Integrative approaches to phytoremediation: Mechanisms, enhancing strategies, and environmental applications

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ABSTRACT

Phytoremediation is a sustainable, plant-based technology for removing or neutralizing environmental pollutants in soil and water. This review identifies and analyzes the five principal mechanisms of phytoremediation such as phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, and phytodegradation and highlights how plant species, soil conditions, and pollutant characteristics affect their efficiency. Through comparative analysis of recent studies, we found that plant-microbe interactions, genetic modifications, and soil amendments significantly enhance contaminant uptake and degradation. The review also underscores the increasing role of phytoremediation in climate change mitigation, especially through carbon sequestration and pollutant-induced greenhouse gas reduction. By synthesizing current advances, we provide an integrated framework that supports the optimized application of phytoremediation in diverse environmental contexts.

1. Introduction

Environmental pollution, particularly due to the accumulation of heavy metals, organic compounds, and radionuclides, has emerged as a critical global challenge over the past few decades. Rapid industrialization, excessive use of agrochemicals, unregulated mining activities, and urban sprawl have resulted in the widespread contamination of terrestrial and aquatic ecosystems [1]. These pollutants persist in the environment, often exhibiting non-biodegradable properties, and pose severe risks to human health, biodiversity, and agricultural productivity [1]. Traditional remediation technologies, such as soil excavation, incineration, and chemical neutralization, are often cost-prohibitive, energy-intensive, and environmentally disruptive, making them unsuitable for large-scale or long-term applications [2].

In this context, phytoremediation, the use of green plants and associated microbiota to remove, degrade, or stabilize pollutants has gained recognition as an effective, sustainable, and eco-friendly approach to environmental restoration [3]. As a green technology, phytoremediation offers multiple advantages, including cost-effectiveness, public acceptance, habitat restoration, and the potential for biomass recovery and carbon sequestration [4]. Unlike mechanical or chemical methods, it integrates with natural ecological cycles, leveraging plant physiology

and plant-microbe interactions to clean up polluted environments with minimal disturbance.

Phytoremediation encompasses several mechanisms, each targeting specific pollutants and environmental contexts. These include phytoextraction (uptake and accumulation of contaminants in plant tissues), phytostabilization (immobilization of pollutants in soil), rhizofiltration (removal of contaminants from water via root absorption or adsorption), phytovolatilization (conversion of pollutants into volatile forms and release into the atmosphere), and phytodegradation (enzymatic breakdown of contaminants within plant tissues) [5,3]. The efficacy of each mechanism is influenced by several biological and environmental factors such as plant species, soil properties, pollutant type, root architecture, and the presence of rhizospheric microbes [6].

The interaction between plant roots and soil microbes plays a pivotal role in enhancing phytoremediation efficiency. Microorganisms such as plant growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF) facilitate pollutant uptake by improving root growth, altering pollutant bioavailability, and enhancing stress tolerance [7]. These microbes secrete siderophores, phytohormones, and chelators, contributing to both plant vigor and pollutant degradation [8].

Despite its promise, phytoremediation is often constrained by slow pollutant removal rates, low biomass yields in hyperaccumulator

species, and limited tolerance to extreme contamination. To overcome these challenges, recent advancements have focused on genetic engineering, bio-stimulation, soil amendments, and nanotechnology-based interventions [9,10]. For instance, transgenic plants overexpressing metal transporters such as AtHMA4 have shown increased uptake and tolerance to cadmium and zinc [11]. Similarly, the application of chelating agents like EDTA and organic amendments such as compost enhances metal solubility and plant bioavailability [12] Bio-augmentation with pollutant-degrading microbes also accelerates contaminant breakdown and increases system resilience [13]

Moreover, phytoremediation has recently been recognized for its role in mitigating climate change by sequestering carbon in plant biomass and soils, reducing greenhouse gas emissions, and enabling the rehabilitation of degraded land for sustainable use [4,14]. The integration of phytoremediation with agroforestry, bioenergy production, and climate-smart agriculture is increasingly being explored for its multidimensional benefits.

This review aims to provide a comprehensive synthesis of current knowledge on phytoremediation by outlining the fundamental mechanisms through which plants remove or neutralize environmental pollutants, including phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, and phytodegradation. It explores the diverse biological, chemical, and environmental factors that influence remediation efficiency, such as plant species selection, pollutant properties, soil conditions, and plant-microbe interactions. Furthermore, the review highlights recent advancements that enhance phytoremediation performance, including genetic engineering, microbial augmentation, and the application of soil amendments and chelating agents. Finally, it emphasizes the growing role of phytoremediation in climate change mitigation through carbon sequestration, reduction of greenhouse gas emissions, and sustainable land restoration. By integrating these aspects, the review provides a holistic framework for optimizing phytoremediation strategies in varied ecological and industrial contexts.

2. Influencing the selection of plants for phytoremediation

The effectiveness of phytoremediation largely depends on the appropriate selection of plant species, particularly their capacity to tolerate, absorb, translocate, and stabilize pollutants. The selection process is influenced by various factors including plant biomass, root system architecture, growth rate, adaptability to contaminated soils, and interaction with microbial communities [15,16]. Many tree and shrub species have shown potential for remediating heavy metal-contaminated soils (Table 1).

Fast-growing species such as *Populus spp.* and *Salix spp.* are particularly attractive due to their high biomass production and adaptability [17]. These species exhibit desirable phytoremediation traits, including tolerance to metal toxicity, deep rooting systems, and the ability to translocate pollutants to aboveground[18].Other species like *Acacia mangium, Azadirachta indica*, and *Eucalyptus camaldulensis* have also demonstrated significant tolerance to lead and other metals under hydroponic and field conditions[16]. The performance of candidate species is often evaluated using indices such as the tolerance index (TI), bioconcentration factor (BF), and translocation factor (TF). Species with a high BF and TF are considered ideal for phytoextraction, while those with low TF but high root retention are better suited for phytostabilization [19]. For instance, Populus deltoides exhibited effective arsenic immobilization with TF and BF values below 1.0, indicating its potential use in phytostabilization strategies [20].

2.1. Rhizomicrobiome dynamics

Recent research underscores the significance of rhizomicrobiome dynamics in enhancing phytoremediation outcomes. The rhizosphere is a dynamic environment where root exudates and microbial populations

Table 1
Phytoremediation potential of tree and shrub species for heavy metal contaminated soils (A: Accumulation, T: Translocation, T (partial): partial translocation).

Pollutants	Group	Species	A/T	References
Pb	Trees	*Acacia mangium*	A	[16]
Pb	Trees	*Acer cappadocium*	A	[24]
Pb	Trees	*Azadirachta indica*	A	[16]
Pb	Trees	*Betula pendula*	A,T (partial)	[25]
Pb	Trees	*Mimosa cesalpiniifolia*	A	[24]
Pb	Trees	*Platycladus orientalis*	A	[18]
Pb,Cd	Trees	*Populus alba*	A	[26,28]
Pb,As	Trees	*Populus deltoides*	A	[27]
Pb	Trees	*Populus nigra*	A	[28]
Pb	Trees	*Populus trichocarpa*	A	[28]
Pb	Trees	*Populus canadensis*	A	[28]
Pb	Trees	*Populus euramericana*	T (partial)	[29]
Cd	Trees	*Populus generosa*	A	[28]
Cd	Trees	*Salix dasyclados*	T	[30]
Zn	Trees	*Salix fragilis*	A	[31]
Zn	Trees	*Salix miyabeana*	A	[31]
Pb,Zn	Trees	*Salix nigra*	A	[27]
Cd,Zn	Trees	*Salix schwerinii*	A	[31]
Pb,Cd	Trees	*Salix viminalis*	A	[32]
Pb	Trees	*Senna siamea*	A	[33]
Pb	Trees	*Buddleja asiatica*	A	[34]
Cd,Pb	Trees	*Dalbergia paniculata*	A	[35]
Zn,Pb	Shrubs	*Euonymus japonicus*	A	[35]
Zn	Shrubs	*Ligustrum vicaryi*	A	[35]
Zn	Shrubs	*Loropetalum chinense*	A, T	[35]
Pb	Shrubs	*Osmanthus fragrans*	A	[35]
Cd	Shrubs	*Rhapis excelsa*	A	[33]
Ni	Shrubs	*Ricinus communis*	A	[36]

interact, influencing contaminant bioavailability and degradation [21].

