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Review article

Phytoremediation strategies for mitigating environmental toxicants

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ABSTRACT

In natural environments, persistent pollutants such as heavy metals and organic compounds, are frequently sequestered in sediments, soils, and mineral deposits, rendering them biologically unavailable. This study examines phytoremediation, a sustainable technology that uses plants to remove pollutants from soil, water, and air. It discusses enhancing techniques such as plant selection, the use of plant growth-promoting bacteria, soil amendments, and genetic engineering. The study highlights the slow removal rates and the limited availability of plant species that are effective for specific pollutants. Furthermore, it investigates bioavailability and the mechanisms underlying root exudation and hyperaccumulation. Applications across diverse environments and innovative technologies, such as transgenic plants and nanoparticles, are also explored. Additionally, the potential for phytoremediation with bioenergy production is considered. The purpose of this study is to provide researchers, practitioners, and policymakers with valuable resources for sustainable solutions.

1. Introduction

Phytoremediation, recognized as a sustainable and environmentally friendly approach, has garnered significant attention as a promising strategy for mitigating the impact of heavy metals and organic compounds on the environment. This innovative technique utilizes plants to naturally remove, detoxify, or immobilize contaminants, thereby contributing to the restoration of polluted ecosystems [1]. Inorganic pollutants, such as heavy metals, metalloids, radionuclides, phosphates, and nitrates are widespread. While some heavy metals are essential for plant growth, excessive levels of lead, cadmium, mercury, and arsenic pose serious health risks to both humans and wildlife, leading to chronic anemia, neurological damage, developmental delays, kidney damage, cognitive impairment, and cancer [2]. Organic pollutants resulting from industrial, urban, and agricultural activities also present substantial threats due to their persistent and harmful nature. Compounds like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), phenols, and pesticides, due to their hydrophobic characteristics, persist in the environment and can bioaccumulate, causing toxicity in organisms and disrupting ecosystems (Singh and Jain, 2003).

Phytoremediation is a promising solution due to its ecological soundness, cost-effectiveness, and versatility in addressing various contaminants. Successful implementation requires understanding of the bioavailability of metals and organic compounds, which influence plant uptake and removal. This knowledge guides the selection of appropriate plant species and remediation strategies [3]. Various phytoremediation techniques include phytoextraction, phytostabilization, rhizodegradation, rhizofiltration, phytodegradation, and phytovolatilization, each has unique applications, advantages, and challenges, offering a comprehensive array of

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strategies for remediation [4].

The uptake of metals and organic compounds is a complex process influenced by the properties of the contaminants, the species of the plants, the characteristics of the soil, and the prevailing environmental conditions [5]. Plants can absorb metals passively through diffusion or actively via specialized transporter proteins, and produce chelating agents to facilitate this uptake. Similarly, plants passively absorb hydrophobic organic compounds while actively transporting water-soluble ones. Once absorbed, contaminants undergo metabolism and detoxification within the plant and may be stored or translocated to different tissues [6]. Investigating the mechanisms of pollutant uptake in plants can enhance remediation efforts.

Strategic plant selection involves evaluating pollutant-removal capabilities and adaptability to the local environment, thereby optimizing the success of phytoremediation. Plant species have demonstrated proficiency in this area, each utilizing distinct biochemical processes. Understanding these processes aids in selecting the most suitable species for specific remediation tasks. Different plant species exhibit varying effectiveness in remediating contaminants; for instance, *Indian mustard* was effective for heavy metals, and *Vetiver* grass excelled in addressing organic pollutants [7].

The field of phytoremediation is evolving through innovative techniques, including genetically modified bacteria and transgenic plants, which enhance the efficiency and specificity of remediation solutions (Mello-Farias et al., 2011) A sustainable remediation assessment evaluates the long-term impacts of phytoremediation projects on environmental, economic, and social resources. Bioremediation technologies, such as microbial stimulation, genetic engineering, and the use of chelates, improve the overall efficacy of phytoremediation practices [8]. Approaches such as metagenomics, proteomics, and metabolomics further enhance our understanding, opening new avenues for improving the precision and efficiency of phytoremediation [9]. Nanoparticles (NPs) have emerged as potential tools in phytoremediation, serving as contaminants and as agents for remediation, which highlights their role and the challenges they present in this context. An exciting development in environmental remediation is the integration of phytoremediation with bioenergy production, utilizing plants for pollution cleanup while generating renewable energy [10].

This review examines phytoremediation, its mechanisms, strategies, and recent advancements. It aims to clarify how phytoremediation functions, the various strategies to enhance its efficacy, and the challenges to its widespread implementation. Overall, this analysis provides a nuanced understanding of phytoremediation's potential for sustainable environmental management, guiding future research and practical applications of plants as eco-friendly tools for cleanup.

2. Heavy metals and uptake mechanism

Heavy metals are persistent and toxic, posing risks to ecosystems and human health. Both industrial and natural activities contribute to their mobility, resulting in soil and water contamination, particularly in mining regions. Their persistence facilitates bioaccumulation and biomagnification, highlighting the need for effective remediation strategies. The solubility and bioavailability of heavy metals are influenced by their chemical forms and soil properties, which are affected by factors such as pH and microbial activity. Plants and microorganisms enhance the availability of these metals through root exudation, the secretion of metal-mobilizing compounds, and enzyme activity, thereby facilitating plant uptake.

