-zero-valent iron (nZVI), metal oxide nanoparticles, and carbon-based nanomaterials in the adsorption, catalytic oxidation, reductive transformation, and degradation of PAHs. Nanomaterials enhance contaminant removal through increased surface area, improved electron transfer and generation of reactive species

Emerging remediation technologies

Nano-remediation of PAHs: Nano-remediation is one of the innovative and effective techniques of the eradication of polycyclic aromatic hydrocarbons (PAHs) in contaminated soils. There are several factors, including the nature of PAH, remediation method, the soil, contamination depth, and economic feasibility, that determine the selection of suitable nanomaterials (NMs). There are three general categories of nanomaterials used in the PAH remediation based on their functional properties, which are metal oxides, nano-zero-valent iron (nZVI), and carbon and polymer-based materials. The nano-remediation mechanism for PAHs using bacteria is shown in Fig. 5.

Carbon and polymer-based nanomaterials: Carbonaceous nanomaterials, including graphene, carbon nanotubes, fullerenes, and their derivatives, have been widely studied because they possess high surface area, hydrophobicity and pi-pi interactions with aromatic PAHs (Mehmeti and Sadiku 2022). Specifically, the most common application of graphene is due to its high thermal conductivity and high specific surface area. Research shows that PAHs adsorb parallel to the graphene surfaces, and the adsorption is determined by the π-π force, van der Waals force, electrostatic force, and the repulsion between the Pauli exclusions (Forján *et al.* 2020).

Nano-sulphonated graphene applied ex situ in the washing of soil showed an excellent adsorption of various PAHs, and multi-walled carbon nanotubes showed a high adsorption of naphthalene, fluorene, phenanthrene, and pyrene in various soils under ex situ conditions. Other nanomaterials, which are polymer-based (*e.g*., cross-linked urethane acrylate nanoparticles and Cu_2O/polylactic acid nanofibers), have also exhibited good solubilization and photocatalytic degradation of PAHs. Nonetheless, exposure to plants and microbes in the soil should be closely considered because it may have an ecological effect (Xu *et al.* 2020).

Metal oxide nanomaterials: Metal oxide nanoparticles are vital in the process of degrading PAH by photocatalytic oxidation and Fenton-like oxidation. Nano-Fe_3O_4, Fe_2O_3, TiO_2 and g-C_3N_4-composites have been reported to have high degradation rates of pyrene, phenanthrene, fluoranthene, chrysene, and benzo[a]pyrene. Iron-based nanomaterials are able to catalyze the degradation of PAH even with neutral pH conditions, whereas TiO_2-based photocatalysts catalyze the degradation of PAH under UV or visible light (Marquès *et al.* 2020). Some of the studies have reported that the efficiencies of degradation are above 80-90 percent using some of the PAHs, depending on the soil type, light intensity, and catalysts structure. The option to employ green nanomaterials to treat PAH is also supported by the fact that the green-synthesized metal hexacyanoferrate nanoparticles could be useful (Rani *et al.* 2019).

Nano-zero-valent iron (nZVI): Nano-zero-valent iron is the most popular type of nanomaterial in the cleanup of PAH-contaminated soil since it is highly reactive and with high affinity to PAHs (Mazarji *et al.* 2021). The nZVI possesses a larger surface area and faster reaction kinetics compared to the microscale zero-valent iron, and is hence more effective in removal. It has also been established that nZVI can increase the pyrene removal rates several fold through reductive transformation and change of the soil redox condition. Application of nZVI increases the pH of soil and creates extremely reducing environments, which are favorable for the decomposition of PAHs. Nevertheless, the surface oxidation and environmental stability are still problems of the long-term field application (Li *et al.* 2023).

CRISPR-engineered microbes: Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology has been shown to allow specific genetic editing of microorganisms, especially bacteria and archaea, and has become a potent technology to improve the biodegradation of polycyclic aromatic hydrocarbons (PAH). Due to the structural heterogeneity of PAHs, the degradation process has a variety of functional routes, and particular microbial strains are specific to certain compounds and metabolic pathways. In turn, synthetic microbial consortia have become popular in the PAH removal process because they allow metabolic separation and allocation of fluxes and, therefore, enhanced degradation (Cui *et al.* 2023a).

The development of gene sequencing and molecular biology has enabled the recognition of dominant strains and major functional gene modules, which would provide the opportunity to genetically engineer them to improve their PAH degradation. Bacteria have been extensively used in the bioremediation of PAH because of their metabolic flexibility, adaptability, short life cycles, and high affinity for PAHs (Premnath *et al.* 2021). Some of the common bacterial genera are *Bacillus*, *Pseudomonas*, *Rhodococcus*, *Mycobacterium*, and *α-, β-* and *γ-Proteobacteria*. Conversely, fungi tend to have less PAH affinity but have a facilitative effect by the provision of nutrients and supporting bacterial activity by extensive mycelial networks (Wang *et al.* 2022a).