The composition and functional diversity of rhizospheric microbes collectively termed the rhizomicrobiome play a pivotal role in determining phytoremediation efficiency. These microbes assist in pollutant solubilization, enzymatic breakdown, and production of chelators that enhance metal mobility and plant uptake [6]. Recent studies have demonstrated that microbial consortia can significantly modulate pollutant transformation and improve the phytoremediation potential of host plants [22].

Certain microbial communities can improve plant tolerance under stress by producing phytohormones, facilitating nutrient cycling, and suppressing pathogen growth, further aiding phytoremediation [23]. These findings suggest that plant selection should not only focus on physiological traits but also consider the compatibility and responsiveness of the plant to beneficial rhizosphere microbiota.

2.2. Plant- microbe interaction

During specific stages of plant growth, a healthy root system produces organic compounds known as root exudates. The effectiveness of phytoremediation largely depends on the appropriate selection of plant species, particularly their capacity to tolerate, absorb, translocate, and stabilize pollutants. The selection process is influenced by various factors including plant biomass, root system architecture, growth rate, adaptability to contaminated soils, and interaction with microbial communities [15,16]. Many tree and shrub species have shown potential for remediating heavy metal-contaminated soils (Table 1).

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Table 1 displays the components of root exudates and how they function in the rhizosphere. Root exudates play an important role in phytoremediation (Fig. 1) because they enable host plants to actively adapt to and survive in metal-stressed environments through allelopathic processes (which influence the growth of other plants and microbes in the rhizosphere) or detoxification processes (which involve metal adsorption, chelation, transformation, and inactivation [37]. Organic acids may be considered as natural chelating agents to improve phytoextraction, as demonstrated by the considerable enhancement of metal (Cd, Cu, and Pb) translocation and bioaccumulation by *Echinochloa crusgalli's* citric and oxalic acids [38]. Certain elements of root exudates, however, neither negatively affect metal mobilization nor affect metal availability [39]. Through the creation of stable metal complexes in the soil, the Low Molecular Weight Organic Acids (LMWOAs), such as oxalate, generated by Scots pine seedlings growing in both mycorrhizal and ectomycorrhizal environments helped immobilize metals [40].

Generally speaking, plants can select their very own root microflora from their environment, and every plant species has a distinct community of related bacteria [8]. The process is probably directly related to the properties of the rhizosphere soil as well as the quantity and composition of root exudates [6]. In nature, interactions between microorganisms associated with plants are very dynamic, driven by coevolutionary pressures [6]. Plants in the rhizosphere can establish an efficient associative symbiosis with their associated microbes by inducing host functional signals (e.g., microbial chemotaxis and colonization), while the microbes can communicate with the plants by exuding chemicals or signals (signaling molecules and their perception, QS) [41].
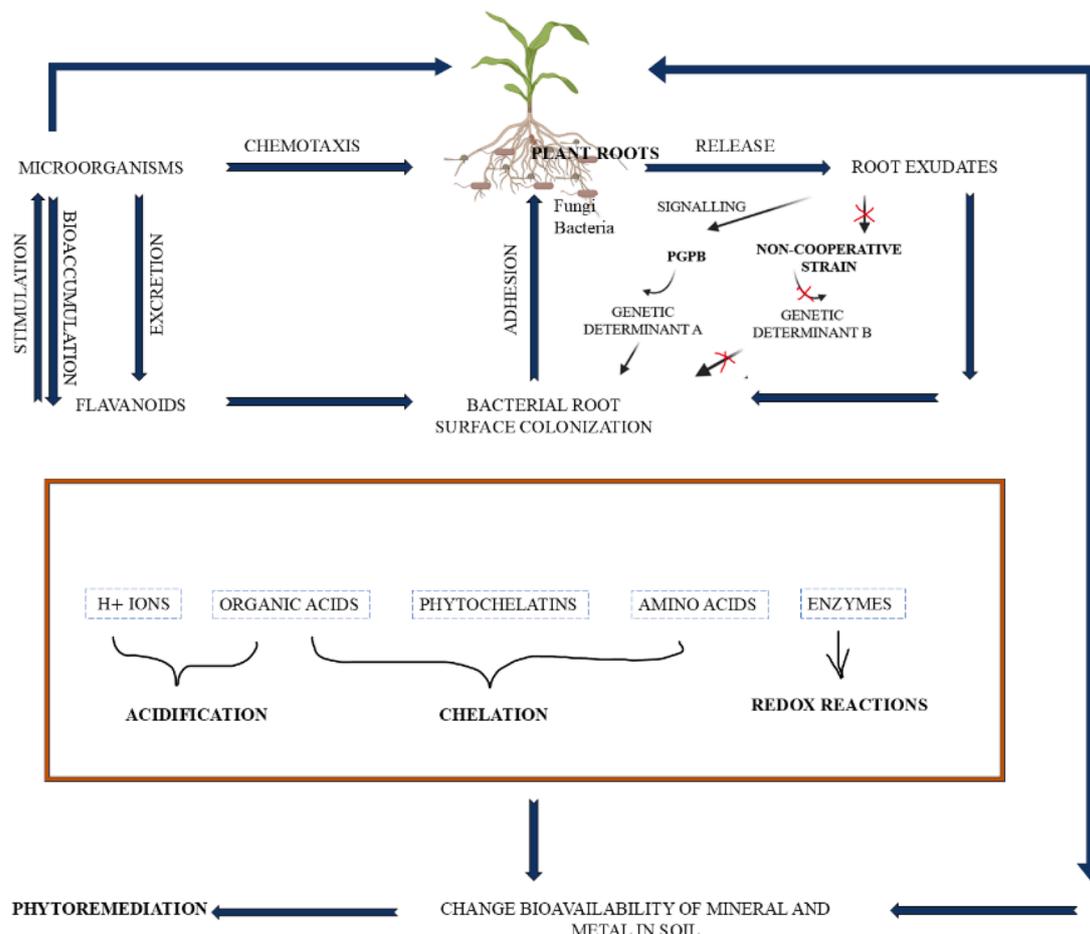

Fig. 1. A schematic overview of the mechanisms of plant-microbe-metal interactions.

