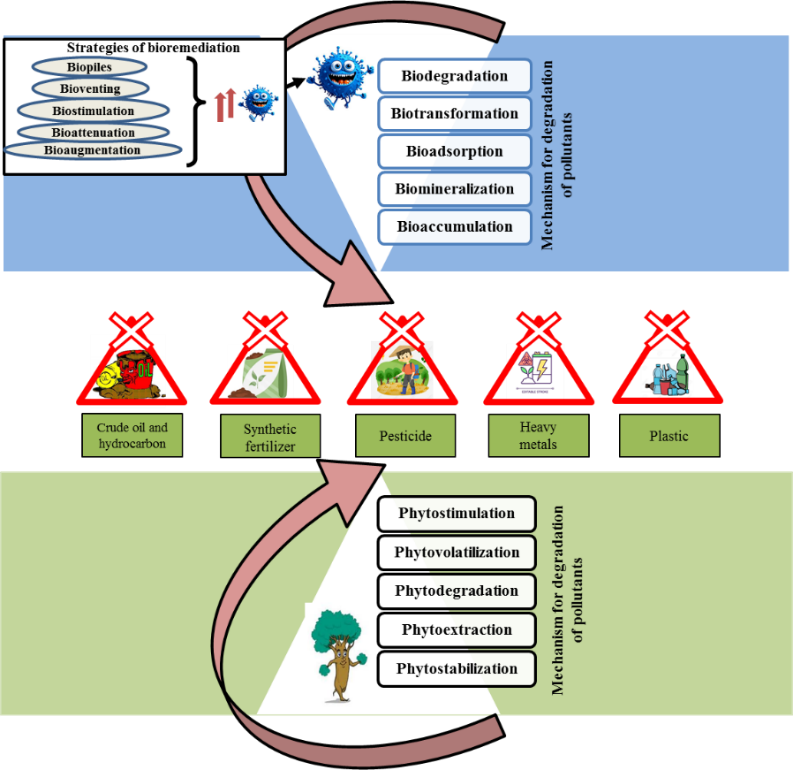
***Review Article***

**Microbial and Phytoremediation Strategies for Agricultural Soil Bioremediation: Mechanisms and Future Perspectives**

ABSTRACT

Bioremediation is an eco-friendly approach that utilizes microbes and plants to effectively remove a wide range of pollutants from the soil. Various strategies—such as bioventing, biopiling, biostimulation, bioattenuation, and bioaugmentation—are employed to enhance biological processes, breaking down complex soil contaminants into simpler, non-toxic forms. These byproducts are absorbed by plants and microorganisms, contributing to a healthier environment. While extensive research exists on bioremediation techniques and microbial mechanisms, reports on their practical applications and proven benefits remain limited. Therefore, developing effective bioremediation strategies is crucial to degrade pollutants at scale, preserve nutrient availability, and optimize microbial populations and processes, including biodegradation, biosorption, biomineralization, bioaccumulation, and biotransformation, tailored to specific contaminants. This paper reviews various bioremediation approaches and their potential as viable solutions for addressing emerging environmental pollutants. With continued advancements, microbial and phytoremediation could mitigate pollution and promote long-term environmental health

**GRAPHICAL ABSTRACT**



**Keywords:** Bioremediation, Contaminants, Bioremediation strategies, Microbial remediation, Phytoremediation.

**1. INTRODUCTION**

On a global basis, soil pollution gets a lot of attention, particularly in slag disposal areas, specialized industrial wastelands, and agricultural farmland (Inbit et al. 2024). Soil contamination is rapidly increasing with the development and growth of the population due to anthropogenic activities such as urbanization and industrialization (Yaqub, 2024). Presently, fertilizer or pesticide application, synthetic chemical manufacturing, fossil fuel burning, and mining are the worst causes of soil contamination such as heavy metal deposition (Adepoju et al. 2024) pesticide residue (Song et al. 2019), and hydrocarbon (Hoang et al. 2021). The presence of heavy metals in agricultural soil poses a serious threat to global food security due to their interference with various physiological processes in plants (Wang et al. 2023). Their toxic nature, bioaccumulation and low degradability pose significant nutritional, ecological, and environmental risks. Therefore, due to their toxicity and low degradability, they are considered high-priority contaminants (Zerizghi et al. 2022). Nowadays, various special pesticides have been introduced worldwide and have revolutionized the agricultural industry by controlling pests and maintaining crop yield (Mali et al. 2023). Hence, these pesticides may be an effective way to crop production, but their non-judicious use leads to a severe negative impact on the global environment (Wuepper et al. 2023). It has been reported that pesticide residues are tightly linked to soil, potentially threatening soil fertility (Alshemmari et al. 2021) and crop quality (Jia et al., 2023). Additionally, hydrocarbons are highly persistent organic pollutants due to their hydrophobicity, carcinogenic properties, and toxicity, contributing to environmental pollution (Chaurasia et al. 2024). These compounds are mainly attributed to human activities from incomplete combustion of organic materials, pipeline sabotage, crude oil refineries, and industrial waste. Consequently, they can negatively impact all environmental ecosystems, such as soil, and water (Ehis-Eriakha et al. 2024). Therefore, understanding the remediation of hydrocarbons is crucial due to their toxicity, which is associated with various harmful health effects in humans, such as mutagenicity, carcinogenicity, and developmental abnormalities (Sun et al. 2021).

Plants suffer from stress caused by soil pollutants, which significantly hinders their growth and development, leading to reduced plant productivity and potentially long-term ecological impacts (Titilayo et al. 2025). The presence of pollutants in soil not only adversely affects plant development but also negatively impacts soil texture, structure, and nutrient cycling along with the diversity, activity, and composition of microbial communities (Chahal et al. 2023). Multiple contaminants cause pollutant accumulation and amplification effects in organisms through the food chain, which is hazardous for wildlife, humans, and natural ecosystems. As a result, decontamination is necessary to improve the efficiency of contaminated soil ecosystems.

Based on above circumstances, extensive research has been performed to minimize soil contaminants and develop effective remediation strategies, including physiochemical and biological methods, while simultaneously reducing their impact from plant and soil. Presently, physicochemical strategies such as chemical oxidation, thermal desorption, soil washing, the use of nanomaterials, solidification, and electrokinetic remediation are commonly employed to remediate contaminated soil (Song et al. 2022). However, these methods can negatively impact soil quality by altering factors such as soil pH and texture, reducing organic content, and increasing oxidation potential. These changes may make it difficult to sustain vegetation in affected soil (Trellu et al. 2021). Therefore, in the current scenario, focusing on agricultural productivity, biological remediation known as bioremediation may be more suitable for maintaing soil health and cost-effective for large-scale in situ cleanup compared to physicochemical approaches (Ali et al. 2022). Bioremediation leverages the natural metabolic abilities of various soil microorganisms, including bacteria, fungi, archaea, and algae, to degrade, detoxify, or immobilize soil contaminants (Rahman et al. 2025). This process promotes sustainable soil ecosystems without producing secondary pollutants (Nie et al. 2020). Therefore, understanding microbial metabolism is essential for applying potential microbes in remediation processes. This review explains a sustainable approach to bioremediation that can contribute the scientific research, drive technological innovation, and support policy development to fully exploit the potential of microbial remediation. By harnessing the capabilities of microbes, we can foster a more sustainable and resilient future for restoring and stabilizing soil ecosystems. Keeping the above crucial consideration, the aim of this review is to find out the various soil bioremediation strategies and their significant role in the degradation of synthetic and organic contaminants and heavy metal passivation. This review aims to: (1) explore bioremediation strategies for addressing multiple contaminants, (2) elaborate on the mechanisms involved in the bioremediation of heavy metals, as well as organic and inorganic pollutants, and (3) conclude with the current needs and future directions for research in this field.

**2. TYPES OF CONTAMINANTS AND THEIR SOURCE IN SOIL**

The percentage of soil pollutants varies significantly depending on the region, the type of pollution, and land use. soil pollution negatively affects 20 to 25% of agricultural soils throughout the world. Heavy metals, pesticides, and industrial chemicals contribute to 30-40% of contamination cases. Specifically, heavy metals, pesticides, and petroleum hydrocarbons account for 15-20% of this contamination. Additionally, plastics are emerging as growing concerns, while other pollutants make up about 5-10%. In heavily industrialized areas, contamination levels can exceed 50%, particularly near mining sites, chemical plants, or locations with untreated waste disposal. Major source of pollutants and their contribution are illustrated in (Table 1) (Yaqub, 2025).

**2.1 HEAVY METALS**

The increasing level of heavy metal pollutants are a serious threat to crop production and quality, ecological safety, and human health, making them significant sources of soil contamination (Zhou et al. 2023). Heavy metals pose significant risks due to their toxicity, persistence in the environment, and potential to accumulate in living organisms. They can have mutagenic and carcinogenic effects on human and plant health, leading to both acute and chronic toxicity that disrupts physiological systems (Tomczyk et al. 2023). The United States Environmental Protection Agency has identified several particularly hazardous elements, including Cd, Cr, As, Pb, Cu, Zn, and Ni (Chen et al. 2015). Heavy metals in the soil can enter the human body through various routes, including the consumption of contaminated agricultural food products and drinking contaminated water. Excessive intake of potentially toxic elements, particularly As, Pb, and Cd, can lead to serious health issues such as cancer, kidney disease, nervous system disorders, and memory impairment (Zhao et al. 2014). Rahman and Singh (2019) revealed that high concentration of these heavy metals (As, Cd, Hg, Pb) in soil impose negative impact on plant growth and development as well as soil habitat.

The primary sources of toxic heavy metals are both natural (geogenic) and human-made (anthropogenic). Toxic heavy metals are widespread in bedrock, which serves as the natural parent material for soil, and they can be found in varying concentrations. Certain types of parent rock, such as basalt and shale, as well as primary minerals like pyrite and sphalerite, contain elevated levels of As, Cd, Cu, and Ni. This concentration is due to sulfur's strong affinity for these metals (FAO and UNEP, 2021). Human activities are significant sources of toxic metals in the pedosphere, which includes our soil environment. Major contributors to metal contamination began during the Anthropocene, particularly in the Bronze Age, mainly due to metal mining and processing (Meharg and Meharg, 2021). Mining operations excavate vast amounts of rock, often containing high levels of metals, and bring it to the surface. This process results in soil pollution through various means, such as leachate and runoff from mining waste, the irrigation of agricultural land with contaminated water, wind erosion that disperses waste rocks, and atmospheric deposition from metal smelters (Macklin et al. 2023).