Single or genetically modified bacterial strains may be useful; however, mixed microbial systems generally exhibit better degradation behavior based on functional diversity, a wider range of carbon metabolism, stronger stress resistance, and synergism. Nonetheless, overall efficiency may be curtailed by factors like the availability of substrate, microbial competition, as well as community stability (Cui *et al.* 2023b). Bacterial metabolic engineering *via* genetic engineering can also be used to further accelerate PAH biodegradation. The incomplete native pathways can be replaced by the introduction of complete degradation gene clusters, including phn and nah clusters. An example is the overexpression of the nah-H gene that encodes catechol 2,3-dioxylase, which has been demonstrated to stimulate the degradation of phenanthrene and pyrene in soil (Patel *et al.* 2019). Equally, recombinant strains have been shown to have increased PAH and alkane degradation capacities, *e.g*., *Acinetobacter* sp. *BS3-C23O* and genetically modified *Escherichia coli* expressing the P450-BM3 gene (Maxel *et al.* 2020). Overall, genetic modification improves the enzyme secretion and metabolic activity of microbial consortia, which play a significant role in the PAH removal of contaminated soils (Pant *et al.* 2021). The comparative overview of integrated and emerging remediation technologies for co-contaminated soils (heavy metals, microplastics and PAHs) is given in Table 3.

Synthesis: integrated remediation for Co-contaminated soils

The literature reviewed in this study demonstrates that remediation of soils contaminated with heavy metals, MPs, and PAHs remains a complex environmental challenge because these contaminants differ substantially in their physicochemical properties, environmental behavior, and remediation requirements. Heavy metals are non-biodegradable contaminants that primarily require immobilization, extraction, or transformation processes,

Table 3: Comparative overview of integrated and emerging remediation technologies for co-contaminated soils (Heavy metals, microplastics and PAHs)

Technology / Approach	Primary Mechanism(s)	Advantages	Limitations	Field Applicability & Scalability	Estimated Relative Cost	Future Prospects / Research Needs
Integrated Treatment Trains	Sequential physical + chemical + biological processes (*e.g*., SVE + oxidation + bioremediation)	Addresses multiple contaminants simultaneously; exploits complementary strengths	High operational complexity; risk of negative interactions if not optimized	Moderate to High	Medium–High	Optimized site-specific designs and real-time monitoring (Dadrasnia and Agamuthu 2014; Cheng *et al*. 2025)
Biochar-Supported Microbial Systems	Adsorption + enhanced biodegradation; improved microbial habitat	Immobilizes metals; boosts MP/PAH degradation; improves soil health	Performance varies with biochar type and soil conditions	High	Low–Medium	Tailored variants for multi-contaminant systems and long-term stability (Nwankwegu *et al.* 2022b; Cheng *et al.* 2025)
Nanoremediation (nZVI, Carbon-based, Metal Oxides)	Adsorption, reduction, π-π interactions, photocatalysis	High reactivity; effective for PAHs and metals; potential for MPs	Ecotoxicity concerns; nanoparticle fate, aggregation, and recovery issues	Moderate (lab/pilot dominant)	Medium–High	Green synthesis, comprehensive ecotoxicity studies, and field trials (Mazarji *et al.* 2021; Yang *et al.* 2024a, b)
EK-PRB	Electrokinetic transport + reactive barrier (adsorption/precipitation/biodegradation)	Efficient for metals in low-permeability soils; in-situ	Complex setup; sensitive to pH, moisture, and voltage	Promising	Medium	Integration with biological or nanomaterial PRBs for co-contaminants (Li *et al.* 2024; Yang *et al*. 2024b)
CRISPR-Engineered Microbial Consortia	Genetic enhancement of catabolic pathways (*e.g*., phn/nah clusters)	High specificity and efficiency for PAHs; potential for multi-pollutant targeting	Biosafety, regulatory hurdles, and limited field data	Emerging (lab-scale)	Medium–High	Rigorous risk assessments and co-contaminated field validation (Pant *et al*. 2021; Cui *et al.* 2023a, b)
PGPR + Phytoremediation + Microbial Consortia	Plant-microbe synergies for uptake, degradation, and stabilization	Sustainable; improves soil fertility and plant health	Slow; highly site- and species-specific	High for agriculture	Low	Multi-contaminant trials and genetic enhancement of PGPR (Khan *et al.* 2024; Luo *et al.* 2025)

whereas MPs and PAHs are carbon-based contaminants that can potentially be degraded through biological, chemical, or catalytic pathways. Consequently, remediation strategies that are highly effective for one contaminant group may be less effective for another.

The evidence reviewed suggests that integrated remediation approaches represent the most promising strategy for co-contaminated soils. Physical and chemical technologies, including soil washing, thermal desorption, electrokinetic remediation, and permeable reactive barriers, can provide rapid contaminant removal but are often associated with higher operational costs and risks of secondary pollution. In contrast, biological approaches such as phytoremediation, microbial remediation, fungal degradation, and PGPR-assisted remediation offer environmentally sustainable alternatives but generally require longer treatment periods and are influenced by environmental conditions. Combining these approaches can exploit their complementary advantages while minimizing their individual limitations.