3. Phytoremediation pathways

Phytoremediation encompasses multiple plant-mediated strategies tailored to mitigate a broad range of environmental contaminants, including heavy metals, pesticides, hydrocarbons, radionuclides, and excess nutrients. While these pathways such as phytoextraction, phytostabilization, phytodegradation, phytovolatilization, and rhizofiltration have been widely reported, emerging research reveals deeper biochemical, genetic, and rhizospheric innovations that can transform their efficiency and application [3,5]

3.1. Phytostabilisation

Phytostabilization aims to prevent the spread of contaminants by immobilizing them within the root zone (Fig. 2). This method is especially suitable for sites with high concentrations of heavy metals or low-permeability soils, where extraction is impractical or unsafe. Plants used for phytostabilization form dense root networks that bind soil particles and limit erosion and leaching.

Recent advances emphasize the incorporation of organic and inorganic amendments such as lime, phosphate, and compost—to further reduce contaminant mobility while improving soil fertility [42]. In addition, field studies show that specific grasses (e.g., *Festuca arundinacea*) and legumes form symbiotic associations with rhizobacteria that help precipitate metals into less soluble forms [22]. This dual function, soil rehabilitation and pollutant containment makes phytostabilization a cornerstone for reclaiming marginal lands.

3.2. Phytoextraction

Phytoextraction relies on the ability of plants to absorb soluble contaminants from the soil and translocate them into the harvestable aerial parts. This strategy is primarily effective for heavy metals such as cadmium, zinc, lead, and arsenic. While hyper accumulator plants like *Thlaspi caerulescens* and *Sedum alfredii* have been traditionally used, their low biomass often limits field-scale application.

Recent research focuses on combining high-biomass crops (e.g., *Brassica juncea*) with soil amendments such as EDTA or organic chelators, which enhance the bioavailability of metals [12].In addition,

CRISPR and transgenic interventions have improved the expression of metal transporter genes (e.g., HMA4, MT, PCS1), enabling common crops to function as phytoextractors [43].These genetically optimized plants offer a balance between pollutant uptake and biomass production, making phytoextraction more viable for large-scale use.

3.3. Phytovolatilization

Phytovolatilization is a process where plants take up water-soluble pollutants and convert them into volatile forms that are released through leaf stomata. While previously viewed as controversial due to the atmospheric release of contaminants, recent innovations have improved control over this mechanism.

Species such as *Populus deltoides* and *Arabidopsis thaliana*, genetically modified to overexpress merA and ARM genes, exhibit improved conversion of mercury and arsenic into elemental or methylated volatile forms, which are less toxic [44]. However, research now focuses on developing buffer zones and filtration barriers (e.g., biochar layers) to capture or neutralize volatilized pollutants before atmospheric dispersion [45].

[46]states the remediation of various toxic metals, such as mercury (Hg), selenium (Se), and arsenic (As) using phytovolatilization. Fig. 3 represent the process of using passive diffusion or active transporters such as ATPases (HMA), transporters (SULTR1), and nitrate transporters (NRT) to uptake the heavy metals by plant roots. Chelators such as phytochelatins (PCs), metallothioneins (MTs), and organic acids like citric acid, malic acid, oxalic acid, and tartaric acid that bind with heavy metals to prevent toxicity in plants [47]. In plants, the chelators play a critical role in detoxification of metal by forming stable, soluble complexes that facilitate the metal transport safely. Once absorbed, the plant transports the metal complexes from the xylem to the aerial parts of the plant. During this journey, the toxic metal ions that are converted into volatile, less harmful form by enzymatic transformation [48]. For instance, $Hg^{2+}$is converted to elemental mercury reductase and then released into atmosphere. Similarly, selenomethyl transfer(SMT) that transfers the selenium into volatile compounds such as dimethyl selenide(DMSe) and dimethyl selenide (DMDSe),while arsenic methyl transferase(ARM) that methylate by the arsenic to form trimethyl arsine (TMA).the stomata that exit these volatile metal derivatives from the
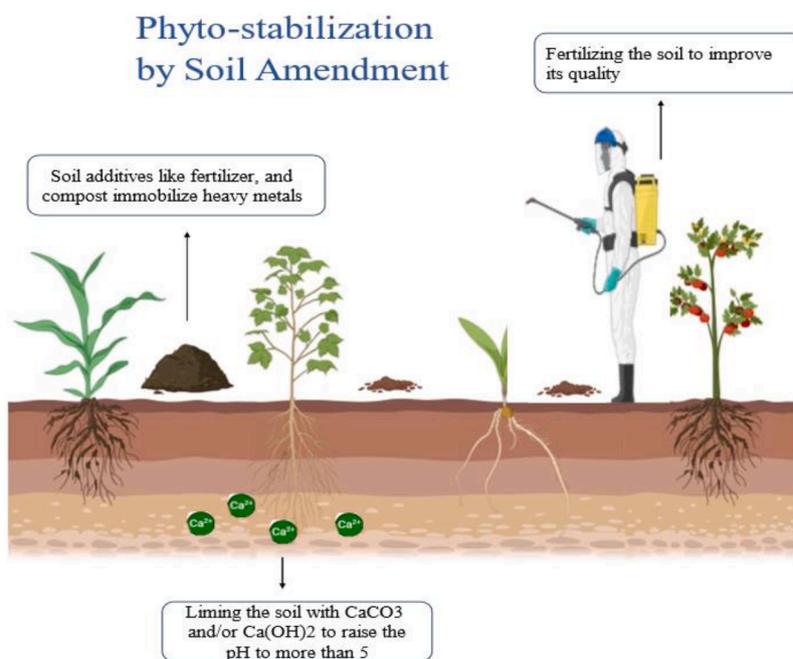

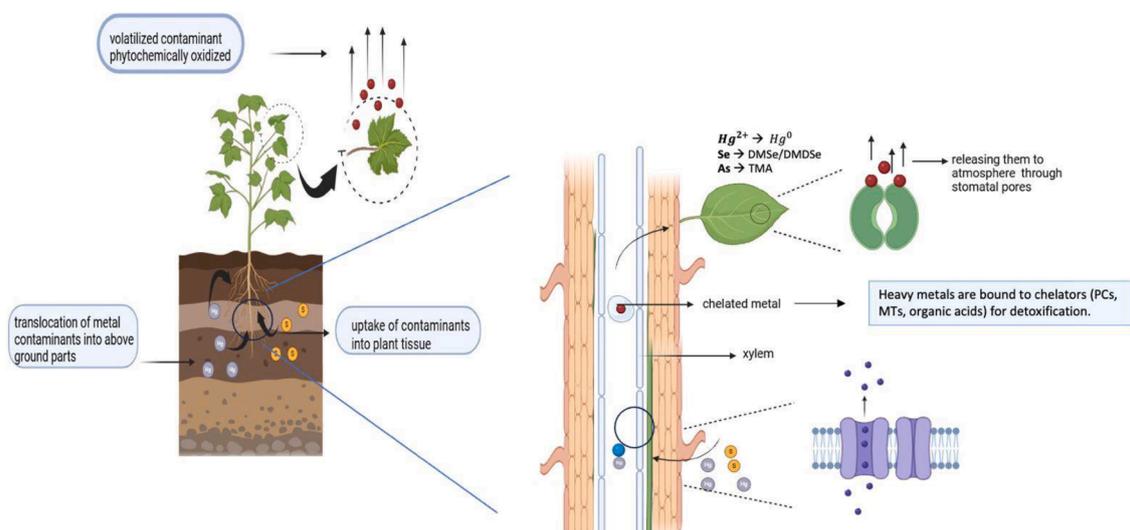**Fig. 2.** Phyto-stabilization by Soil Amendment.