**2.2 PESTICIDE**

The global reliance on pesticides application has been vital for preventing yield loss through insects and diseases and ensuring crop production (Tang et al. 2021). They incorporate different types of synthetic products, such as fungicides, insecticides, nematicides, herbicides, and rodenticides, which are applied in agricultural fields for pest control (Tsaboula et al. 2019). These pesticides have significantly contributed to improve food security. however, continuous and non-judicious use of these pesticides have resulted in widespread contamination of agricultural soils (Brühl et al. 2024). They are toxic to non-target organisms, including beneficial species that are essential for nutrient recycling and maintaining soil health (Silva et al. 2023). The accumulation and biomagnification of these pesticides increase exposure risks, which can lead to population declines and reduced biodiversity of soil ecosystems (Stuligross and Williams, 2021). Pesticide residues can be absorbed and accumulate as they move from soil to plants and then to human’s body. Their toxicity is associated with various human health issues, including headaches, nausea, skin rashes, neurotoxicity, cancer, and endocrine dysfunction. These effects can result from both direct and indirect exposure to pesticides (Kalyabina et al. 2021). Therefore, it is crucial to assess the ecological risks associated with pesticide residues in soil to develop effective regional risk mitigation strategies.

The main source of pesticide contamination comes from the use of agrochemicals such as insecticides, fungicides, and herbicides for pest control. Pesticide contamination in the soil is especially significant in agricultural areas (Grafkina and Pitryuk, 2022). When these chemicals are applied to croplands, a large portion of them gets absorbed into the soil (Fantke et al. 2011). Problems arise when excessive use leads to issues such as off-field spray drift, infiltration into groundwater, or surface runoff into nearby water bodies. Consequently, soil can become a major source of pesticide residues in various environmental compartments.

**2.3 CRUDE OIL AND HYDROCARBON**

Hydrocarbons are naturally occurring organic substances that are mostly produced from plant and animal fossils as a result of natural or human-caused processes. They are made up of carbon and hydrogen and serve as the basis for natural gas, crude oil, and coal, which provide a major amount of the world's energy. They contain many hazardous chemicals such as toluene, ethylbenzene, xylene, naphthalene, benzene etc. which is harmful to soil, plants, and human life. Intentionally or accidentally, hydrocarbon and their derivatives product are released into soil and oceans and primarily existed in three physical state such as solid, liquid and gas (Liu et al. 2019). Hydrocarbon and crude oil contaminants has taken on a worldwide scale because of the hazard it represents to all life form such as soil microbes, animals and human as well as groundwater quality. The hydrocarbon and their derivative adversely affect the environment. Thereby, the ecosystem's functioning along with its living microflora and nonliving components, deteriorates as a result of hydrocarbon contamination (Essabri et al. 2019).

**2.4 SYNTHETIC FERTILIZER**

Chemical fertilizers are synthetic substances that contain the high nutrient concentrations required for plant growth and development. These are man-made fertilizers that provide the required plant nutrient for higher crop yield. Fertilizers and other chemical products are inherent dangers in agriculture. Nonetheless, they remain critical tools for global food security, and their negative consequences cannot be overlooked, especially given the global target of sustainable agriculture. The chemical fertilizers play vital role in enhancing the crop productivity along with soil fertility. In agriculture, only 10% to 40% applied fertilizer can be directly utilized by plant and remaining fertilizers are available in insoluble form as inorganic salt which accounts a great threat for soil biodiversity (Zheng et al. 2019). Therefore, unreasonable long-term use of chemical fertilizers increases environmental pollution and soil acidity which has negative impact on crop yield and quality along with soil biodiversity (Battaglia et al. 2021; Seleiman et al. 2021).

**2.5 PLASTICS**

Plastic is a conveniently available, cost-effective, and accessible material which is commonly used in industries and in our daily lives all over the world, and they provide a great deal of convenience to humanity. Presently, it is undeniably due to increasing plastic production levels, use and disposal patterns, minimal recovery rates, and demographic details all are leading to an increase in plastic waste accumulation in the environment (Kumar et al. 2021). Even though plastics are persistent, only about 5% of them are recycled (Kumar et al. 2020). Brahney et al. (2020) estimated that the increasing utilization and demand of plastics will accumulate about 11 billion tons of plastic waste material in our environment by 2025. Surface embrittled plastics are micro-cracked by microbial-mediated, weathering conditions and mechanisms such as UV light and hydrolysis, and are increasingly degraded into small fragments term as microplastics, which are projected to cause severe environmental problems over a hundred years (Auta et al. 2017). Microplastic is called “white pollution” because of plastic garbage pollutes the ecosystem and will not disintegrate in the natural environment for at least 100 years (Ricardo et al. 2021).

**Table: 1 Major source of pollutants and their contribution in soil pollution**

|  |  |  |
| --- | --- | --- |
| **Pollutants** | **Source of pollutants** | **Estimated contribution** |
| Heavy metals (Pb, Cd, Hg), chemicals, solvents | Industrial Waste | ~30% |
| Pesticides, herbicides, fertilizers | Agricultural Chemicals | ~35% |
| Arsenic, lead, sulfur, radioactive waste | Mining & Smelting | ~20% |
| Plastics, microplastics, heavy metals, e-waste | Urban Waste & Landfills | ~15% |

**3. SIGNIFICANT ROLE OF MICROORGANISMS AND PLANTS IN BIOREMEDIATION**

Soil microorganisms play an important role in cleaning and reclamation of contaminated soil for enhancing the degradation of toxic pollutants such as hydrocarbon, pesticides, heavy metals, and plastics (Verma et al. 2014). Soil rhizomicrobiome as a plant growth promoting rhizobacteria (PGPR) facilitates the bioremediation process along with plant growth mechanism through directly or indirectly in polluted soil. According to Thavamani et al. (2015), bacteria with the capacity for hydrocarbon metabolism and Cd tolerance displayed outstanding remediation capabilities in soil that had been contaminated by a variety of various contaminants. In tests for bacterial accumulation, Cd2+ (chemisorption) and Zn2+ (physisorption) were found to be primarily adsorbed onto the cell walls rather than accumulating inside the bacteria. Additionally, chelators, surfactants, and organic acids released by soil microbes are explored as modifying techniques to regulate the bioavailability of pollutants during the microbial remediation process in polluted soil. Moreover, the enzyme activity of soil microbes may efficiently remove pollutants such as petroleum hydrocarbons, polychlorinated biphenyls, Zinc, Lead, organophosphates, organochlorines, and carbamates (Sharma et al. 2018).

Phytoremediation is a plant-based mechanism using green and living plants to remove pollutants from a contaminated environment. Phytoremediation is recommended as cost effective, eco-friendly and economic remediation process for our environment. Plants depict their capabilities to absorb soil pollutants (organic pollutants, pesticide, heavy metals) at very low concentrations. They expand their root system and set up their rhizosphere eco-system into a soil matrix for translocation or accumulation of pollutants and regulate their bioavailability, thereby reclaiming the soil fertility (Jacob et al. 2018). Meanwhile, exudates released by plant roots attract abundance microbial populations which contributes to the degradation of pesticide residual. For example, differentgenotypes of *Ricinus communis* (castor) removed the Cd and DDTs from contaminated soil (Huang et al. 2011). Similarly, *Zea mays* plants showed a strong removal capacity of benzene and also removed 97 % of pesticides e.g. atrazine in soil (Feng et al. 2017). Various plants such as *Cucurbita pepo, Lolium perenne, Spinacia oleracea,*and *Medicago sativa L.* have revealed their capacity to degrade pesticides, organic pollutants, and heavy metals from contaminated soil (Zhang et al. 2019).

**4. BIOREMEDIATION STRATEGIES**

There are some treatment strategies of contaminated soil which has described by Rajendran and Gunasekaran (2019).

**4.1 BIOSTIMULATION**

This type of strategy involves the addition of particular nutrients and growth regulators to the contaminated soil and water to promote the activity of microorganisms. Moreover, environmental conditions such as oxygen, temperature, and pH enhance their metabolic activity (Adams et al. 2015).

**4.2 BIOATTENUATION**

Natural attenuation is the removal of maximum pollutants from a contaminated area using biological (aerobic and anaerobic biodegradation), chemical reaction (complexion and ion exchange), and physical (volatilization, sorption, diffusion, dilution, advection, and dispersion) (Li et al. 2010).

**4.3 BIOAUGMENTATION**

Bioaugmentation includes the incorporation of pollutant-degrading microbes which may be exotic and genetically modified to increase the biodegradation process of contaminants and also augment the metabolic pathway of indigenous microbial communities. Microorganisms are isolated from the contaminated site, cultivated separately, genetically altered, and then released back onto the site. For evidence, soil and groundwater contaminated with trichloroethylene and tetrachloroethylene result in the presence of all necessary microorganisms in contaminated areas. It is utilized to make sure that the in-situ microbes can eliminate and transform these pollutants into non-toxic ethylene and chloride (Niu et al. 2009).

**4.4 BIOVENTING**

Bioventing involves venting oxygen into the soil to promote the growth of native and introduced bacteria and fungi by supplying soil microbes with oxygen. It works with chemicals that degrade aerobically. Low airflow rates are used in bioventing to deliver just enough oxygen to support microbial activity. The most typical method of supplying oxygen is direct air injection into the soil with residual pollution using wells. As vapors flow slowly through biologically active soil, adsorbed fuel residuals and volatile chemicals are both biodegraded. Agarry and Latinwo, (2015) demonstrated that hydrocarbon-contaminated soil may be effectively bio-remediated through bioventing.

**4.5 BIOPILES**

Using biopiles is a method of storing excavated soil tainted with hydrocarbons that can be remedied aerobically. During the biodegradation process, biopiles (also called bioheaps, biocells, biomounds, and compost piles) are employed to lower petroleum concentrations in excavated soils. A system of pipework and pumps that either pushes air into the biopile under positive pressure or pulls air through the pile under negative pressure is used to supply air to the biopile system during this process. The breakdown of adsorbed petroleum pollutants increased as a result of increased microbial activity due to microbial respiration (Emami et al. 2012).