Future remediation frameworks should increasingly focus on contaminant-specific and site-specific treatment designs that consider contaminant speciation, bioavailability, soil characteristics, ecological risks and economic feasibility. Such integrated systems have the potential to improve remediation efficiency while enhancing long-term soil restoration and environmental sustainability.

Research gaps and future directions

Despite significant advances in soil remediation technologies, several important scientific and technological challenges remain unresolved.

1. Most remediation studies continue to focus on single-contaminant systems, whereas real-world contaminated soils frequently contain mixtures of heavy metals, MPs, PAHs, and other emerging contaminants. Future research should prioritize the development of remediation strategies specifically designed for multi-contaminant environments and investigate interactions among different contaminant classes during remediation.
2. Many emerging remediation technologies have primarily been evaluated under laboratory or pilot-scale conditions. Long-term field studies are needed to assess their effectiveness, environmental safety, scalability, and economic feasibility under realistic environmental conditions.
3. Although microbial, fungal, and PGPR-based remediation strategies have shown promising results, the molecular mechanisms governing contaminant degradation, microbial adaptation, and community dynamics remain incompletely understood. Advances in metagenomics, transcriptomics, proteomics, and metabolomics could facilitate the identification of key degradation pathways and improve remediation performance.

4. Nanoremediation technologies require further investigation regarding nanoparticle fate, transport, persistence, ecotoxicity, and regulatory acceptance. Similarly, CRISPR-engineered microbial systems offer significant potential for enhanced contaminant degradation, but biosafety concerns, environmental risk assessments, and regulatory frameworks must be established before large-scale deployment.

Finally, future remediation efforts should move beyond contaminant removal alone and incorporate broader sustainability metrics, including carbon footprint, energy consumption, ecosystem restoration, economic viability, and circular-economy principles. The integration of artificial intelligence, machine learning, precision monitoring systems, and smart remediation technologies may further accelerate the development of efficient and sustainable remediation solutions over the next five years.

Research roadmap for future development and deployment

To facilitate the transition from laboratory research to practical remediation applications, future studies should adopt a phased research and implementation framework. In the short term, research efforts should focus on improving mechanistic understanding of contaminant interactions in co-contaminated soils, optimizing integrated remediation systems, and developing standardized protocols for evaluating remediation efficiency under realistic environmental conditions. Particular emphasis should be placed on understanding the interactions among heavy metals, microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs), which may influence contaminant mobility, bioavailability and treatment outcomes.

At the intermediate stage, pilot-scale and field-scale validation studies should become a priority. Although many emerging technologies, including nanoremediation, biochar-supported microbial systems, PGPR-assisted remediation, and CRISPR-engineered microbial consortia, have demonstrated promising laboratory-scale performance, their effectiveness under variable field conditions remains insufficiently understood. Future investigations should evaluate long-term remediation performance, resilience to environmental fluctuations, soil health recovery, and economic feasibility under agricultural conditions.

Environmental safety assessment should be integrated throughout technology development. For example, nanomaterial-based remediation systems require detailed investigation of nanoparticle persistence, transport, ecotoxicity, and potential accumulation within soil food webs. Similarly, the deployment of genetically engineered microorganisms necessitates comprehensive biosafety assessments, monitoring of horizontal gene transfer risks, and development of robust containment strategies. Life-cycle assessment (LCA) and environmental risk assessment frameworks should be routinely incorporated into remediation studies to ensure that pollutant removal does not generate unintended ecological consequences.

From a commercialization perspective, future research should address challenges associated with large-scale production, operational costs, regulatory approval, technology standardization, and stakeholder acceptance. The development of cost-effective remediation materials, scalable production methods, and performance certification standards will be essential for accelerating technology adoption. Public–private partnerships, government incentives, and industry participation may further facilitate commercialization and large-scale deployment of advanced remediation technologies.

Ultimately, the successful remediation of co-contaminated agricultural soils will require interdisciplinary collaboration among environmental scientists, microbiologists, agronomists, engineers, policymakers, and industry stakeholders. The integration of artificial intelligence (AI), machine learning, remote sensing, and precision environmental monitoring systems may further enhance decision-making, site-specific remediation design, and long-term performance assessment, supporting the development of sustainable and commercially viable remediation solutions.