Fig. 3. Phytovolatilization in plants.

plant. The accumulated metal is reduced effectively from soil and plant tissue. phytovolatilization potential have been identified in various plant species, including *Brassica juncea* (Indian mustard), *Populus spp.* (poplar trees), *Arabidopsis thaliana*, and *Astragalus spp* [49]. Minimizing soil disturbance and reducing metal toxicity, offers various advantages by this method,volatilized metals is potentially re-deposition and exist in the environment concern. Nonetheless, phytovolatilization remains a promising approach in green remediation strategies, especially when integrated with other phytoremediation techniques to enhance efficiency and sustainability [45].

A number of contaminants have been demonstrated to volatilize through plants (Table 2), including the elements selenium, mercury, arsenic, and VOCs. *Brassica juncea* has been demonstrated to volatilize a toxic metalloid, which can accumulate hazardously in soil and water [50].

Many factors either inhibit or promote phytovolatilization. pH limitation of the uptake of the pollutants to the plants by soils; acidic soils have positive charges that favor positively charged pollutants such as mercury [57]. Limitations of nutrient availability, since nutrient-rich soils cause faster growth rates of plants, promoting greater uptakes of the pollutants. Microbial interactions can indeed be very useful in phytovolatilization. Some microbes can increase the biodegradation of some pollutants; hence, making the pollutants more available for uptake by the plants. Conversely, some other microorganisms could interfere

with this process of phytovolatilization either through competition with the plants over uptake of the pollutants or through growth inhibitors [58].

3.4. Rhizofiltration

Rhizofiltration is ideal for treating contaminated water bodies, wetlands, and industrial effluents. It involves the adsorption and absorption of pollutants onto and into plant roots submerged in water. Unlike other pathways, rhizofiltration systems can be engineered for continuous flow, allowing for modular, scalable design.

Floating treatment wetlands (FTWs), consisting of aquatic plants like *Eichhornia crassipes* or *Typha latifolia*, have been deployed in stormwater ponds and mining sites, showing success in removing nitrates, phosphates, and metals like Cu and Pb [59]. Recent studies highlight that inoculating roots with metal-tolerant rhizobacteria or fungi enhances root permeability and nutrient exchange, significantly increasing remediation efficiency [60]. Since they are essential components of many proteins and enzymes, a number of heavy metals aid in the growth and development of plants. However, high levels of both essential and non-essential HM in plants caused heavy metal-associated phytotoxicity, which inactivates enzymes, inhibits functional groups, displaces critical components, and destroys membrane integrity. Plant growth and development are therefore impacted by modifications to different

Table 2
Pollutants that are commonly volatilized and their key plant species.

Pollutant	Key Plant Species	Mechanism of Phytoremediation	Applications	Reference
Mercury (Hg)	Populus spp. (Poplars), Arabidopsis thaliana	Phytovolatilization	Used to clean up mercury-contaminated soils through volatilization into the atmosphere.	[44]
Selenium (Se)	Brassica juncea (Indian Mustard), Astragalus bisulcatus (Milkvetch)	Phytovolatilization	Applied to soils with excess selenium, converting it into less toxic volatile forms.	[49]
Arsenic (As)	Pteris vittata (Chinese Brake Fern)	Phytovolatilization and Phytoextraction	Utilized in areas with arsenic-contaminated soils; arsenic volatilized as arsines.	[51]
Trichloroethylene (TCE)	Populus deltoides (Eastern Cottonwood), Medicago sativa (Alfalfa)	Phytovolatilization	Applied in areas contaminated by industrial solvents like TCE, removing them from groundwater.	[52]
Dimethyl mercury (MeHg)	Lycopersicon esculentum (Tomato), Arabidopsis thaliana	Phytovolatilization	Utilized to reduce mercury contamination in soil and water by volatilizing organic mercury.	[53]
Chlorinated Solvents (e.g., Perchloroethylene)	Populus spp. (Poplars), Salix spp. (Willows)	Phytovolatilization and Rhizofiltration	Applied in sites with contamination from chlorinated solvents like dry cleaning chemicals.	[54]
Volatile Organic Compounds (VOCs)	Populus trichocarpa (Black Cottonwood), Leucaena leucocephala	Phytovolatilization and Phytodegradation	Applied in areas with VOC contamination from industrial waste.	[55]
Dimethyl selenide (Se)	Brassica oleracea (Cabbage), Brassica juncea (Mustard)	Phytovolatilization	Used in regions with high selenium contamination; selenium volatilized as dimethyl selenide.	[56]

physiological processes at the molecular or cellular level. One prevalent instance of heavy metal-associated phytotoxicity is the increased production of oxygen radicals that disrupt electron transport processes [5].

3.5. Phytodegradation

Phytodegradation, also called phytotransformation, involves the enzymatic breakdown of organic pollutants either within plant tissues or in the rhizosphere (Fig. 4). Plants possess diverse metabolic enzymes such as dehalogenases, nitroreductases, and laccases that convert complex pollutants into less toxic forms [61].

Recent studies have shown that transgenic expression of bacterial enzymes in plants enhances their ability to degrade compounds like polychlorinated biphenyls (PCBs) and pesticides [62]. Additionally, rhizosphere microorganisms complement plant metabolism by degrading breakdown intermediates, forming a cooperative detoxification system. This pathway is especially useful for treating petroleum hydrocarbons, dyes, and explosives in situ.

Microbial agents have opened the gates of possibilities in the degradation process of organic pollutants that collaborate with the plant for the biodegradation process [2]. But the productivity of phytodegradation is significantly impacted by some of the variables such as nature and concentration of pollutants, types of plant and environmental parameters [63]. With these restriction, scientists have addressed that the rate of degradative organic pollutants is increased by the resort of microbes(Awa & Hadibarata, 2020). Wide range of organic pollutants like pesticide, PAHs, and PCBs have been removed by the microorganisms such as bacteria, fungi and algae [63]. The ways through which the pollutants is break down the microorganisms may include enzymatic degradation, oxidation, and reduction. PAH-degrading capability in Pseudomonas putida strains may be expressed through degradative enzymes breaking the pollutant molecules apart [64]. Plant-Microbe Interactions highly encourages biodegradation, as plants offer habitat and nutrient to the microorganism with protection from environmental stressors; they also offer nutrients such as nitrogen and phosphorus for the microorganism in return for protection against pathogens [65]. Such relationships also lead to mutualistic symbiosis between the plant and the microbe. For instance, it has been proven that mycorrhizal fungi increase the biodegradation of PAHs in soil. Similarly, studies have also shown that Rhizobia bacteria enhance the breakdown of pesticides in soils through association with the plant roots [20].

Plant-microbe interactions occur through several mechanisms:

(1) **Root exudates** - Substances secreted by plant roots that attract microbes and provide them with nutrients [20]
(2) **Mycorrhizal relationships** - These mutualistic relationships between mycorrhizal fungi and plant roots promote nutrient uptake alongside biodegradation.
(3) **Rhizosphere interactions** - The rhizosphere, a zone of soil immediately surrounding plant roots, is a hotspot of microbial activity where microbes interact with plant roots and degrade pollutants[13].