**5. REMEDIATION MECHANISM OF MICROORGANISMS AND PLANTS**

The persistent metals, hydrocarbon, plastics, synthetic fertilizers and pesticides in soils have escalated into a severe environmental concern because to their widespread use in industries and agriculture activities. Microbes have a lot of protective mechanism against toxicity of pollutants in contaminated soil.  An effective and promising method to clean up contaminated soils is known as bioremediation, which uses active microbes (Table 2) and plants (Table 3) to remove contaminants from soil (Fenner et al. 2013).

**Table: 2 Microorganisms Involved in the Remediation of Pollutants**

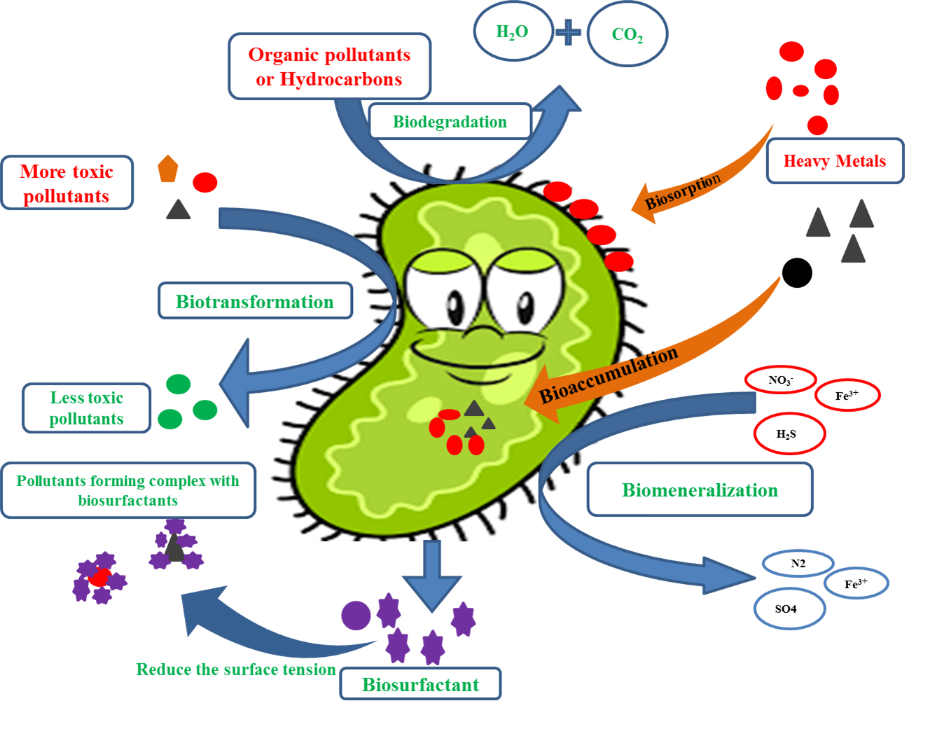
|  |  |  |
| --- | --- | --- |
| **Pollutants** | **Used microbes** | **Reference** |
| **Heavy metals** | | |
| Cr and Cd | *Bacillus cereus* and *Staphylococcus cohnii* | (Liu et al. 2024) |
| Cd, Hg, As Pb, and Ni | *Achromobacter denitrificans, Klebsiella oxytoca,* and*Rhizobium radiobacter*. | Atuchin et al. 2023)\_ |
| Cd, As, and Pb, | *Pseudomonas taiwanensis* | (Liu et al. 2022) |
| Ni and Pb | *Achromobacter denitrificans, Klebsiella oxytoca,* and *Rhizobium radiobacter* | Khan et al. (2025) |
| Cd | *Burkholderia spp.* | Li et al. (2023) |
| **Pesticide** | | |
| [Fipronil](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/fipronil), Profenofos and Chlorantraniliprole | *Ciceribacter azotifigens* and[*Serratia marcescens*](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/serratia-marcescens) | Shahid and Singh, (2024) |
| Chlorpyrifos | *Serratia rubidaea* | Salem et al. (2022) |
| Carbendazim, Methomyl, and Imidacloprid | *Bacillus cereus, Pseudomonas aeruginosa,* and *Pseudomonas donghuensis* | Bandopadhyay et al. (2023) |
| **Hydrocarbons (Organic pollutants)** | | |
| Petroleum hydrocarbons | *Alcaligenes faecalis, Sphingobacterium spiritivorum* and *Stenotrophomonas rhizophila* | Ali et al. (2024) |
| Polycyclic aromatic hydrocarbons (PAHs) | *Rhodococcus spp., Pseudomonas aeruginosa, Pseudomonas fuorescence, Fusarium solani,* and *Talaromyces helices* | Imam et al., (2022) |
| Pyrene and Benzo-pyrene | *Bosea, Mycolicibacterium, Arthrobacter, Paenibacillus, Bacillus,* and *Rhodococcus* | Kumari et al. (2022) |
| Fluoranthene | *Chlorella vulgaris* | Tomar and Jajoo, (2021) |
| Phenol | *Myroides xuanwuensis* | Wang et al. (2024) |
| Biphenyland triphenylmethane | *Phanerochaetechrysosporium* | Erika et al. (2013) |
| **Oil contaminants** | | |
| Crude oil | *Xanthomonas boreopolis, Microbacterium schleiferi, Pseudomonas aeruginosa,* and *Bacillus velezensis* | Tripathi et al. (2024) |
| Crude oil and Diesel oil | *Bacillus coagulans, Bacillus cereus, Pseudomonas cepacia, Serratia ficaria and Citrobacter koseri* | Kehinde and Isaac (2016) |
| Diesel oil | *Arthrobacter globiformis, Pantoea agglomerans,* and*Nitratireductor soli* | Espinosa-López et al., (2025) |
| Crude oil | *Bacillus toyonensis, Bacillus sp.* and*Bacillus cereus* | Valizadeh et al. (2024) |

**Table: 3 Plants involved in the remediation of pollutants**

|  |  |  |
| --- | --- | --- |
| **Pollutants** | **Used plant** | **Reference** |
| Cd, Ni, Cu, As, Cr, and Pb | *Artemisia vulgaris* | Antoniadis et al. (2021) |
| Cd and Zn | *Quercus texana* | Li et al. (2023) |
| Pb and As | *Spergularia rubra*and*Lamarckia aurea* | Paniagua-López et al. (2024) |
| Pb, Cd, and Cr | *Helianthus annus* | [Waseem et al. (2024](https://www.sciencedirect.com/science/article/pii/S014765132400959X" \l "bib220)) |
| Pentachlorophenol | *Typha angustifolia*and*Schoenoplectus* | Werheni-Ammeri et al. (2023) |
| Chlorpyrifos | *Mentha piperita* | Aioub et al. (2024) |
| Hexazinone | *Canavalia ensiformes* | Teóflo et al. (2020) |
| Atrazine | *Zea mays* | Ibrahim et al. (2013) |
| Triazophos | *Iris pseudacorus* | Li et al. (2014) |
| Polycyclic aromatic hydrocarbons | *Eleocharis ochrostachys* | Al-Sbani et al. (2021) |
| Petroleum hydrocarbons | *Scirpus grossus* | Sharuddin et al. (2024) |
| Total petroleum hydrocarbons | [*Lolium multiflorum*](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/lolium-multiflorum)*, Trifolium repens* and[*Medicago sativa*](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/medicago-sativa) | Yousaf et al., (2022) |

**5.1 MICROBIAL REMEDIATION**

Microbial bioremediation is a method for removing, degrading and immobilizing pollutants that involves microbes such as bacteria, fungi and archaea. Soil microbes degrade or immobilize metals and organic pollutants into end product using metabolism for cell growth (Verma and Kuila 2019). Therefore, microbes are essential component of remediation process for both aerobic and anaerobic decomposition. Due to their ability to thrive in a variety of environmental circumstances, microorganisms are best suited to be used in the treatment of polluted soils using a variety of ways such as biodegradation, biosorption, bio mineralization, bioaccumulation and biotransformation (Fig.1).



**Fig 1. Remediation mechanism by microorganisms in soil**

**5.1.1 BIODEGRADATION**

Microbial biodegradation occurs under aerobic or anaerobic circumstances. While various enzymes are involved in each situation, it appears that both aerobic and anaerobic microbial degradation should take place if mineralization is anticipated to occur.Pesticide biodegradation means incorporation of efficient microbial enzyme to break down the residue of pesticide into low molecular product. Various microbial diversity and their communities have a great ability to reduce pesticide persistency as eco-friendly. The anti-catabolic plasmid of microorganisms contains the pesticide-degrading gene, which encodes the contaminant-degrading enzymes. For example, *lin* gene of gram-negative soil bacteria inscribe the specific enzyme such as dehydrogenase, dehalogenase, and hydrolase which degrade the hexachlorocyclohexane (Pan et al. 2012).

**5.1.2 BIOTRANSFORMATION**

Biotransformation is not degradation process but it transforms the toxic pollutants into other form which is less toxic or degradable by other microbial communities. It involves conversion of heavy metals, plastics and hydrocarbons to either a less toxic compound or a water-soluble state due to altered physic-chemical properties by soil microorganisms during bioremediation (Emenike et al. 2018). The heavy metals cannot be destroyed but can only be precipitated, leached, chelated, and methylated. To make the metals less poisonous, water-soluble, and perceptible, it is crucial to modify their redox state and convert them from organic to inorganic forms. In an oxidizing environment, microorganisms assist in the oxidation of the heavy metal, and nitrates and sulfates serve as terminal electron acceptors. The oxidation of organic contaminants proceeds more quickly due to the increased availability of the metals. Therefore, metal serve as terminal electron acceptor is known as dissimilatory metal reduction. For example, many bacterial and fungal communities transformed Cr (VI) to Cr (III) and Hg (II) into volatile Hg (0) which is soluble and less poisonous for the ecosystem (Hansda et al. 2016).