Conclusion

The remediation of soils contaminated with heavy metals, microplastics, and polycyclic aromatic hydrocarbons requires multidisciplinary and integrated approaches due to the diverse physicochemical characteristics of these contaminants. Conventional physical and chemical remediation technologies provide rapid contaminant removal, whereas biological approaches offer environmentally sustainable alternatives for long-term soil restoration. Emerging technologies, including nanoremediation, PGPR-assisted remediation, electrokinetic systems, and CRISPR-engineered microbial consortia, have demonstrated considerable potential for improving remediation efficiency. However, challenges related to scalability, cost-effectiveness, environmental safety, and field applicability remain. The future of soil remediation will likely depend on integrated treatment strategies that combine physical, chemical, and biological processes while incorporating advanced monitoring and sustainable management practices to achieve effective restoration of contaminated soils.

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Authors' Contributions

Bashir Ahmed: Conceptualization, Methodology, Writing-original draft preparation, Writing-review and editing. Khushi Ali: Conceptualization, Methodology, Writing-original draft preparation, Writing-review and editing. Syed Ali Hassan: Conceptualization, Methodology, Writing-review and editing.

Conflict of Interest

The authors declare that they have no known competing interests that could affect the work reported in this paper.

Data Availability

Data will be made available upon request.

Ethical Approval

This work does not involve experiments on animals or humans.

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References

Akhbarizadeh R, S Dobaradaran, TC Schmidt, I Nabipour, J Spitz (2020). Worldwide bottled water occurrence of emerging contaminants: A review of the recent scientific literature. *J Hazard Mater* 392:122271

Ali SS, R Al-Tohamy, J Sun (2025). Unmasking microplastics in anaerobic digestion: Hidden threats, synergistic pollutants, and biodegradation frontiers—A comprehensive hotspot review. *Environ Chem Ecotoxicol* 7:980–1010

Ameen F, HA Al-Shwaiman, R Almalki, AE Al-Sabri, EN Sholkamy (2025). Degradation of polyvinyl chloride (PVC) microplastics employing the actinobacterial strain *Streptomyces gobitricini*. *Biodegradation* 36:19

Amin MM, MS Hatamipour, F Momenbeik, H Nourmoradi, M Farhadkhani, F Mohammadi-Moghadam (2014). Toluene removal from sandy soils via in situ technologies with an emphasis on factors influencing soil vapor extraction. *Sci World J* 2014:416752

Auta HS, CU Emenike, SH Fauziah (2017). Screening of Bacillus strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation. *Environ Pollut* 231:1552–1559

Azuazu IN, K Sam, P Campo, F Coulon (2023). Challenges and opportunities for low-carbon remediation in the Niger Delta: Towards sustainable environmental management. *Sci Total Environ* 900:165739

Behera S, S Das (2023). Environmental impacts of microplastic and role of plastisphere microbes in the biodegradation and upcycling of microplastic. *Chemosphere* 334:138928

Chandel R, L Singh, NA Khan, S Thakur (2025a). Microbial remediation of microplastic-contaminated soil, focusing on mechanisms, benefits, and research gaps. *NPJ Emerg Contamin* 1:14

Chandel R, L Singh, NA Khan, S Thakur (2025b). Microbial remediation of microplastic-contaminated soil, focusing on mechanisms, benefits, and research gaps. *NPJ Emerg Contamin* 1:14

Chaturvedi P, P Shukla, BS Giri, P Chowdhary, R Chandra, P Gupta, A Pandey (2021). Prevalence and hazardous impact of pharmaceutical and personal care products and antibiotics in environment: A review on emerging contaminants. *Environ Res* 194:110664

Cheng T, T Huang, P Zhou, Y Zhang, X Xu, B Wu, B Wang (2025). Remediation of PAHs and heavy metals co-contaminated sediments by biochar-supported immobilized microbial systems: A review. *J Water Proc Eng* 78:108815

Cui J Q, ZQ He, S Ntakirutimana, ZH Liu, BZ Li, YJ Yuan (2023a). Artificial mixed microbial system for polycyclic aromatic hydrocarbons degradation. *Front Microbiol* 14:1207196

Cui JQ, ZQ He, S Ntakirutimana, ZH Liu, BZ Li, YJ Yuan (2023b). Artificial mixed microbial system for polycyclic aromatic hydrocarbons degradation. *Front Microbiol* 14:1207196

Dadrasnia A, P Agamuthu (2014). Diesel toxicity and soil remediation-technical report. *Malays J Sci* 33:92–97

Dai Y, J Li, X Yang, S Wang, X Zhao, Y Wang, D Zhang, C Luo, G Zhang (2023). New insight into the mechanisms of autochthonous fungal bioaugmentation of phenanthrene in petroleum contaminated soil by stable isotope probing. *J Hazard Mater* 452:131271

Diao W, Z Wang, Z Xu, X Yu, Q Zhang, X Zeng (2019). Isolation of *Aspergillus niger* SY1 and its role in bioleaching of heavy metals from contaminated river sediments. *Chin J Ecol* 38:1067–1074

Dissanayake PD, S Kim, B Sarkar, P Oleszczuk, MK Sang, MN Haque, JH Ahn, MS Bank, YS Ok (2022). Effects of microplastics on the terrestrial environment: A critical review. *Environ Res* 209:112734