4. Role of soil micro-organisms in phytoremediation

4.1. Synergistic effect of microbes and plants

Mechanisms have been developed for reducing pollutant emissions and developing effective bioremediation techniques. Phytoremediation can be utilized to clean polluted soil based on the type of pollution, soil quality, and plant growth rate. For than a century, soil microorganisms have been used to improve plant tolerance, degradation, and pollutant metabolism [66]. Many microbes have been employed in cleaning polluted soils through the bioremediation of hazardous complex organic compounds into more easily disposed-of materials. Specifically, the main method for breaking down PAHs is microbial degradation [67]. The effectiveness of Bacillus, Escherichia, and Mycobacterium throughout the bioremediation of heavy metals and PAHs has been well documented. Natural soil contains mycobacterium, which has a potent ability to break down PAHs.Through the mechanism of bioaccumulation, microorganisms can potentially accumulate pollutants in both particulate and insoluble forms.

In such a ways,

1. Preventing the absorption of metals by modifying metabolic pathways.
2. Enzymes transform metals into safe forms.
3. Using precise efflux mechanisms, the intracellular environment's metal concentrations are decreased.
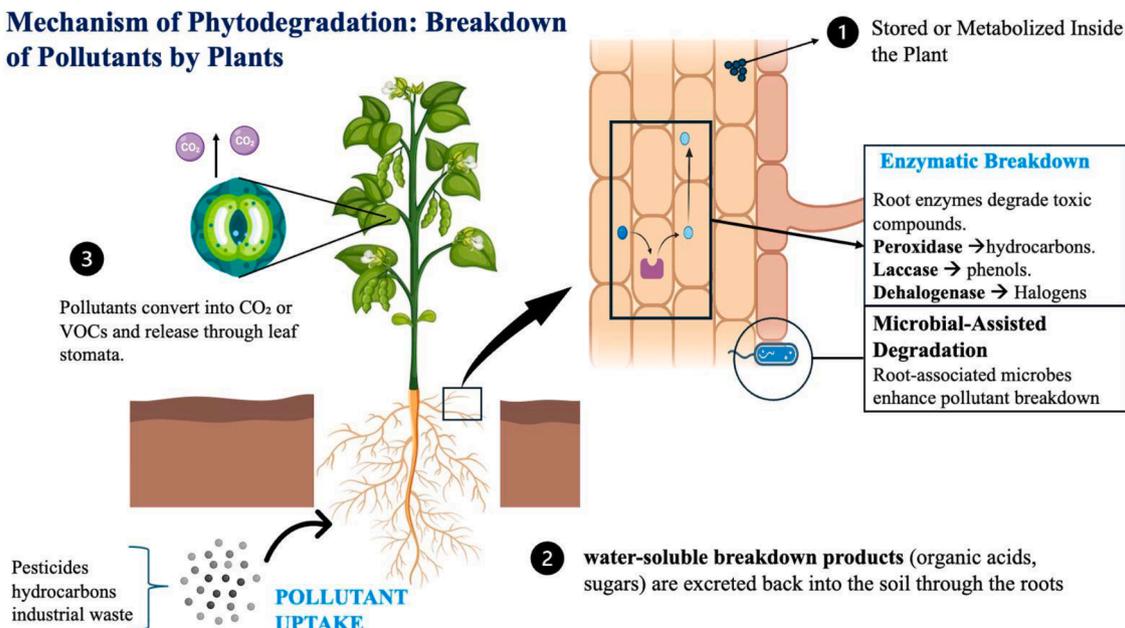

Fig. 4. Breakdown of pollutants by phytodegradation.

Bacteria which promote plant development (PGPB) and fungi which produce mycorrhizae (arbuscular mycorrhizae (AM) and ectomycorrhizae (ECM). Plant-microbe interactions result in the production of compounds by PGPB, including ammonia, siderophores, and phytohormones (auxins, cytokinins, and 1-aminocyclopropane-1-carboxylate). Additionally, PGPB can mineralize organic molecules that promote plant development, fix nitrogen, and dissolve phosphate. By enhancing the oxidative enzyme systems and raising the bioavailability of pollutants, which ultimately enhance the accumulation of pollutants in plants, PGPB may reduce the oxidative stress produced on by the presence of pollutants [7].

Furthermore, it has been noted that arbuscular mycorrhizae, the most prevalent fungus found in agricultural soils, enhance plant growth by tolerating contaminants, raising nutrient levels, and activating antioxidant enzymes. Plants, bacteria, and fungi work together to decolorize colors more effectively than either alone. Previous research have hypothesized numerous detoxifying and bio-transformation mechanisms in dye metabolism, such as sorption in plant parts, enzymatic activity, and stress avoidance. Enzymes from Pseudomonas putida and *Portulaca grandiflora*, two bacteria and plants, facilitated the decolourization of a diazo dye [24].

4.2. Bio-stimulation and Bio-augmentation to boost Phytoremediation

Bioremediation which involves bio-augmentation and/or bio-stimulation has become the most popular approach for in situ bioremediation of accidental spills and chronically contaminated sites worldwide, as it is the most cost-effective and environmentally friendly method for clearing up contaminated soil and water containing heavy metals and/or organic pollutants. Bio-augmentation entails employing pre-grown microbial cultures to accelerate the breakdown of undesirable substances, whereas bio-stimulation entails adding nutrients and other supplementary components to the natural microbial population to increase proliferation rates [13].

As a result, bioaugmentation increases the gene pool and, consequently, the site's genetic diversity. In addition to these, a number of other factors influence how quickly bioaugmentation takes place in soil. Noted variables or elements that affect the bioaugmentation process include pH, temperature, moisture content, organic matter content, aeration, nutrient content, and soil type. When any of these soil properties are absent in its natural state, the remediation procedure is rendered ineffective [68].

Process of bioaugmentation: Any planned intervention that involves screening and then customizing a competent microbial formula for a specific place must first undergo feasibility assessments. The metabolic potential of the microorganism as well as critical characteristics that allow the cells to remain persistent and functionally active in the intended environmental settings should be taken into account during the initial screening and selection process. When two or more organic pollutants and high metal concentrations are present at a place, the co-contaminants may prevent the microbial community from breaking down the organic compounds [69].

The most important factor influencing bioaugmentation efficiency is the amount of organic matter in the soil. It affects pollutant bioavailability, inoculation strain survival, and biodegradation [70]. When microorganisms are selected to be applied in bioaugmentation, the factors controlling growth of the microorganisms used in bioaugmentation should include chemical structure and concentration of pollutants, the availability of the contaminant to the microorganisms, the size, and composition of the microbial population, and the physical environment [71].

The consumption of carrier materials increases the survival opportunities of the microbe. Biomass provides physical support to the microbe and improves nutrient, moisture, and oxygen access. By protecting cells from stressful environmental conditions, microbial cell encapsulation or immobilization can increase the survival rate and

typically promote a quicker and more effective biodegradation. Encapsulation works similarly to a tiny bioreactor in the environment, controlling nutrient flow, lowering toxic compound concentrations in the cell microenvironment, minimizing cell membrane damage by reducing toxic compound exposure, and protecting against competition and predation [20].

Bioaugmentation is a strategy for promoting the repair of petroleum hydrocarbon-impacted environments. It requires introducing microorganisms that have been isolated from the polluted site, a historical location, or that have been carefully chosen and genetically engineered. This is predicated on the premise and/or demonstration that the impacted site's native species are incapable of biodegrading petroleum hydrocarbons [13].