**5.1.3 BIOADSORPTION**

Bioadsorption is metabolism independent mechanism in which different heavy metals are absorbed by microorganism in their extracellular structures without any energy being used. Bioadsorption includes various mechanisms such as ion exchange, complexation, electrostatic interaction, diffusion, chelation, surface adsorption, and micro-precipitation which assist during effective bioremediation (Yang et al. 2015). This mechanism happens in the cell wall which has extracellular polymeric substance having acid-base properties. The cell walls, which are mostly made of lipids, polysaccharides, and proteins, provide various functional groups, such as amine, hydroxyl, phosphate, carbonyl, thiol, and sulfate groups. These compounds absorb pollutants through electrostatic, proton exchange, or micro-precipitation of heavy metals. For example, *Cunnighamellaelegans*and *Saccharomyces cerevisiae* were shown as bio-adsorbent and eliminate Cd and Zn through ion exchange process (Fang et al. 2010).

**5.1.4 BIOMINERALIZATION**

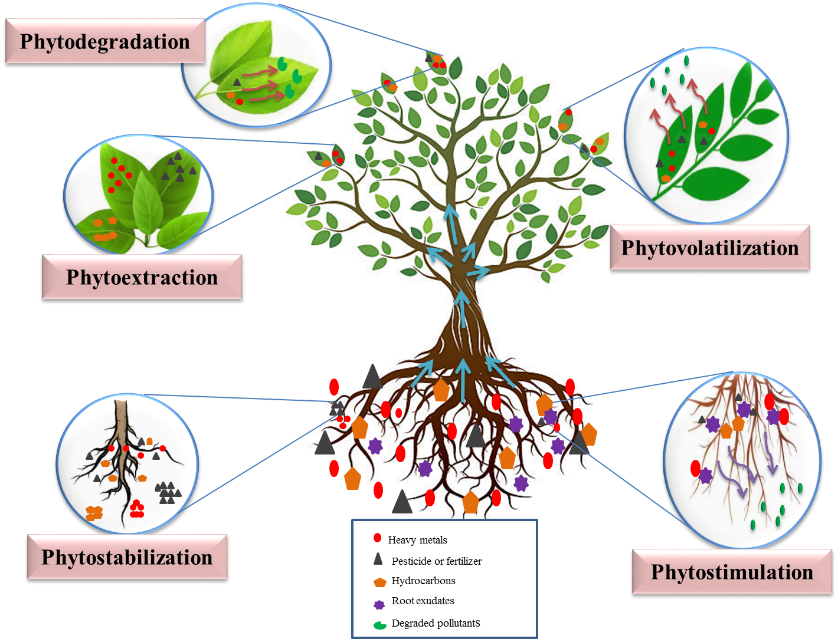
The process of converting ionic metals into solid minerals in cells and particular tissues while being influenced or controlled by biological organic matter is known as biomineralization. Depending on how much the product is regulated by biology, this mechanism can be classified into two groups (1) biologically induced mineralization which takes place outside of the cell, and (2) biologically controlled mineralization which involves two ways. Cations are first actively carried within the cell, where they are subsequently dispersed throughout the organic matrix. Second, cations accumulate in the cell to form vesicles, which are subsequently transferred outside of the cell where they disintegrate in the organic matrix to liberate cations and produce minerals. Many microbial communities play a significant role in the mineralization of heavy metals from polluted area. For example, In addition to being intensively researched for their ability to immobilize Pb ions, phosphorus solubilizing bacteria (PSB) are also capable of degrading organic phosphorus and releasing enzymes such as phosphatase and phytase. These released substances by PSB could enhance the mineralization of insoluble phosphate and increase the quick formation of lead phosphate in Pb-contaminated soil (Zhu et al. 2019).

**5.1.5 BIOACCUMULATION**

Bioaccumulation is the metabolic process of microorganisms that accumulates pollutants inside the cell (Ayangbenro and Babalola 2017). Bioaccumulation includes active and passive process which is dependent on chemical, physical and biological activity for removal of pollutants. When a substance's concentration in the biosphere is significantly higher than in its surroundings, bioaccumulation occurs. Pollutants can affect the biota through the process of bioaccumulation. The lipophilic element of the cell membrane easily absorbs lipophilic pesticides using the octanol and water ratio parameters in cell metabolism. Microbial cells accumulate contaminants inthe cytoplasm in the form of insoluble products and by-products (Ojuederie and Babalola 2017). Meanwhile, soil pollutants (organic pollutants and heavy metals) significantly influence the bioaccumulation process. Furthermore, the coexistence of organic contaminants and heavy metals has a significant impact on bioaccumulation.

**5.2 PLANT-BASED REMEDIATION: PHYTOREMEDIATION**

Phytoremediation is a plant-based remediation process that is an eco-friendly and cost-effective *in-situ* mechanism which involves rhizosphere associated microbes to remove, transfer, and stabilize the contaminants. Plants can significantly contributeto cleaning organic and inorganic pollutants as well as radionuclides using various mechanisms such as phytodegradation, phytoextraction, phytostabilization, phytovolatilization, and phytostimulation (Alkorta et al. 2004) (Fig.2).

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**Fig 2. Remediation mechanism by plants in soil**

**5.2.1 PHYTODEGRADATION AND PHYTOTRANSFORMATION**

Phytodegradation is the transformation of contaminants to less toxic, immobile, and more stable forms using the plant enzyme. Phytodegradation activity does not include only microbial enzyme but also include the plants enzyme such as nitroreductase, laccase, dehalogenase, nitrilase and peroxidase. For example, plant *Canna indicaLinn*. increase phosphatase enzyme activity which promote degradation of triazophos in rhizosphere (Cheng et al. 2007). Sometimes, organic pollutants are absorbed by roots through the stimulation process and degraded by dehalogenases and oxygenase enzyme activity inside the plants. A transgenic plant using an enzyme from bacteria that hydrolyzes organophosphorus destroyed more than 99 percent of the chemical methyl parathion after 14 days of growth (Wang et al 2008).

**5.2.2 PHYTOEXTRACTION**

Phytoextraction is the process through which pollutants are taken up by plant roots, transported through the soil, and then accumulated in plant tissues. The main purpose of phytoextraction is to accumulate or store large quantities of pollutants from soil in plants that can be disposed of. The pollutants are translocated by plants on two way; (1) Air to plants and (2) soil to plants (Singh and Singh 2017). In the air-to-plant system, heavy metal-containment particles are accumulated on plant surfaces, while, foliar-applied pesticide are absorbed by leaves and deposited on leave surface. For example, Gjorgieva et al. (2011) reported that some heavy metals such as Cd, Zn, Mn, Pb Ni and Cu were accumulated on foliar plant part of *Robinia pseudoacacia, Urtica dioica* and*Matricaria recutita* growing in the industrial field. In soil to plant system, the root systems absorb pollutants close to the root surface and mostly transmit them through the xylem vessels into the shoots and leaves. The bioaccumulation factor (bioconcentration factor) of the root depicts the capacities of phytoextraction pollutants and the translocation factor of the root system represents the translocation abilities in contaminated soil (Mercado-Borrayo et al. 2015).

**5.2.3 PHYTOSTABILIZATION**

Phytostabilization is a stabilizing procedure that uses vegetation to minimize bioavailability or prevent the migration of contaminants in contaminated areas. The phytostabilization focuses on decreasing the movement and availability of contaminants, thus restricting their entry and leaching into groundwater and food systems, respectively (Khalid et al. 2017). Generally, plants containing fibrous root systems such as grasses, wetland species, and many herbaceous plants are preferred for stabilization of soil pollutants. For example, the plants*Cecropia hololeucaMiq.* and *Cecropia hololeucaMiq.* have the capacity for reducing the bioavailability of atrazine in pesticide-contaminatedfields. Pereira et al. (2013) found that *Cordia africana* plant prevented the movement of some heavy metals such as Cd, Pb, and Zn using the phytostabilization process in contaminated soil.

**5.2.4 PHYTOVOLATILIZATION**

Plants have great capability for conversion of original pollutants into volatile compounds which is released from plant body into atmosphere through transpiration, is known as phytovolatilization. Sometimes plants evaporate the pollutants in the volatile form directly through foliage and stem activity and indirectly from soil due to root activity (Limmer and Burken 2016). Contaminants are absorbed and translocated by plants by direct phytovolatilization that is more logical idea for understanding of phytoremediation. When root activities enhance the flux of volatile pollutants underground, this is known as indirect phytovolatilization. Pollutants that are easily converted into vapor and discharged into the atmosphere, such as volatile and semivolatile organic chemicals and some heavy metals, are subject to phytovolatilization. For example, pesticide trichloroethylene can be eliminated by volatilizing from the trunk of a poplar tree, leaves (0.34 ± 0.16 Kg/year), and soil-driven by root activity (0.48 ± 0.36 kg/year) (Doucette et al. 2013). Similarly, many pollutants can be removed through phytovolatilization such as heavy metals e.g. Hg, As, and Se, and pesticides e.g. carbon tetrachloride, methyl-tert-butyl ether, ethylenedibromide (Niti et al. 2013).

**5.2.5 PHYTOSTIMULATION**

Phytoremediation is the performance of plants to alter the rhizosphere's properties through rhizodeposition stimulating the rhizomicrobial community to break down toxic pollutants into less toxic compounds. Phytostimulationplaysan important role in the mineralization of heavy metals e.g. Cu, Pb, Zn, Cd, As (Imperator et al. 2019), herbicides e.g. trifloxysulfuron-sodium (Santos et al. 2010), sulfentrazone (Belo et al. 2011) and hydrocarbon (Hoffma and Yarrow 2003). Various root exudates such as carbohydrates, protein, amino acids and organic acid are released by plant root for increasing the soil microbial population and their activity which have the ability to degrade toxic compounds. Plant roots can stimulate rhizomicrobiome in different pathways (Song et al. 2019); (i) plant root offers attachment of rhizomicrobiome on the surface as residency for proliferation. (ii) Plant roots enhance the potential of microbial function by releasing the root exudate and facilitating the nutrient dynamics in the rhizosphere. (iii) Root exudates change the properties of pollutants in the rhizosphere.

**6. CURRENT CHALLENGES IN BIOREMEDIATION**

Even though bioremediation has been applied successfully to treat contaminated sites, several issues sometimes arise that make the approach less advantageous. This results in various technology-related drawbacks and the necessity for more research, both of which impose several restrictions or limitations.