Esmaeili A, O Knox, A Juhasz, SC Wilson (2022). Differential accumulation of polycyclic aromatic hydrocarbons (PAHs) in three earthworm ecotypes: Implications for exposure assessment on historically contaminated soils. *Environ Adv* 7:100175

Fei Y, S Huang, H Zhang, Y Tong, D Wen, X Xia, H Wang, Y Luo, D Barceló (2020). Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. *Sci Total Environ* 707:135634

Forján R, I Lores, C Sierra, D Baragaño, JLR Gallego, AI Peláez (2020). Bioaugmentation treatment of a PAH-polluted soil in a slurry bioreactor. *Appl Sci* 10:2837

Ghanbarzadeh M, V Niknam, N Soltani, H Ebrahimzadeh, MH Shahavi (2022). Removal of Phenanthrene by some microalga species and study of antioxidative compounds in *Nostoc calcicola* ISC 89. *J Soils Sedim* 22:109–119

Guo Y, Z Wang, C Hou, H Li, W Chen, H Li, H Chen, L Shi (2025). Remediation of polycyclic aromatic hydrocarbon-contaminated soil using microwave-activated persulfate oxidation system. *Sustainability* 17:4897

Hou L, J Xi, J Liu, P Wang, T Xu, T Liu, W Qu, YB Lin (2022). Biodegradability of polyethylene mulching film by two Pseudomonas bacteria and their potential degradation mechanism. *Chemosphere* 286:131758

Hu PJ, Z Li, L Wu (2018). Current remediation technologies of heavy metal polluted farmland soil in China. *Res Agric Modern* 39:535–542

Hu W, J Zhang, D Li, Y Yuan, Y Tang, K Hui, Y Jiang, W Tan (2025). Study on factors influencing the transport and transformation of polycyclic aromatic hydrocarbons in soil–groundwater systems. *Emerg Contamin* 11:100472

Huang Y, Q Liu, W Jia, C Yan, J Wang (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environ Pollut* 260:114096

Imam A, SK Suman, PK Kanaujia, A Ray (2022). Biological machinery for polycyclic aromatic hydrocarbons degradation: A review. *Bioresour Technol* 343:126121

Islam MN, S Ganguli, N Saha, MM Huda, MA Hoque, C Peng, JC Ng (2024). Uncovering the impact of mega-scale shipbreaking yards on soil and crop quality in Bangladesh: A spatiotemporal dynamics and associated health risks of metal/loid contamination. *J Hazard Mater* 464:132931

Jesus RD, R Alkendi (2022). A minireview on the bioremediative potential of microbial enzymes as solution to emerging microplastic pollution. *Front Microbiol* 13:1-9

Khan AR, Z Ulhassan, G Li, J Lou, B Iqbal, A Salam, W Azhar, S Batool, T Zhao, K Li, Q Zhang, X Zhao, D Du (2024). Micro/nanoplastics: Critical review of their impacts on plants, interactions with other contaminants (antibiotics, heavy metals, and polycyclic aromatic hydrocarbons), and management strategies. *Sci Total Environ* 912:169420

Lara-Moreno A, E Morillo, F Merchán, J Villaverde (2021). A comprehensive feasibility study of effectiveness and environmental impact of PAH bioremediation using an indigenous microbial degrader consortium and a novel strain *Stenotrophomonas maltophilia* CPHE1 isolated from an industrial polluted soil. *J Environ Manage* 289:112512

Lee H, K Sam, F Coulon, S De Gisi, M Notarnicola, C Labianca (2024).

Recent developments and prospects of sustainable remediation treatments for major contaminants in soil: A review. *Sci Total Environ* 912:168769

Li Y, Y Yuan, X Qi, S Wang, Y Wang, H Yin, Z Dang (2024). A novel soil remediation technology for simultaneous heavy metals immobilization and nitrogen supplementation. *J Environ Chem Eng* 12:111628

Li Y, S Yi, R Duan, S Li, Z Sun, J Shi, L Gao (2023). Enhanced photocatalytic performance of Na1.8Zn2.1Mo3O12/g-C3N4 heterojunction for tetracycline degradation. *J Environ Chem Eng* 11:110471

Lin Z, T Jin, T Zou, L Xu, B Xi, D Xu, J He, L Xiong, C Tang, J Peng, Y Zhou, J Fei (2022). Current progress on plastic/microplastic degradation: Fact influences and mechanism. *Environ Pollut* 304:119159

Liu LH, T Yuan, JY Zhang, GX Tang, H Lü, HM Zhao, H Li, YW Li, CH Mo, ZY Tan, QY Cai (2022). Diversity of endophytic bacteria in wild rice (*Oryza meridionalis*) and potential for promoting plant growth and degrading phthalates. *Sci Total Environ* 806:150310

Liu Y, CTQ Mai, FTT Ng (2021). Glycerol hydrogenolysis with in situ hydrogen produced via methanol steam reforming: The promoting effect of pd on a $Cu/ZnO/Al_2O_3$ catalyst. *Catalysts* 11:1–21