Bio-stimulation, or the addition of nutrients such as nitrogen or phosphorus, has been shown to accelerate the microbial breakdown of petroleum hydrocarbons in polluted soils caused by oil spills or underground storage tank breaches. In heavy metal-contaminated soils (such as those containing lead, cadmium, or arsenic), biostimulation approaches have been applied to encourage microbial metal immobilization or transformation. Two of these tactics are raising the pH and adding organic materials [4]. Mechanism: Rate-limiting nutrients are introduced, which accelerates the cleaning process and increase the breakdown capacity of the bacteria that live there. Biostimulation is often regarded as the most successful bioremediation method for hydrocarbon cleanup. The efficiency of biostimulation as a remediation technique for the breakdown of hydrocarbons, particularly petroleum compounds and their derivatives, has been established in the literature. In particular, the biostimulation procedure or the addition of specific rate-limiting nutrients can greatly boost the microbial population at petroleum-contaminated locations, which are less effective and have poor metabolism [66].

Several kinds of bioaugmentation and biostimulation products can be used to significantly improve the biodegradation process. The biodegradability of fuel oil was investigated over a 31-day incubation period utilizing mixed cultures from a domestic treatment plant and the commercial product DBCTM, which contains nine different dried bacterial mixed cultures [4].

In a study on the remediation of hydrocarbon-contaminated lake sediments, bioaugmentation and bio-stimulation were combined to increase the efficiency of biodegradation. Three sets such as of bio-stimulated (N), bio-stimulated and bioaugmented (NB), unaltered (K) and unaltered (K), batch incubation was conducted for 32 days. In which the *betaproteobacteria* were abundant and the most common genus in the bio-stimulated set was *Pseudomonas*. While comparing the hydrocarbon concentration with the unamended set, the concentration of hydrocarbons was lower during the incubation period. The study highlights the importance of understanding that in lake sediment, the bioremediation was created effectively by the microbial interaction, the bio-augmentation, and bio stimulation were approaches by demonstrating in concert to increase the hydrocarbon biodegradation [72].

4.3. Impact of rhizosphere bacteria and fungi

The benefits of phytoremediation are increased by the microbes that encourage plant growth, the process is directly impacted by the plant growth and biomass. Phytoremediation was most successful when plant growth-promoting rhizobacteria (PGPR), primarily Bacillus and Pseudomonas species, were injected. Apart from that, the plant growth was facilitated by the generating enzymes, the bioavailability of insoluble organic salts and phytohormones precursors, including vitamins and Phyto-siderophores, was augmented by the diverse metabolites that are generated by the phytohormone precursor region. Ethylene synthesis was lowered by ACC deaminase, which in turn inhibits plant growth. 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase is produced by some PGPR to promote plant development [73]. Enhancing phytoremediation by releasing Pseudomonas, ACC deaminase, and Bacillus

enhanced phytoremediation and boosted plant biomass. Fungi such as *Ectomycorrhizae* (ECM) and *Arbuscular mycorrhizae fungi* (AMF) help in plant growth by creating mycorrhizae. They have two methods in their arsenal to improve phytoremediation. The first technique involves expanding the region in which the roots may absorb contaminants, hence boosting the plant's ability to do so. In the second stage, the AMF hyphae combine organic acids, glycoproteins, and cyclosporin to produce metal complexes, limiting the quantity of pollution transfer from the roots to the shoot. AMF, like other plant species, employs both approaches. AMF inoculation increased the quantity of metal species transferred in lucerne shoots while decreasing the amount in oat shoots in zinc, cadmium, and nickel-contaminated soils. This was explained by the AMF inoculation lengthening the oats' roots while shortening [74].

5. Mechanisms for enhanced activity in phytoremediation

5.1. Intracellular transport and detoxification in plant cells

Phytoremediation efficacy begins at the cellular level, where plants orchestrate the uptake, transport, and detoxification of heavy metals and organic pollutants (Fig. 5). Contaminants such as cadmium, zinc, and arsenic are absorbed via membrane-bound transporters like the ZIP (ZRT/IRT-like protein) and NRAMP (Natural Resistance-Associated Macrophage Protein) families [11].Once inside root cells, they are chelated by thiol-rich ligands such as phytochelatins and metallothioneins. These complexes are actively transported into vacuoles through ATP-binding cassette (ABC) transporters, isolating them from sensitive cellular processes. Overexpression of *AtHMA4* has been shown to increase translocation of Cd and Zn from roots to shoots, a desirable trait in phytoextractor species [10]. This tightly regulated process is supported by antioxidant systems and stress-response signaling, ensuring continued growth under toxic conditions.

5.2. Enzymatic degradation of organic pollutant

In Phase II, conjugation reactions are catalyzed by glutathione-S-transferases (GSTs) and UDP-glucosyltransferases, facilitating the formation of water-soluble, less toxic conjugates. These are then transported and stored in vacuoles or bound to cell walls in Phase III. In addition, enzymes like laccases and peroxidases catalyze the oxidative degradation of phenols, dyes, and polyaromatic hydrocarbons[61], while nitroreductases and dehalogenases contribute to the transformation of nitroaromatic and halogenated compounds [62].These enzyme systems are central to phytodegradation and detoxification in contaminated soils.

5.3. Rhizomicrobiome contributions to phytoremediation

The rhizosphere plays a pivotal role in enhancing phytoremediation, as plant-associated microbes assist in contaminant mobilization, transformation, and stress alleviation. Microbial species within the rhizomicrobiome produce siderophores that bind and solubilize metals, increase bioavailability, and facilitate uptake (Chakraborty et al., 2024). Others secrete phytohormones such as indole-3-acetic acid (IAA), which stimulate root branching and expansion. Additionally, ACC deaminase-producing microbes help modulate plant ethylene levels under stress, promoting root health and resilience. Arbuscular mycorrhizal fungi like *Glomus* spp. extend the effective root surface area, enhancing uptake while also sequestering pollutants in fungal tissues. Recent studies have shown that co-inoculation with plant growth-promoting rhizobacteria (PGPR) and AMF results in improved biomass, antioxidant enzyme activity, and metal uptake (Aryal, 2024).

5.4. Genetic engineering for mechanistic enhancement

Advances in genetic engineering have unlocked the potential to tailor plants for specific phytoremediation tasks (Fig. 6). Transgenic expression of microbial genes such as *merA* (mercuric reductase) or cytochrome *p450* enzymes has enabled enhanced degradation or volatilization of pollutants like mercury and hydrocarbons [75]. These engineered plants exhibit superior tolerance and processing capacity. Modern gene-editing tools like CRISPR/Cas9 now offer the ability to precisely modify or activate native plant genes responsible for metal transport, detoxification, or root exudation without introducing foreign DNA [43]. These approaches help develop next-generation phytoextractors or phytodegraders with improved specificity and environmental resilience.