**6.1 INCOMPLETE DEGRADATION**

There is uncertainty regarding the amount to which a successful degradation process can occur because the idea of a complete transformation into nontoxic compounds is simply a theoretical probability (Das and Chandran 2011). Many factors play an important role in the breakdown of pollutants such as quantities and nature of pollutants. One illustration would be the fact that the daughter product's toxicity ended up being higher as compared to parent compound, demonstrating that the method of changing a compound into a safe compound is not always certain.

**6.2 BIOLOGICAL SYSTEMS ARE HIGHLY SPECIFIC**

Environmental elements have a crucial role in influencing the success of plant and microbial activity because plants or microbes are very condition-specific when performing a process, whether it is in connection to growth circumstances or degrading activity (Das and Chandran 2011). The environment, provided nutrient quality and quantity are extremely significant in observing the process after conditioning the place of interest. In practice, it may be challenging to maintain consistency when conditions differ from one contaminated site to another due to a variety of complicated existing ecosystems. Furthermore, even under perfect circumstances, the organisms are required to metabolize the supplied nutrients to contact with the relevant pollutant. Nutrient addition may have been mainly to enhance microbial growth under favorable conditions.

**6.3 INTRODUCTION OF NON-NATIVE ORGANISMS**

Although the introduction of non-native species may have been done with the best of intentions to clean up the contaminated area, questions remain about whether the organisms do not present a hazard to other native creatures that are already present in the ecosystem. As more research is needed to understand the long-term impacts of the biodegradation process

**6.4 TECHNOLOGY STILL IN ITS INFANCY**

Although bioremediation has been successfully used on a variety of projects, it is still relatively new as a strategy for treating pollutants. Numerous studies need to be conducted to better understand the situation and build a sound theoretical foundation that will enable the advancement of current technology as well as the continued development of fresh approaches to increase efficiency and the scope of applications. Presently, there are many troubles onto generalizing a benchmark and pilot studies with regard to large scale operation (Kostka et al. 2011).

**6.5 NOT ALL POLLUTANTS ARE BIODEGRADABLE**

Only biodegradable pollutants are degraded by microbes but not all contaminants are degradable such as highly aromatic hydrocarbon and chlorinated organic compounds are unaffected by microbial degradation. Therefore, sometimes microbial remediation process may take more time as compared to other methods (Zeyaullah et al. 2009).

**6.6 TOXIC INTERMEDIATES DURING BIOREMEDIATION**

The presence of native species and a high pollution concentration could both hinder the growth of inoculated microbes (Cycon et al. 2017). Sometimes toxic intermediates are released during the breakdown of HCN and lindane which inhibit the remediation capacity of inoculated microbes as well as some native microbial population growth.

**7. FUTURE PROSPECT**

* Many findings have been reported under controlled conditions in the lab. The experimental parameters should apply under field conditions, including pollutant and weather conditions. Further research should be conducted to verify the efficiency of bioremediation in natural conditions, using alternative pot experiments. Field application of any bioremediation process should be tested at multiple locations. It is necessary to screen naturally occurring highly efficient new microbes for practical application.
* In the process of bioremediation, it's important to not only focus on specific pollutants such as heavy metals, organic pollutants, and hydrocarbons, but also consider their metabolites. The byproducts of pollutants are often more toxic than the original pollutants and can persist in the soil for a long time.
* Plants for papermaking, phytomining, bioenergy, and wood processing should be managed for harvest and post-harvest. Harvesting waste material from plant biomass must not affect the natural ecosystem.
* It is important to have the right materials, infrastructure, and tools for experiments. In order to obtain accurate results, all the materials and tools should work properly at a high level of success after being used in a contaminated site. It's important to note that if the technology is not relatively advanced, a lack of specialized advanced instruments can ultimately hinder the ability to develop and conduct research on bioremediation processes.
* It is essential to consider the intricate interaction of two or more contaminants during phytoremediation and microbial-based remediation. Their interaction could be beneficial for degrading complex pollutants. In addition, it is important to focus on understanding the interaction between plants, microbes, and the interactions between different plants and different microbes in contaminated soil conditions.

**8. CONCLUSION**

It is imperative to conduct future studies and research to develop effective bioremediation techniques that are both environmentally friendly and socially acceptable. This is crucial for removing emerging pollutants and their toxic intermediate compounds, which continue to present significant challenges to ecosystems, natural resources, and human health. It is necessary to focus on isolating, culturing, and studying naturally occurring microbes and plants with unique metabolic pathways that enable their survival in polluted areas, as this holds great promise for bioremediation efforts.

Considering the current state of bioremediation, this paper emphasizes that various factors, such as the remediation mechanisms of plants and microbes, their activity, pollutant concentration, as well as the category and characteristics of pollutants, play crucial roles in efficient and eco-friendly bioremediation. Furthermore, the implementation of multidisciplinary strategies can enhance the predictability of removing pollutants from different environments. It is also important to prioritize the development and utilization of cutting-edge technologies for monitoring, preventing, and mitigating environmental and health concerns. Identifying future challenges is essential for minimizing the environmental impacts associated with emerging contaminants.

**DECLARATION OF INTERESTS**

* The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.
* The authors declare the following financial interest or relationship that may be considered potential competing interests.

**DATA AVAILABILITY STATEMENT**

No datasets were generated or analysed during the current study.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declares that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**COMPETING INTERESTS**

Authors have declared that no competing interests exist

**REFERENCES**

Adams GO, Fufeyin PT, Okoro SE, Ehinomen I (2015) Bioremediation, Biostimulation and Bioaugmention: A Review**.**International Journal of Environmental Bioremediation & Biodegradation3(1):28-39. https://doi.org/[10.12691/ijebb-3-1-5](http://dx.doi.org/10.12691/ijebb-3-1-5)

Adepoju AO, Femi-Adepoju A, Jalloh A, Faeflen S, (2024) Soil pollution and management practices. In Environmental Pollution and Public Health, Frazer-Williams, R., Ogundiran, M.B., Unuabonach, E.I., Eds.; Elsevier: Amsterdam, The Netherlands, pp. 187–236.

Agarry S, Latinwo GK (2015) Biodegradation of diesel oil in soil and its enhancement by application of Bioventing and amendment with brewery waste effluents as Biostimulation-Bioaugmentation agents. Journal of Ecological Engineering16:82-91. https://doi.org/[10.12911/22998993/1861](https://doi.org/10.12911/22998993/1861)

Aioub AAA, Fahmy MA, Ammar EE, Maher M, Ismail HA, Yue J, Zhang Q, & Abdel-Wahab SIZ, (2024). Decontamination of Chlorpyrifos Residue in Soil by Using *Mentha piperita* (Lamiales: Lamiaceae) for Phytoremediation and Two Bacterial Strains. Toxics, 12(6):435. <https://doi.org/10.3390/toxics12060435>

Ali M, Song X, Ding D, Wang Q, Zhang Z and Tang Z, (2022) Bioremediation of PAHs and heavy metals co-contaminated soils: challenges and enhancement strategies. Environmental Pollution, *295*:118686.

Ali MH, Khan MI, Naveed M, and Tanvir MA, (2024) Microbe-assisted rhizodegradation of hydrocarbons and growth enhancement of wheat plants in hydrocarbons contaminated soil. International Journal of Environmental Science and Technology, 21(3):3169-3184.

Alkorta I, Hernandez-Allica J, Becerril JM, Amezaga I, Albizu I Garbisu C (2004) Recent fndings on the phytoremediation of soils contaminated with environmentally toxic heavy metals and metalloids such as zinc, cadmium, lead, and arsenic. Review of Environmental. Science and Biotechnology 3:71–90.  <https://doi.org/10.1023/B:RESB.0000040059.70899.3d>

AlSbani NHA, Abdullah SRS, Idris M, Hasan HA, Halmi MIE, Jehawi OH, (2021) PAH-degrading rhizobacteria of Lepironia articulata for phytoremediation enhancement J. Water Process Eng., 39, Article 101688, [10.1016/j.jwpe.2020.101688](https://doi.org/10.1016/j.jwpe.2020.101688)

Alshemmari H, Al-Shareedah AE, Rajagopalan S, Talebi LA, Hajeyah M, (2021) Pesticides driven pollution in Kuwait: The first evidence of environmental exposure to pesticides in soils and human health risk assessment. Chemosphere. 1(273):129688. <https://doi.org/10.1016/j.chemosphere.2021.129688>

Antoniadis V, Shaheen SM, Stärk HJ, Wennrich R, Levizou E, Merbach I, and Rinklebe J, (2021) Phytoremediation potential of twelve wild plant species for toxic elements in a contaminated soil. Environment International, *146*:106233.

Atuchin VV, Asyakina LK, Serazetdinova YR, Frolova AS, Velichkovich NS, and Prosekov AY, (2023) Microorganisms for bioremediation of soils contaminated with heavy metals. Microorganisms, 11(4):864.

Auta HS, Emenike CU, Fauziah SH (2017) Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. [Environment International](https://www.sciencedirect.com/journal/environment-international) 102:165-176. <https://doi.org/10.1016/j.envint.2017.02.013>

Ayangbenro SA, Babalola OO (2017) A new strategy for heavy metals polluted environments: a review of microbial biosorbents*.* International Journal of Environmental Research Publication Health 14(1):94.  <https://doi.org/10.3390/ijerph14010094>

Bandopadhyay A, Roy T, Alam S, Majumdar S, Das N, (2023) Influence of pesticidetolerant soil bacteria for disease control caused by Macrophomina phaseolina (Tassi.) Goid and plant growth promotion in Vigna unguiculata (L.) Walp. Env. Develop. Sustain. Times 25, 14693–14713. https://doi.org/10.1007/s10668-022-02684-x.