Lu D, S Sha, J Luo, Z Huang, XZ Jackie (2020). Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): A critical review. *J Hazard Mater* 386:121963

Luo N, XJ Zhang, LF Gong, LQ Yang, Q Yao, JF Song (2025). Review of remediation methods for soil contaminated with cadmium. *Euras Soil Sci* 58:3

Luo S, L Ren, W Wu, Y Chen, G Li, W Zhang, T Wei, YQ Liang, D Zhang, X Wang, Z Zhen, Z Lin (2022). Impacts of earthworm casts on atrazine catabolism and bacterial community structure in laterite soil. *J Hazard Mater* 425:127778

Mai X, J Tang, J Tang, X Zhu, Z Yang, X Liu, X Zhuang, G Feng, L Tang (2025). Research progress on the environmental risk assessment and remediation technologies of heavy metal pollution in agricultural soil. *J Environ Sci* 149:1–20

Marquès M, D Cervelló, M Mari, J Sierra, M Schuhmacher, JL Domingo, M Nadal (2020). The role of iron oxide on the photodegradation of polycyclic aromatic hydrocarbons: Characterization and toxicity. *Polycycl Aromat Comp* 40:524–534

Maxel S, E King, Y Zhang, R Luo, H Li (2020). Leveraging oxidative stress to regulate redox balance-based, *in vivo* growth selections for oxygenase engineering. *ACS Synth Biol* 9:3124–3133

Mayakaduwage S, A Ekanayake, S Kurwadkar, AU Rajapaksha, M Vithanage (2022). Phytoremediation prospects of per- and polyfluoroalkyl substances: A review. *Environ Res* 212:113311

Mazarji M, T Minkina, S Sushkova, S Mandzhieva, GN Bidhendi, A Barakhov, A Bhatnagar (2021). Effect of nanomaterials on remediation of polycyclic aromatic hydrocarbons-contaminated soils: A review. *J Environ Manage* 284:112023

Mehmeti V, M Sadiku (2022). A comprehensive dft investigation of the adsorption of polycyclic aromatic hydrocarbons onto graphene. *Computation* 10:68

Michael-Igolima U, SJ Abbey, AO Ifelebuegu (2022). A systematic review on the effectiveness of remediation methods for oil contaminated soils. *Environ Adv* 9:100319

Muter O (2023). Current trends in bioaugmentation tools for bioremediation: A critical review of advances and knowledge gaps. *Microorganisms* 11:710

Neshati J, F Biabanaki, N Shariatmadari (2023). An investigation into the efficiency of electrokinetic and electrokinetic coupled with calcium peroxide permeable reactive barriers techniques for soil remediation using a statistical analysis. *Environ Monit Assess* 195:145

Nwankwegu AS, L Zhang, D Xie, CO Onwosi, WI Muhammad, CK Odoh, K Sam, JN Idenyi (2022). Bioaugmentation as a green technology for hydrocarbon pollution remediation, problems and prospects. *J Environ Manage* 304:114313

Olabemiwo FA, A Hagan, M Cham, FM Cohan (2024). Two plant-growth-promoting *Bacillus* species can utilize nanoplastics. *Sci Total Environ* 907:167972

Paço A, K Duarte, JPD Costa, PSM Santos, R Pereira, ME Pereira, AC Freitas, AC Duarte, TAP Rocha-Santos (2017). Biodegradation of polyethylene microplastics by the marine fungus *Zalerion maritimum*. *Sci Total Environ* 586:10–15

Pant G, D Garlapati, U Agrawal, RG Prasuna, T Mathimani, A Pugazhendhi (2021). Biological approaches practised using genetically engineered microbes for a sustainable environment: A review. *J Hazard Mater* 405:124631

Patel AB, S Singh, A Patel, K Jain, S Amin, D Madamwar (2019). Synergistic biodegradation of phenanthrene and fluoranthene by mixed bacterial cultures. *Bioresour Technol* 284:115–120

Peng WD (2019). Present situation and remediation technology of cadmium pollution in farmland soil. *Chem Technol* 88–89

Premnath N, K Mohanrasu, RGR Rao, GH Dinesh, G S Prakash, V Ananthi, K Ponnuchamy, G Muthusamy, A Arun (2021). A crucial review on polycyclic aromatic Hydrocarbons - Environmental occurrence and strategies for microbial degradation. *Chemosphere* 280:130608

Priya KL, KR Renjith, CJ Joseph, MS Indu, R Srinivas, S Haddout (2022). Fate, transport and degradation pathway of microplastics in aquatic environment — A critical review. *Reg Stud Mar Sci* 56:102647

Qi Y, N Beriot, G Gort, E Huerta Lwanga, H Gooren, X Yang, V Geissen (2020). Impact of plastic mulch film debris on soil physicochemical and hydrological properties. *Environ Pollut* 266:115097