5.5. Role of amendments and nanomaterials in activity enhancement

Soil and environmental amendments offer additional routes to improve phytoremediation efficiency. Chelating agents such as EDTA and EDDS can increase the mobility of metals in soil, facilitating their uptake by plants [76]. Organic matter amendments like compost, vermicompost, or biochar improve soil aeration, pH, microbial diversity, and nutrient cycling [13]. Recent developments in nanotechnology have introduced metal and oxide nanoparticles such as Fe_3O_4, ZnO, and TiO_2 that serve dual purposes: adsorbing pollutants while acting as
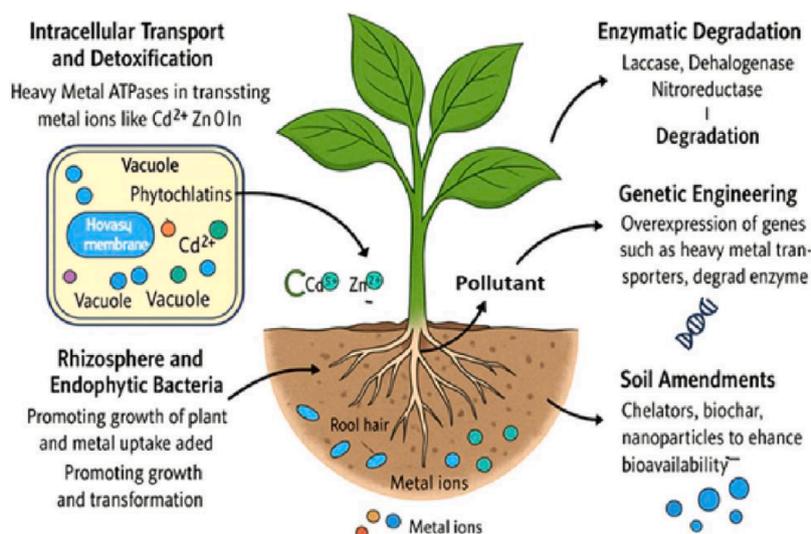

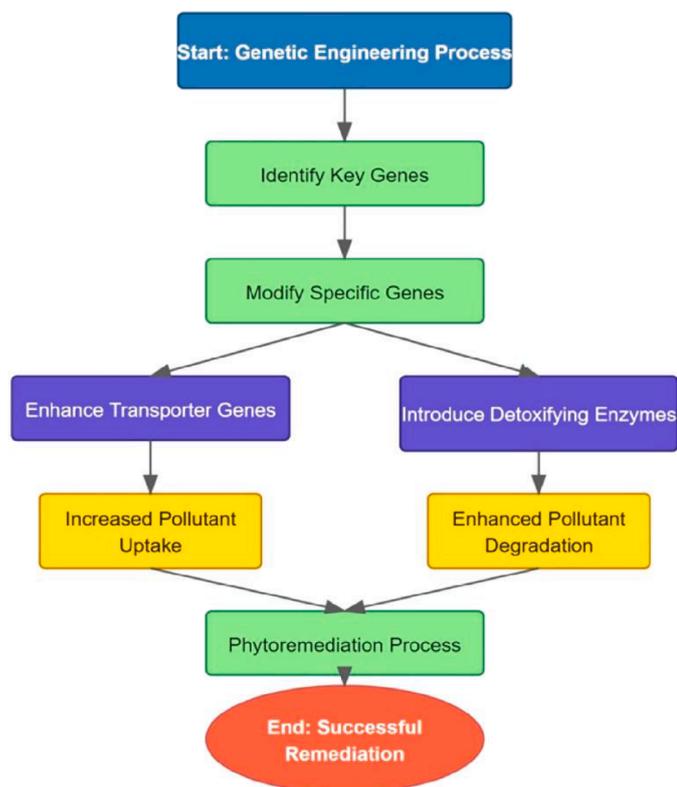**Fig. 5.** Mechanisms for enhanced activity in phytoremediation.

Fig. 6. Flowchart showing how genetic engineering modifies specific genes, leading to increased pollutant uptake and degradation.

micronutrient sources for plants. These nanoparticles can enhance contaminant availability and stimulate antioxidant enzyme activity, improving stress tolerance and remediation outcomes[59].

6. Phytoremediation and its role in climate change mitigation

Phytoremediation is one of the promising technologies for environmental remediation and practice through utilizing plants for cleaning contaminated soil, water, and air. Increasing human activities against the environment created awareness about sustainable or eco-friendly

solutions to pollution remediation. Cost-effective and friendly decontamination of contaminated sites without harming the environment has emerged as the goal of phytoremediation, and in past years, this has seen growing promise to help mitigate climate change (Fig. 7). The most critical environmental challenge of this century is climate change, which will have tremendous consequences for the environment, health for human beings, and the economy. Higher levels of greenhouse gases in the atmosphere, the primary being carbon dioxide (CO2), lead to an overall increase in the average temperatures of the entire world by over 1°C from the late 19th century (IPCC, 2019). Climate change has several implications that it brings with it, and some of the most direct ones are the increase in extreme weather, sea level rise, and changes in precipitation patterns. It offers great hope to mitigate global warming through sequestration of CO2 in the atmosphere to minimize the emission of GHG. Plants absorb this carbon dioxide from the atmosphere through their roots during the process of photosynthesis and deposit it in their biomass and in the soil, often termed carbon sequestration, thereby decreasing the carbon dioxide in the atmosphere and all Allied climatic influence.

Phytoremediation is huge in terms of carbon sequestration potential with an estimate of 3.5 tons per year by per hectare [4]. Additives and amendments may be added to the plants that will enhance the phytoremediation potential. Organic amendments includes compost or manure added directly into the soil for its richness and improved soil structure as Amending with compost increases *Thlaspi caerulescens* growth and uptakes of the pollutants [67].

6.1. Carbon sequestration potential

Carbon sequestration is the capture and storage of atmospheric carbon dioxide, either naturally or by human activity (Fig. 8). One of the most promising emerging carbon sequestration technologies is phytoremediation, which involves utilizing plants to detoxify polluted soil, water, and air. Photosynthesis enables plants to collect carbon from the environment and store it in their soil and biomass. By decreasing atmospheric greenhouse gas, Carbon sequestration affects climate change. Research has revealed that a huge amount of CO_2 is removed from the atmosphere by phytoremediation. It is reported that a phytoremediation agent in switchgrass can uptake CO_2 up to 3.5 tons per hectare per year [63]. Another research study resulted in the sequestration of phytoremediation using miscanthus as 5.5 tonnes of CO_2 per year in every hectare [5].
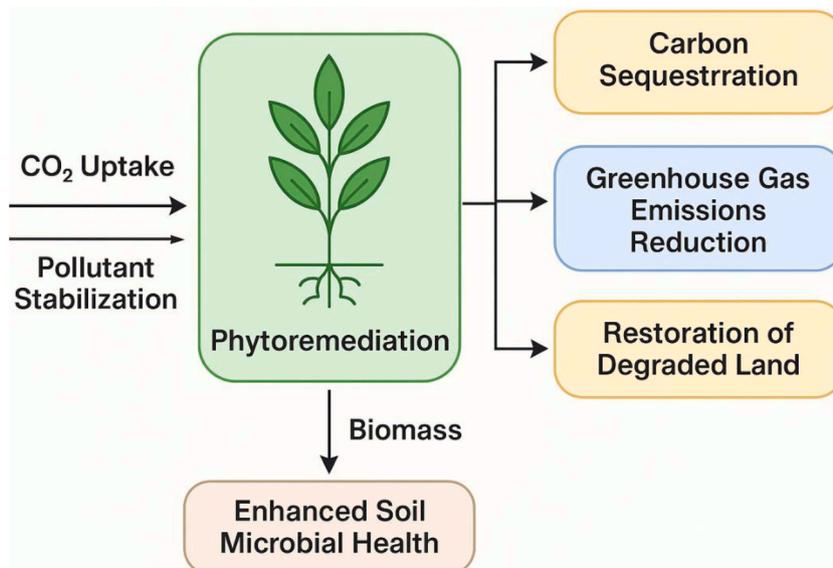