Battaglia ML, Ketterings QM, Godwin G, Czymmek KJ (2021) Conservation tillage is compatible with manure injection in corn silage system. Agronomy journal 113(3):2900-2912.  <https://doi.org/10.1002/agj2.20604>

Belo AF, Coelho A, Ferreira LR, Silva AA, Santos JB (2011) Potential of plant species in the remediation of soil contaminated with sulfentrazone. Planta Daninha 29(4):821-828. <https://doi.org/10.1590/S0100-83582011000400012>

Brahney J, Hallerud M, Heim E, Hahnenberger M, Sukumaran S (2020) Plastic rain in protected areas of the United States. Science368(6496):1257-1260. <https://doi.org/10.1126/science.aaz581>

Brühl CA, Engelhard N, Bakanov N, Wolfram J, Hertoge K, and Zaller JG, (2024) Widespread contamination of soils and vegetation with current use pesticide residues along altitudinal gradients in a European Alpine valley. Communications Earth & Environment, *5*(1):72. <https://doi.org/10.1038/s43247-024-01220-1>

Chahal S, Wang P, Bueno V, et al. (2023) Effect of emerging contaminants on soil microbial community composition, soil enzyme activity, and strawberry plant growth in polyethylene microplastic-containing soils. Environ Sci Adv. 2:629–44

Chaurasia J, Ghimirey V, Marahatta S, (2024) Understanding the impact of polycyclic aromatic hydrocarbons: soil, environment, and human health. Environment & Ecosystem Science. 8(2):43-6. DOI: <http://doi.org/10.26480/ees.02.2024.43.46>

Chen H, Teng Y, Lu S, Wang Y, Wang J, (2015) Contamination features and health risk of soil heavy metals in China. Sci Total Environ 512:143–153. https:// doi.org/10.1016/j.scitotenv.2015.01.025.

Cheng S, Xiao J, Xiao H, Zhang L, Wu Z (2007) Technical note phytoremediation of triazophos by Canna indica Linn. in a hydroponic system. Inter4national Journal of Phytoremediation 9:453-463. <https://doi.org/10.1080/15226510701709531>

Cycon M, Mrozik A, Piotrowska-Seget Z (2017) Bioaugmentation as a strategy for the remediation of pesticide-polluted soil: A review. [Chemosphere](https://www.sciencedirect.com/journal/chemosphere)[172](https://www.sciencedirect.com/journal/chemosphere/vol/172/suppl/C):52-71. <https://doi.org/10.1016/j.chemosphere.2016.12.129>

Das N, Chandran P (2011) Microbial Degradation of Petroleum Hydrocarbon Contaminants: An Overview. Biotechnology Research Interntional 13. <https://doi.org/10.4061/2011/941810>

Doucette W, Klein H, Chard J, Dupont R, Plaehn W, Bugbee B (2013) Volatilization of Trichloroethylene from Trees and Soil: Measurement and Scaling Approaches. Environmental Science and Technology47(11):5813-5820. https://doi.org/[10.1021/es304115c](https://doi.org/10.1021/es304115c)

Ehis-Eriakha CB, Ajuzieogu CA, Orogu JO, and Akemu SE, (2024) Overview of petroleum hydrocarbon pollution and bioremediation technologies. Bioremediation Journal, pp.1-23. <https://doi.org/10.1080/10889868.2024.2349014>

Emami S, Pourbabaee AA, Alikhani HA (2012) Bioremediation Principles and Techniques on Petroleum Hydrocarbon Contaminated Soil. Technical Journal of Engineering and Applied Sciences 2:320-323. <http://tjeas.com/wp-content/uploads/2012/12/320-323.pdf>

Emenike CU, Jayanthi B, Agamuthu P, Fauziah SH (2018) Biotransformation and removal of heavy metals: a review of phytoremediation and microbial remediation assessment on contaminated soil. Environmental Review 26:156-168. <https://doi.org/10.1139/er-2017-0045>

Erika AW, Vivian B, Claudia C, Jorge FG (2013) Biodegradation of phenol in static cultures by *Penicillium chrysogenumer* k1: catalytic abilities and residual phytotoxicity*.*Rev Argent Mcrobiol 44: 113-121.

Espinosa-López F, Pelcastre-Guzmán K, Cerón-Nava A, Rivera-Noriega A, Loza-Mejía MA, and Islas-García A, (2025) Sustainable Remediation Using Hydrocarbonoclastic Bacteria for Diesel-Range Hydrocarbon Contamination in Soil: Experimental and In Silico Evaluation. Sustainability, *17*(12):5535.

Essabri AMA, Aydinlik NP, Willia NE (2019) Bioaugmentation and biostimulation of total petroleum hydrocarbon degradation in a petroleum-contaminated soil with fungi isolated from olive oil effluent. Water, Air, and Soil Pollution 230:1-16. https://doi.org/10.1007/s11270-019-4127-8

Fang L, Huang Q, Wei X, Liang W, Rong X, Chen W Cai P (2010) Microcalorimetric and potentiometric titration studies on the adsorption of copper by extracellular polymeric substances (EPS), minerals and their composites. Bioresource Technology. 101:5774-5779. <https://doi.org/10.1016/j.biortech.2010.02.075>

Fantke P, Charles R, Alencastro LF, de Friedrich R, Jolliet O, (2011) Plant uptake of pesticides and human health: dynamic modeling of residues in wheat and ingestion intake. Chemosphere. <https://doi.org/10.1016/j.chemosphere.2011.08.030>.

FAO and UNEP, (2021) Food and Agriculture Organization of the United Nations and United Nations Environment Programme, Global Assessment of Soil Pollution (FAO and UNEP, 2021).

## Feng NX, Yu J, Zhao HM, Cheng YT, Mo CH, Cai QY, Li Y.W., Li H, Wong MH (2017) Efficient phytoremediation of organic contaminants in soils using plant-endophyte partnerships. Science of the total environment 583:352-368. <https://doi.org/10.1016/j.scitotenv.2017.01.075>

Fenner K, Canonica S, Wackett LP, Elsner M (2013) Evaluating Pesticide Degradation in the Environment: Blind Spots and Emerging Opportunities, Science 341:752-758. https://doi.org/[10.1126/science.1236281](https://doi.org/10.1126/science.1236281)

Gjorgieva D. Kadifkova-Panovska T, Baceva K, Stafilov T (2011) Assessment of heavy metal pollution in Republic of Macedonia using a plant assay. Archive of Environmental Contamination and Toxicology. 60:233-240.  <https://doi.org/10.1007/s00244-010-9543-0>

Grafkina MV, and Pitryuk AV, (2022) February. Evaluation of statistical data on soil contamination of the Krasnodar Territory with pesticides. In *IOP* Conference Series: Earth and Environmental Science (Vol. 979, No. 1, p. 012131). IOP Publishing.

Hansda A, Kumar V, Anshumali A (2016) Comparative review towards potential of microbial cells for heavy metal removal with emphasis on biosorption and bioaccumulation, World Journal of Microbiology and Biotechnology 32:170. <https://doi.org/10.1007/s11274-016-2117-1>

Hoang SA, Lamb D, Seshadri B, Sarkar B, Choppala G, Kirkham MB, Bolan NS (2021) Rhizoremediation as a green technology for the remediation of petroleum hydrocarbon-contaminated soils. [Journal of Hazardous Materials](https://www.sciencedirect.com/journal/journal-of-hazardous-materials) 401:123282. <https://doi.org/10.1016/j.jhazmat.2020.123282>

Hoffman KM., Nelson YM (2003) Phytostimulation of hydrocarbon biodegradation by arroyo willows in laboratory microcosms. In Phytoremediation of Petroleum-contaminated Sites-Seventh International Conference on *In Situ* and On-Site Bioremediation (Orlando FL; June 2003). Battelle Press. ISBN 1-57477-139-6. <https://doi.org/10.1016/S1001-0742(13)60417-9>

## Huang H, Yu N, Wang L, Gupta DK, Z. He, K. Wang, Z. Zhu, X. Yan, T. Li, X.E. Yang (2011) The phytoremediation potential of bioenergy crop *Ricinus communis* for DDTs and cadmium co-contaminated soil. Bioresource Technology102:11034-11038. <https://doi.org/10.1016/j.biortech.2011.09.067>

Ibrahim SI, Abdel LMF, Khalifa HMS, Abdel MAE (2013) Phytoremediation of atrazine-contaminated soil using Zea mays (maize). Annals of Agricultural Sciences 58(1):69-75. <https://doi.org/10.1016/j.aoas.2013.01.010>

Imam A, Suman SK, Vempatapu BP, Tripathi D, Ray A, and Kanaujia PK, (2022) Pyrene remediation by Trametes maxima: an insight into secretome response and degradation pathway. Environmental Science and Pollution Research, 29(29):44135-44147. https://doi.org/10.1007/s11356-022-18888-7

Imperato V, Portillo-Estrada M, McAmmond BM (2019) Genomic diversity of two hydrocarbon-degrading and plant growth-promoting pseudomonas species isolated from the oil field of Bobrka (Poland). Genes (Basel) 10(6):443.  <https://doi.org/10.3390/genes10060443>

Inbit MJO, Kazem AAA, Hussein HH, Abd AL-kadum mageed Brism, R. (2024) The Impact of Human Activities on Environmental Sustainability. *J. Med.* Genet. Clin. Biol. *1*:119–141.

## Jacob JM, Karthik C, Saratale RG, Kumar SS, Prabakar D, Kadirvelu K (2018) Biological approaches to tackle heavy metal pollution: a survey of literature. Journal of Environmental. Management217:56-70. <https://doi.org/10.1016/j.jenvman.2018.03.077>

Jia Y, Kang L, Wu Y, Zhou C, Li D, Li J, Pan C, (2023) Review on pesticide abiotic stress over crop health and intervention by various biostimulants. Journal of Agricultural and Food Chemistry. 71(37):13595-611. <https://pubs.acs.org/doi/10.1021/acs.jafc.3c04013>

Kalyabina VP, Esimbekova EN, Kopylova KV, et al. (2021) Pesticides: formulants, distribution pathways and effects on human health–a review. Toxicology Reports. 8:1179-1192. doi: 10.1016/j.toxrep.2021.06.004

Kehinde FO, Isaac SA (2016) Effectiveness of augmented consortia of Bacillus coagulans, Citrobacter koseri and Serratia ficaria in the degradation of diesel polluted soil supplemented with pig dung. Afr J Microbiol Res 10:1637-1644. <https://doi.org/10.5897/AJMR2016.8249>

Khalid S, Shahid M, Niazi NK, Murtaza B, Bibi I, Dumat C (2017) A comparison of technologies for remediation of heavy metal contaminated soils. Journal of Geochemical Explore 182:247-268. <https://doi.org/10.1016/j.gexplo.2016.11.021>

Khan AA, Kamal A, Alrefaei AF, and Zaman W, (2025) Utilization and Characterization of Microbes for Heavy Metal Remediation. Polish Journal of Environmental Studies, *34*(2).