Rajadurai M, N Karmegam, S Kannan, A Yuvaraj, R Thangaraj (2022). Vermiremediation of engine oil contaminated soil employing indigenous earthworms, *Drawida modesta* and *Lampito mauritii*. *J Environ Manage* 301:113849

Rani M, U Shanker (2019). Degradation of tricyclic polyaromatic hydrocarbons in water, soil and river sediment with a novel TiO2 based heterogeneous nanocomposite. *J Environ Manage* 248:109340

Rathi BS, PS Kumar, PL Show (2021). A review on effective removal of emerging contaminants from aquatic systems: Current trends and scope for further research. *J Hazard Mater* 409:124413

Satpati GG, S Gupta, RK Biswas, AK Choudhury, JW Kim, MA Davoodbasha (2023). Microalgae mediated bioremediation of polycyclic aromatic hydrocarbons: Strategies, advancement and regulations. *Chemosphere* 344:140337

Saxena G, D Purchase, SI Mulla, GD Saratale, RN Bharagava (2020). Phytoremediation of heavy metal-contaminated sites: Eco-environmental concerns, field studies, sustainability issues, and future prospects. *Rev Environ Contam Toxicol* 249:71–131

Sharma P, A Bano, SP Singh, YW Tong (2023). Microbial inoculants: Recent progress in formulations and methods of application. *Appl Microbiol Biotechnol* 2023:1–28

Singh RK, SK Singh (2025a). Persistent polycyclic aromatic hydrocarbons (PAHs) in the soil, its bioremediation, and health effects. *Environ Sci Eur* 37:187

Singh RK, SK Singh (2025b). Persistent polycyclic aromatic hydrocarbons (PAHs) in the soil, its bioremediation, and health effects. *Environ Sci Eur* 37:187

Song P, D Xu, J Yue, Y Ma, S Dong, J Feng (2022). Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. *Sci Total Environ* 838:156417

Srivastava S, M Kumar (2019). Biodegradation of polycyclic aromatic hydrocarbons (PAHs): A sustainable approach. *Sustain Green Technol Environ Manage* 2019:111–139

Sun X, M Wang, L Qin, L Yu, J Wang, H Zheng, W Zhou, S Chen (2024). Cellular Cd^{2+} fluxes in roots confirm increased Cd availability to rice (*Oryza sativa* L.) induced by soil acidifications. *J Environ Sci* 139:516–526

Sushila D, C Sanya (2023). Soil microplastic remediation: exploring the role of microorganism/PGPR in sustainable cleanup. *ACS Symp Ser* 1459:57–70

Taghavi R, S Rostamnia, M Farajzadeh, H Karimi-Maleh, J Wang, D Kim, HW Jang, R Luque, RS Varma, M Shokouhimehr (2022). Magnetite metal-organic frameworks: Applications in environmental remediation of heavy metals, organic contaminants, and other pollutants. *Inorg Chem* 61:15747–15783

Tomczyk P, A Wdowczyk, B Wiatkowska, A Szymańska-Pulikowska

(2023). Assessment of heavy metal contamination of agricultural soils in Poland using contamination indicators. *Ecol Indic* 156:111161

Touliabah HES, MM El-Sheekh, MM Ismail, H El-Kassas (2022). A review of microalgae- and cyanobacteria-based biodegradation of organic pollutants. *Molecules* 27:1141

Tsui L, A Paul, YT Chen, E Tz-Chi (2022). Potential mechanisms contributing to the high cadmium removal efficiency from contaminated soil by using effective microorganisms as novel electrolyte in electrokinetic remediation applications. *Environ Res* 215:114239

Vijayanand M, A Ramakrishnan, R Subramanian, PK Issac, M Nasr, KS Khoo, R Rajagopal, B Greff, NIW Azelee, BH Jeon, SW Chang, B Ravindran (2023). Polyaromatic hydrocarbons (PAHs) in the water environment: A review on toxicity, microbial biodegradation, systematic biological advancements, and environmental fate. *Environ Res* 227:115716

Wan X, M Lei, J Yang, T Chen (2020). Three-year field experiment on the risk reduction, environmental merit, and cost assessment of four in situ remediation technologies for metal(loid)-contaminated agricultural soil. *Environ Pollut* 266:115193

Wang D, L Qin, E Liu, G Chai, Z Su, J Shan, Z Yang, Z Wang, H Wang, H Meng, X Zheng, H Li, J Li, Y Lin (2022a). Biodegradation performance and diversity of enriched bacterial consortia capable of degrading high-molecular-weight polycyclic aromatic hydrocarbons. *Environ Technol* 43:4200–4211

Wang N, Y Luo, Z Liu, Y Sun (2022b). Spatial distribution characteristics and evaluation of soil pollution in coal mine areas in Loess Plateau of Northern Shaanxi. *Sci Rep* 12:16440