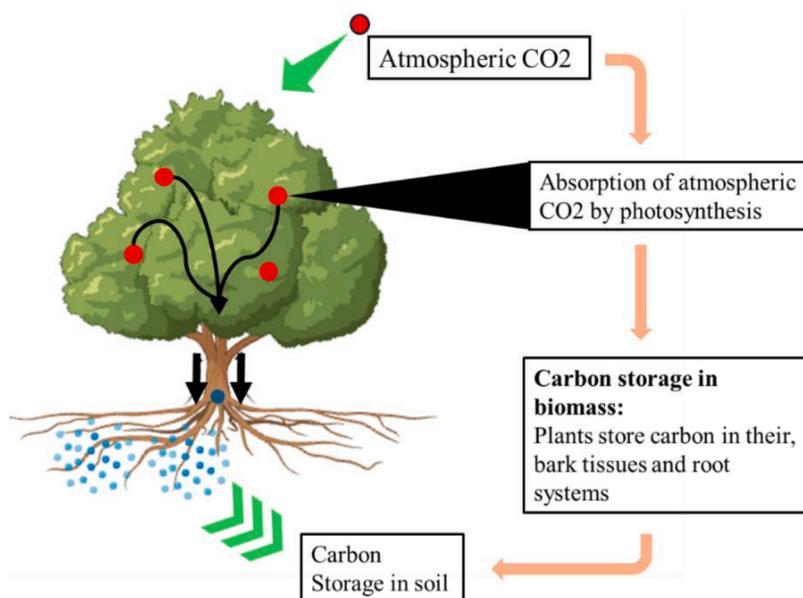Fig. 7. Phytoremediation role in climate change mitigation.

Fig. 8. Carbon sequestration in phytoremediation.

The efficiency of carbon sequestration in phytoremediation can be enhanced through several approaches: selecting plant species with high carbon sequestration potential, where C_4 crops like switchgrass and *Miscanthus* demonstrate superior capacity compared to C_3 crops such as wheat and rice [77]; applying soil amendments like compost or manure to improve soil fertility and promote carbon storage [45]; and optimizing irrigation management to stimulate plant growth and increase carbon uptake [78].

6.2. Reducing greenhouse gas emissions

Another advantage of the phytoremediation technique is that it lowers greenhouse gas emissions. This would be primarily due to lower levels of contaminants in soil and water. Pesticides and heavy metals are specialized pollutants that, by altering the microbial ecology of soil, emit huge amounts of greenhouse gases into the atmosphere, such as N_2O and CH_4, respectively. Phytoremediation could help reduce the levels of these toxins in soil and water. Thus, phytoremediation could help to reduce greenhouse gas emissions. Greenhouse gas emissions would be further reduced by promoting sustainable land use, such as reducing pollution levels. Land reclamation using phytoremediation may help sequester carbon dioxide, hence reducing the emission of greenhouse gases [14].

7. Future trends in phytoremediation

As environmental challenges evolve, the future of phytoremediation is poised to move beyond traditional plant-based contaminant removal into a multidimensional approach involving cutting-edge science, sustainable land use, and policy integration. Future research and implementation will focus on increasing efficiency, reducing remediation time, and broadening the scope of pollutants addressed, especially in complex and mixed-contaminant environments.

A key trend is the genetic improvement of phytoremediator species. Advances in genetic engineering, transcriptomics, and CRISPR-based gene editing are enabling the development of plants with enhanced metal uptake, detoxification, and tolerance capacities. Transgenic lines expressing genes for metallothioneins, phytochelatin synthases, or heavy metal transporters have shown great promise in laboratory studies and are gradually advancing toward field-level applications [43].

Another major shift lies in rhizosphere engineering, where soil microbial communities are actively shaped through inoculation with tailored consortia of plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), or engineered microbes. These microbes not only enhance contaminant solubilization and uptake but also improve plant stress tolerance and soil health, forming a sustainable foundation for long-term land use recovery [79].

Nanotechnology is emerging as a complementary tool, with nanoparticles being used to increase contaminant bioavailability, enhance plant stress resistance, and facilitate targeted delivery of growth stimulants or gene modulators. Additionally, biochar-assisted phytoremediation is gaining traction as it stabilizes contaminants, improves soil physicochemical properties, and supports microbial activity.

As concerns about climate change intensify, integrating phytoremediation with climate-resilient land management is expected to become a central focus. Plants used in remediation can contribute to carbon sequestration, erosion control, and restoration of degraded landscapes, aligning remediation goals with ecosystem regeneration and carbon neutrality strategies.

The future also points toward the use of phytoremediation in urban and industrial brownfield redevelopment, transforming previously unusable land into green infrastructure, recreational spaces, or biomass cultivation zones. In this context, phytoremediation supports both environmental and socio-economic regeneration. Furthermore, the integration of AI-driven environmental monitoring and remote sensing technologies will allow real-time tracking of phytoremediation progress, optimizing species selection, irrigation, and nutrient supplementation. Coupled with environmental big data, this precision approach will streamline decision-making and reduce trial-and-error interventions.

8. Conclusion

Phytoremediation has emerged as a sustainable, cost-effective, and environmentally friendly approach for the remediation of contaminated environments, particularly heavy metal- and organic pollutant-laden soils and water bodies. This review has comprehensively discussed the types, mechanisms, and plant-based strategies involved in phytoremediation, alongside the role of soil microorganisms and enhancement technologies that improve its efficacy. Key phytoremediation pathways such as phytoextraction, phytostabilization, rhizofiltration, phytovolatilization, and phytodegradation have been critically examined,

highlighting both their practical applications and their biological underpinnings.

The selection of plant species remains a cornerstone of successful phytoremediation. Factors such as plant growth rate, tolerance to contaminants, biomass production, and the ability to establish symbiotic interactions with beneficial rhizomicrobes are critical. The inclusion of microbial partners, especially plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi further augments phytoremediation capacity by enhancing metal availability, reducing stress in host plants, and stabilizing the rhizosphere ecosystem.

Advances in biotechnology, particularly genetic engineering, nanotechnology, and biochar application, have significantly improved the remediation potential of both plants and their microbial allies. Additionally, the integration of phytoremediation with sustainable agriculture opens new possibilities for reclaiming marginal lands, improving soil health, and supporting biomass-based energy systems, all while ensuring environmental safety and long-term land productivity.

As we look toward the future, phytoremediation is expected to evolve into a more precise, data-informed, and ecosystem-based strategy. With the advent of omics technologies, real-time monitoring tools, and AI-assisted decision-making, phytoremediation can transition from experimental plots to large-scale environmental and agricultural rehabilitation projects. Moreover, its role in climate change mitigation—-through carbon sequestration, restoration of degraded land, and promotion of circular bioeconomy practices underscores its broader ecological significance.

Despite certain limitations, such as the time required for cleanup and depth of root zone penetration, phytoremediation stands as a viable green alternative to conventional remediation technologies. Continued interdisciplinary research, supported by policy frameworks and stakeholder engagement, will be vital to unlocking its full potential and mainstreaming its application in diverse environmental contexts.

In summary, phytoremediation not only represents a practical solution to environmental contamination but also embodies a forward-thinking approach that aligns with global sustainability goals and the transition toward regenerative ecological practices.

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CRediT authorship contribution statement

Shanmuga Pavithra Kannan: Writing – original draft, Supervision. **Bhavadharani Hari Babu:** Writing – original draft. **Govardhan Murali krishnan:** Writing – original draft. **Melvin William Stanislas:** Writing – original draft. **Yuvaraj Dinakarkumar:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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