Kostka JE, Prakash OM, Overholt WA, Green SJ, Freyer G, Canion A, Delgardio J, Norton N, Hazen TC, Huettel M (2011) Hydrocarbon-Degrading Bacteria and the Bacterial Community Response in Gulf of Mexico Beach Sands Impacted by the Deepwater Horizon Oil Spill. Applied and Environmental Microbiology 77:7962–7974. <https://doi.org/10.1128/AEM.05402-11>

Kumar M, Chen HY, Sarsaiya S, Qin SY, Liu HM, Awasthi MK, Kumar S, Singh L, Zhang ZQ, Bolan NS, Pandey A, Varjani S, Taherzadeh MJ (2021) Current research trends on micro- and nano-plastics as an emerging threat to global environment: a review. Journal of Hazardous Materials409:124967. <https://doi.org/10.1016/j.jhazmat.2020.124967>

Kumar M, Xiong X, He M, Tsang DC, Gupta J, Khan E, Harrad S, Hou D, Ok YS, Bolan NS (2020) Micro-plastics as pollutants in agricultural soils. Environmental Pollution 265:114980. <https://doi.org/10.1016/j.envpol.2020.114980>

Kumari K, Cherian S, & Bauddh K (2022). Microbial augmented phytoremediation with improved ecosystems services. In Advances in microbe-assisted phytoremediation of polluted sites, pp. 27–62. Elsevier. https://doi.org/10. 1016/B978-0-12-823443-3.00017-X

## Li CH, Wong YS, Tam NF 2010 (2010) Anaerobic biodegradation of polycyclic aromatic hydrocarbons with amendment of iron (III) in mangrove sediment slurry. Bioresource Technology101(23):8083-8092. <https://doi.org/10.1016/j.biortech.2010.06.005>

Li W, Zhu Y, Li K, Wang L, Li D, Liu N, Huang S, (2023) Synergistic remediation of phenanthrene–cadmium co-contaminants by an immobilized acclimated bacterial–fungal consortium and its community response Chemosphere, 336, Article 139234, [10.1016/j.chemosphere.2023.139234](https://doi.org/10.1016/j.chemosphere.2023.139234)

Li X, Xiao J, Gai X, Du Z, Salam MMA, and Chen G, (2023) Facilitated remediation of heavy metals contaminated land using Quercus spp. with different strategies: Variations in amendments and experiment periods. Science of the Total Environment, *876*:163245.

Li Z, Xiao HP, Cheng SP, Zhang LP, Xie XL, Wu ZB (2014) A comparison on the phytoremediation ability of triazophos by different macrophytes. Journal of Environmental Sciences 26(2):315-322.

Limmer M, Burken J (2016) Phytovolatilization of Organic Contaminants. Environmental Science and Technology 50:6632-6643. https://doi.org/10.1021/acs.est.5b04113

Liu E, Terumasa T, (2022) Effects of applying recycled urban green waste compost made from pruning materials to soil on the growth of plants. J. Soil Sci. Plant Nut. 22, 1088–1097. <https://doi.org/10.1007/s42729-021-00717-4>.

Liu F, Zhang K, Zhao Y, Li D, Sun X, Lin L, Feng H, Huang Q, Zhu Z, (2024) Screening of cadmium-chromium-tolerant strains and synergistic remediation of heavy metal-contaminated soil using king grass combined with highly efficient microbial strains. Sci. Total Environ. 912, 168990 [https://doi.org/10.1016/j. scitotenv.2023.168990](https://doi.org/10.1016/j.%20scitotenv.2023.168990).

Liu Q, Tang J, Liu X, Song B, Zhen M, Ashbolt NJ (2019) Vertical response of microbial community and degrading genes to petroleum hydrocarbon contamination in saline alkaline soil. Journal of Environmental Sciences 81:80-92. <https://doi.org/10.1016/j.jes.2019.02.001>

Macklin MG, Thomas CJ, Mudbhatkal A, Brewer PA, Hudson-Edwards KA, Lewin J, Scussolini P, Eilander D, Lechner A, Owen J, and Bird G, (2023) Impacts of metal mining on river systems: a global assessment. *Science*, *381*(6664):1345-1350. [DOI: 10.1126/science.adg67](https://doi.org/10.1126/science.adg6704)04

Mali H, Shah C, Raghunandan BH, Prajapati AS, Patel DH, Trivedi U, Subramanian RB, (2023) Organophosphate pesticides an emerging environmental contaminant: Pollution, toxicity, bioremediation progress, and remaining challenges. Journal of Environmental Sciences. 1(127):234-50. <https://doi.org/10.1016/j.jes.2022.04.023>

Meharg AA, and Meharg C, (2021) The pedosphere as a sink, source, and record of anthropogenic and natural arsenic atmospheric deposition. Environmental science & technology, *55*(12):7757-7769. <https://doi.org/10.1021/acs.est.1c00460>

Mercado-Borrayo BM, Cram Heydrich S, Rosas Pérez I, Hernandez Quiroz M, Ponce De Leon Hill (2015) Organophosphorus and Organochlorine Pesticides Bioaccumulation by Eichhornia crassipes in Irrigation Canals in an Urban Agricultural System. International Journal of Phytoremediation 17(7):701-708. <https://doi.org/10.1080/15226514.2014.964841>

Nie J, Sun Y, Zhou Y, Kumar M, Usman M, Li J, Shao J, Wang L, and Tsang DC, (2020) Bioremediation of water containing pesticides by microalgae: Mechanisms, methods, and prospects for future research. Science of the Total Environment, *707*:136080.

Niti, C., Sunita, S., Kamlesh, K., & Rakesh, K. (2013). Bioremediation: An emerging technology for remediation of pesticides. Research Journal of Chemistry and Environment 17(4).

Niu GL, Zhang JJ, Zhao S, Liu H, Boon N (2009) Bioaugmentation of a 4- chloronitrobenzene contaminated soil with Pseudomonas putida ZWL73. Environmental Pollution57(3):763-771. <https://doi.org/10.1016/j.envpol.2008.11.024>

Ojuederie OB, Babalola OO (2017) Microbial and Plant-Assisted Bioremediation of Heavy Metal Polluted Environments: A Review. International Journal of Environmental Research Publication Health 14(12):1504.  <https://doi.org/10.3390/ijerph14121504>

Pan LW, Siegrist RL, M Crimi (2012) Effects of *In Situ* Remediation Using Oxidants or Surfactants on Subsurface Organic Matter and Sorption of Trichloroethene. Groundwater Monitaring and. Remediation 32:96-105.  <https://doi.org/10.1111/j.1745-6592.2011.01377.x>

Paniagua-López M, García-Robles H, Aguilar-Garrido A, *et al.* (2024) Vegetation establishment in soils polluted by heavy metal(loid)s after assisted natural remediation. Plant Soil 497:257–275. <https://doi.org/10.1007/s11104-024-06521-0>

Pereira ACC, N.M.B.D.A. Sobrinho NMBDA, Tolon-Becerra A, Magalhaes MOL, Lastra-Bravo X (2013) Use of Cordia Africana in the Phytostabilization of Substrates from Excavations of the Ore Courtyard at the Port of Itaguai. Brazil, Soil & Sediment Contamination 22(4):376-389. https://doi.org/10.1080/15320383.2013.733446

Rahman MA, Dey B, Halim MA, Ahmed R, (2025). Mobilizing Microbes for Bioremediation Strategies in the Context of Climate Change. In: Abdel Latef, A.A.H., Zayed, E.M., Omar, A.A. (eds) Sustainable Remediation for Pollution and Climate Resilience. Springer, Singapore. <https://doi.org/10.1007/978-981-96-5674-5_13>

Rahman Z, Singh VP (2019) The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. Environmental. Monitaring and Assessment 191(7):419. <https://doi.org/10.1007/s10661-019-7528-7>

## Rajendran, P, Gunasekaran, P (2019) Microbial bioremediation. MJP Publisher.

Ricardo IA, Alberto EA, Junior AHS, Macuvele DLP, Padoin N, Soares C, Riella HG, Starling MCVM, Trovo AG (2021) A critical review on micro-plastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. Chemical Engineering Journal 424:130282. <https://doi.org/10.1016/j.cej.2021.130282>

Salem AB, Chaabane H, Ghazouani T, Caboni P, Coroneo V, Devers M, B´eguet, J, Martin-Laurent F, Fattouch S, (2022) Evidence for enhanced dissipation of chlorpyrifos in an agricultural soil inoculated with Serratia rubidaea strain ABS 10. Env. Sci. Pol. Res. 1–10 <https://doi.org/10.1007/s11356-021-17772-0>

Santos EA, Costa MD, Ferreira LR, Reis MR, Franca AC, Santos JB (2010) Atividaderizosferica de solo tratado com herbicidaduranteprocesso de remediacaopor*Stizolobium aterrimum*. Pesquisa Agropecuaria Tropical 40(1):1-7. https://doi.org/[10.5216/PAT.V40I1.4670](https://doi.org/10.5216/PAT.V40I1.4670)

Seleiman MF, Almutairi KF, Alotaibi M, Shami A, Alhammad BA, Battaglia ML (2021) Nano fertilizer as an emerging fertilization technique: why modern agriculture can benefit from its use? Plants 10(1):2.  <https://doi.org/10.3390/plants10010002>

Shahid M, Singh UB, (2024) Enhancing Spinach (*Spinacia oleracea* L.) Resilience in Pesticide-Contaminated Soil: Role of Pesticide-Tolerant *Ciceribacter azotifigens* and *Serratia marcescens* in Root Architecture, Leaf Gas Exchange Attributes and Antioxidant Response Restoration. Chemosphere, 361:142487. [https://doi.org/10.1016/j.chemosphere.2024.14248](https://doi.org/10.1016/j.chemosphere.2024.142487)

Sharma B, Dangi AK, Shukla P (2018) Contemporary enzyme based technologies for bioremediation: a review. Journal of Environmental Management 210:10-22. <https://doi.org/10.1016/j.jenvman.2017.12.075>

Sharuddin SSN, Abdullah SRS, Hasan HA, Othman AR, and Ismail NI, (2024) Rhizobacterial-assisted phytoremediation for accelerated petroleum-hydrocarbon removal in crude-oil sludge. Science of The Total Environment, 954:176189.