Wang D, G Li, S Qin, W Tao, S Gong, J Wang (2021). Remediation of Cr(VI)-contaminated soil using combined chemical leaching and reduction techniques based on hexavalent chromium speciation. *Ecotoxicol Environ Saf* 208:111734

Wiśniewska KA, AU Lewandowska, S Śliwińska-Wilczewska, M Staniszewska, G Budzałek (2023). The ability of airborne microalgae and cyanobacteria to survive and transfer the carcinogenic benzo(a)pyrene in coastal regions. *Cells* 12:1073

Wójcik A, M Stephan, W Ryczek, K Olechowska, P Wydro, R Dimova, M Broniatowski (2022). Interactions of polycyclic aromatic hydrocarbons and their nitro derivatives with bilayer and monolayer models of fungal membranes. *J Mol Liq* 360:119591

Wu Y, X Li, L Yu, T Wang, J Wang, T Liu (2022a). Review of soil heavy metal pollution in China: Spatial distribution, primary sources, and remediation alternatives. *Resour Conserv Recycl* 181:106261

Wu Y, X Li, L Yu, T Wang, J Wangm T Liu (2022b). Review of soil heavy metal pollution in China: Spatial distribution, primary sources, and remediation alternatives. *Resour Conserv Recycl* 181:106261

Xia F, Z Zhao, X Niu, Z Wang (2024). Integrated pollution analysis, pollution area identification and source apportionment of heavy metal contamination in agricultural soil. *J Hazard Mater* 465:133215

Xu Q, Z Huang, S Ji, J Zhou, R Shi, W Shi (2020). Cu2O nanoparticles grafting onto PLA fibers *via* electron beam irradiation: bifunctional composite fibers with enhanced photocatalytic of organic pollutants in aqueous and soil systems. *J Radioanal Nucl Chem* 323:253–261

Yan X, X Liu, M Zhang, X Cui, J Zhong, X Hu (2021). Research progress in biosorption technology for chromium contamination. *Chin J Rare Met* 45:240–250

Yang JW, C Park, EH Jho (2024a). Removal technologies of microplastics in soil and water environments: Review on sources, ecotoxicity, and removal technologies. *J Appl Biol Chem* 67:106

Yang Z, J Tang, H Feng, X Liu, X Zhuang, H Wang, Y Wu, Y Guo, L Tang (2024b). Research progress on remediation of heavy metal contaminated soil by electrokinetic-permeable reactive barrier. *Chem Eng J* 490:2042–2051

Yi Y, H Feng, J Wang, J Tang, Y Wu, X Liang, Y Guo, L Tang (2023).Simultaneous recovery of NH3–N and removal of heavy metals from manganese residue leachate using an electrodialysis system. *ACS ES&T Water* 3:793–803

Yin K, Q Wang, M Lv, L Chen (2019). Microorganism remediation strategies towards heavy metals. *Chem Eng J* 360:1553–1563

Yoshida S, K Hiraga, T Takehana, I Taniguchi, H Yamaji, Y Maeda, K Toyohara, K Miyamoto, Y Kimura, K Oda (2016). A bacterium that degrades and assimilates poly (ethylene terephthalate). *Science* 351:1196–1199

You X, R Kallies, I Kühn, M Schmidt, H Harms, A Chatzinotas, LY Wick (2022). Phage co-transport with hyphal-riding bacteria fuels bacterial invasion in a water-unsaturated microbial model system. *ISME J* 16:1275–1283

Zeng X, C Deng, Y Liang, J Fu, S Zhang, T Ni (2023). Ecological risk evaluation and sensitivity analysis of heavy metals on soil organisms under human activities in the Tibet Plateau, China. *PLoS One* 18:1-19

Zhang J, D Gao, Q Li, Y Zhao, L Li, H Lin, Q Bi, Y Zhao (2020). Biodegradation of polyethylene microplastic particles by the fungus *Aspergillus flavus* from the guts of wax moth *Galleria mellonella*. *Sci Total Environ* 704:135931

Zhang X, X Zhang, S Wang, S Zhao (2022). Improved remediation of co-contaminated soils by heavy metals and PAHs with biosurfactant-enhanced soil washing. *Sci Rep* 12:3801

Zhang X, Y Li, D Ouyang, J Lei, Q Tan, L Xie, Z Li, T Liu, Y Xiao, TH Farooq, X Wu, L Chen, W Yan (2021). Systematical review of interactions between microplastics and microorganisms in the soil environment. *J Hazard Mater* 418:126288

Zhao B, W Zhu, S Hao, M Hua, Q Liao, Y Jing, L Liu, X Gu (2023). Prediction heavy metals accumulation risk in rice using machine learning and mapping pollution risk. *J Hazard Mater* 448:130879

Zhu Y, X Ren, M Xiang (2024). Enhanced thermal desorption of chlorinated hydrocarbons by nanoscale zero-valent iron: The effect of in situ dechlorination. *RSC Adv* 14:14254–14262