Silva V, Gai L, Harkes P, Tan G, Ritsema CJ, Alcon F, Contreras J, Abrantes N, Campos I, Baldi I, and Bureau M, (2023) Pesticide residues with hazard classifications relevant to non-target species including humans are omnipresent in the environment and farmer residences. Environment international, 181:108280. <https://doi.org/10.1016/j.envint.2023.108280>

Singh T, Singh DK (2017) Phytoremediation of organochlorine pesticides: Concept, method, and recent developments. International Journal of Phytoremediation 19:834-843. <https://doi.org/10.1080/15226514.2017.1290579>

Song B, Xu P, Chen M, Tang W, Zeng G, Gong J, Zhang P, Ye S (2019) Using nanomaterials to facilitate the phytoremediation of contaminated soil. Critical. Review in Environmental Science and Technology49(9):791-824. <https://doi.org/10.1080/10643389.2018.1558891>

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

Stuligross C, Williams NM, (2021) Past insecticide exposure reduces bee reproduction and population growth rate. Proc. Natl. Acad. Sci. 118, e2109909118.

Sun K, Song Y, He F, Jing M, Tang J, and Liu R, (2021) A review of human and animals exposure to polycyclic aromatic hydrocarbons: Health risk and adverse effects, photo-induced toxicity and regulating effect of microplastics. Science of The Total Environment, 773:145403. <https://doi.org/10.1016/j.scitotenv.2021.145403>

Tang FH, Lenzen M, McBratney A, Maggi F, (2021) Risk of pesticide pollution at the global scale. Nat. Geosci. 14:206–210.

Teóflo TMS, Mendes KF, Fernandes BCC, de Oliveira FS, Silva TS, Takeshita V, Silva DV (2020) Phytoextraction of diuron, hexazinone, and sulfometuron-methyl from the soil by green manure species. Chemosphere 256:127059. [https://doi.org/10.1016/j. chemosphere.2020.127059](https://doi.org/10.1016/j.%20chemosphere.2020.127059)

Thavamani P, Megharaj M, Naidu R (2015) Metal-tolerant PAH-degrading bacteria: development of suitable test medium and effect of cadmium and its availability on PAH biodegradation. Environmental Science and Pollution Research 22:8957-8968. https://doi.org/10.1007/s11356-013-1850-3

Titilayo OA, Adam AB, and Japhet, AT, (2025) Unraveling the Impact of Organic Pollutants on Plant Nutrient Uptake and Soil Microbiome Dynamics. ldealistic Journal of Advanced Research in ProgressiveSpectrums (IJARPS) eISSN–2583-6986, 4(06):65-70.

Tomar RS, & Jajoo A, (2021). Enzymatic pathway involved in the degradation of fuoranthene by microalgae Chlorella vulgaris. Ecotoxicology, 30(2):268–276. https://doi. org/10.1007/s10646-020-02334-w

Tomczyk P, Wdowczyk A, Wiatkowska B, and Szymańska-Pulikowska A, (2023) Assessment of heavy metal contamination of agricultural soils in Poland using contamination indicators. Ecological Indicators, *156*:111161. <https://doi.org/10.1016/j.ecolind.2023.111161>

Trellu C, Pechaud Y, Oturan N, Mousset E, van Hullebusch ED, Huguenot D, and Oturan MA, (2021) Remediation of soils contaminated by hydrophobic organic compounds: How to recover extracting agents from soil washing solutions?. Journal of hazardous materials, *404*:124137.

Tripathi V, Gaur VK, Kaur I, Srivastava PK, and Manickam N, (2024) Unlocking bioremediation potential for site restoration: a comprehensive approach for crude oil degradation in agricultural soil and phytotoxicity assessment. Journal of Environmental Management, 355:120508.

Tsaboula A, Menexes G, Papadakis EN, Vryzas Z, Kotopoulou A, Kintzikoglou K, Mourkidou EP (2019) Assessment and management of pesticide pollution at a river basin level part II: Optimization of pesticide monitoring networks on surface aquatic ecosystems by data analysis methods. [Science of The Total Envir](https://www.sciencedirect.com/journal/science-of-the-total-environment)onmental[653](https://www.sciencedirect.com/journal/science-of-the-total-environment/vol/653/suppl/C):1612-1622. <https://doi.org/10.1016/j.scitotenv.2018.08.240>

Valizadeh S, Enayatizamir N, Nadian Ghomsheh H, Motamedi H, Khalili Moghadam, B, and Bogard M, (2024) Bioremediation of crude oil contaminated saline soil using a bacterial consortium and different carriers. Journal of Geophysical Research: Biogeosciences, *129*(5):2023JG007874.  <https://doi.org/10.1029/2023JG007874>

Verma JP, Jaiswal DK, Sagar R (2014) Pesticide relevance and their microbial degradation: a-state-of-art, Review in Environmental Science and Biotechnology 13:429-466. https://doi.org/10.1007/s11157-014-9341-7

Verma S, Kuila A (2019) Bioremediation of heavy metals by microbial process. Environmental Technology and Innovation14:100369. <https://doi.org/10.1016/j.eti.2019.100369>

Wang J, Deng P, Wei X, Zhang X, Liu J, Huang Y, She J, Liu Y, Wan Y, Hu H, (2023) Hidden risks from potentially toxic metal (loid) s in paddy soils-rice and source apportionment using lead isotopes: A case study from China, Sci. Total. Environ. (9):856. <https://doi.org/10.1016/j.jtemin.2024.100180>

Wang X, Wu N, Guo J, Chu X, Tian J, Yao B, Fan Y (2008) Phytodegradation of organophosphorus compounds by transgenic plants expressing a bacterial organophosphorus hydrolase. Biochemical and biophysical research communications 365(3):453-458. <https://doi.org/10.1016/j.bbrc.2007.10.193>

Wang Z, Zhang H, Zhang D, Wang Y, Han Y, Xue X and Jiang Y, (2024) Biodegradation of phenol-contaminated soil and plant growth promotion by Myroides xuanwuensis H13. Microbiology Spectrum, 12(8):00266-24.

Waseem M, Khilji SA, Tariq S, Jamal A, Alomrani SO, Javed T, (2024) Phytoremediation of heavy metals from industrially contaminated soil using sunflower (*Helianthus annus L.*) by inoculation of two indigenous bacteria Plant Stress, 11, Article 100297, [10.1016/j.stress.2023.100297](https://doi.org/10.1016/j.stress.2023.100297)

Werheni Ammeri R, Eturki S, Simeone GDR, Ben Moussa K, Hassen W, Moussa M, & Hassen A (2023). Effectiveness of combined tools: adsorption, bioaugmentation and phytoremediation for pesticides removal from wastewater. International Journal of Phytoremediation, 25(11):1474–1487. <https://doi.org/10.1080/15226514.2022.2164249>

Wuepper D, Tang FH, Finger R. (2023) National leverage points to reduce global pesticide pollution. Global Environmental Change. 1(78):102631. <https://doi.org/10.1016/j.gloenvcha.2022.102631>

Yang T, Chen ML, Wang JH (2015) Genetic and chemical modification of cells for selective separation and analysis of heavy metals of biological or environmental significance, TrAC-Trends in. Analytical Chemistry 66:90-102. <https://doi.org/10.1016/j.trac.2014.11.016>

Yaqub KQ, (2024) The role of oil revenue in shaping Iraq's public budget. British Journal of Interdisciplinary Research, 1(2):1-24. **DOI:**<https://doi.org/10.58934/bjir.v1i2.6>

Yaqub KQ, (2025) Analysis of Nominal and Real Exchange Rates in the Iraqi Economy (1970-2013). British Journal of Interdisciplinary Research, 2(3):17-41.

Yousaf U, Khan AHA, Farooqi A, Muhammad YS, Barros R, Tamayo-Ramos JA, Iqbal M, and Yousaf S, (2022) Interactive effect of biochar and compost with Poaceae and Fabaceae plants on remediation of total petroleum hydrocarbons in crude oil contaminated soil. Chemosphere, 286:131782. <https://doi.org/10.1016/j.chemosphere.2021.131782>

Zerizghi T, Guo Q, Tian L, Wei R, Zhao C, (2022) An integrated approach to quantify ecological and human health risks of soil heavy metal contamination around coal mining area. Science of the Total Environment. 814(25):152653.

Zeyaullah MD, Atif M, Islam B, Abdelkafe AS, Sultan P, ElSaady MA, Ali A (2009) Bioremediation: A tool for environmental cleaning. Affrican Journal of Microbiology Research.3(6):310-314. https://www.researchgate.net/publication/237500789\_Bioremediation\_A\_tool\_for\_environmental\_cleaning

## Zhang M, Wang J, Bai SH, Zhang Y, Teng Y, Xu Z (2019) Assisted phytoremediation of a co-contaminated soil with biochar amendment\_ Contaminant removals and bacterial community properties. Geoderma 348:115-123. <https://doi.org/10.1016/j.geoderma.2019.04.031>

Zhao Q, Wang Y, Cao Y, Chen A, Ren M, Ge Y, et al., (2014) Potential health risks of heavy metals in cultivated topsoil and grain, including correlations with human primary liver, lung and gastric cancer, in Anhui province, Eastern China. Sci Total Environ 470:340–347. <https://doi.org/10.1016/j.scitotenv.2013.09.086>.

Zheng F, Zhu D, Giles M, Daniell T, Neilson R, Zhu YG, Yang XR (2019) Mineral and organic fertilization alters the microbiome of a soil nematode Dorylaimusstagnalis and its resistome. Science of Total. Environmental 680:70-78. <https://doi.org/10.1016/j.scitotenv.2019.04.384>

Zhou H, Chen Y, Yue X, Ren D, Liu Y, Yang K, (2023) Identification and hazard analysis of heavy metal sources in agricultural soils in ancient mining areas: a quantitative method based on the receptor model and risk assessment, J. Hazard. Mater. 445, 130528.

Zhu X, Lv B, Shang X, Wang J, Li M, Yu X (2019) The immobilization effects on Pb, Cd and Cu by the inoculation of organic phosphorus-degrading bacteria (OPDB) with rapeseed dregs in acidic soil. Geoderma 350:1-10. <https://doi.org/10.1016/j.geoderma.2019.04.015>