Heavy metal accumulation in plants involves several processes, including mobilization, uptake, transport, and sequestration. Metals are absorbed at the root surface and enter cells through either passive or active pathways. Within root cells, they form complexes with chelators like organic acids and are sequestered in cell walls or vacuoles (Peuke and Rennenberg, 2005). These metals are subsequently transported to the shoots via the xylem. In leaves, they are stored in cell walls or vacuoles to prevent accumulation in the cytosol [11].

Heavy metals interact with cellular biomolecules, leading to an increase in reactive oxygen species. Metal cations form complexes with phytochelatins, which sequester these metals in vacuoles, isolating toxic metals from essential cellular processes [11]. Metallothioneins bind to nutrient metals and protect plants from harmful ions. Cysteine-rich peptides, such as metallothioneins and phytochelatins sequester metals by forming bonds with sulfur residues. Increasing the concentrations of these peptides can enhance metal accumulation in plants [12]. Phytochelatins detoxify heavy metals and are synthesized by enzymes such as γ-glutamylcysteine synthetase (γECS) and glutamine synthetase [13]. Engineered phytoremediation systems utilize bacterial genes to convert mercury into less toxic forms. Ferric Chelate Reductase (FRO2) facilitates iron uptake by reducing Fe(III) to Fe(II). Balancing the activities of metal transporters is crucial for ensuring proper metal distribution, storage, and utilization in metalloproteins and metalloenzymes [14].

Heavy metal uptake and translocation involve various molecules, including metal ion transporters and complexing agents. Specialized transporters in the root cell membranes mediate the influx and efflux of metals [5]. Genetic and molecular techniques have identified several genes involved in metal transport, such as heavy metal ATPases (HMAs), natural resistance-associated macrophage proteins (Nramps), the cation diffusion facilitator (CDF) family, the zinc-regulated, iron-regulated transporter-like protein (ZIP) family, and cation/proton antiporters (CPAs) [15]. For example, OsZIP9 in rice enhances zinc uptake under zinc-limited conditions [16]. HMA proteins and metal tolerance proteins (MTPs) play crucial roles in heavy metal transport and accumulation in plants [17].

3. Organic pollutants and uptake mechanisms

Organic pollutants present significant challenges due to their complex structures and resistance to degradation, leading to environmental persistence and health issues such as cancer, reproductive disorders, immune system alterations, hypertension, and diabetes. Hydrophobic organic compounds (HOCs) strongly bind to soil particles, which reduces their concentration in water [3]. The bioavailability of HOCs is influenced by their distribution between soil and water, with soil organic matter serving as a sorbent. Microbial activity plays a crucial role in the degradation and fate of HOCs. Additionally, different plant species exhibit varying abilities to absorb and transport organic compounds, a process influenced by root exudates, mycorrhizal associations, and rhizospheric bacteria that enhance HOC degradation [18].

Plant roots often serve as the primary tissue for encountering organic pollutants, making root absorption the predominant mechanism for uptake. This is followed by diffusion, which facilitates the uptake of organic pollutants and their subsequent translocation to various parts of the plant [19]. The detoxification process involves several key steps, including chemical modification, functionalization, conjugation, and compartmentalization, with enzymes playing a crucial role in either completely mineralizing pollutants or partially degrading them into stable intermediates [20]. The conjugation of pollutants with endogenous compounds, such as amino acids and proteins, aids in their sequestration in vacuoles and cell walls. Active transport mechanisms, including the ATP-dependent glutathione pump, facilitate the movement of these conjugates [21]. This system recognizes a variety of compounds, including oxidized glutathione, glutathione conjugates of organic compounds, diverse high-molecular-weight toxic organic xenobiotics, and peptide-metal complexes such as phytochelatins. In plants, conjugation and compartmentalization are critical steps in the detoxification of xenobiotics. Once inside the cells, xenobiotic compounds are primarily metabolized by xenome enzymes, which reduce their toxicity in the form of conjugates before compartmentalization or excretion [12].

4. Soil, water, and air: phytoremediation essentials

Phytoremediation is a sustainable approach for mitigating pollution in soil, water, and air by using plants to absorb, degrade, or transform contaminants. This method effectively addresses pollutants like heavy metals, organic compounds, and radioactive elements, providing a versatile alternative to traditional remediation techniques. Its efficiency is influenced by several factors, including plant species, soil characteristics, root exudates, the type of contaminant, and plant-microbe interactions within the rhizosphere.

It is an effective and sustainable method for cleaning up contaminated soil. This process can be enhanced through the use of soil amendments, which improve the efficiency of contaminant removal. Additionally, mycorrhizal fungi have been shown to enhance the uptake and translocation of heavy metals from the soil into plants. Certain plant species, such as *Viola baoshanensis, Sedum alfredii, Vertiveria zizanioides, Dianthus chinensis, Rumex* K-1 (*Rumex patientia* × *R. timschmicus*), *Rumex crispus,* and *Rumex acetosa,* have shown notable potential for remediating heavy metals in soils [22]. For example, *Chenopodium ambrosioides* exhibited resistance to Cd with a growth tolerance index ranging from 117.64 % to 194.11 % for overall growth and from 188.23 % to 264.70 % for shoots growth [23]. In contrast, *Brassica juncea* showed a tolerance index of 87.4 % for shoots and 89.6 % for roots in contaminated soils [24]. Hernández et al. [25] compared the phytoextraction capacities of *Lactuca sativa* and *Lolium perenne* for removing Ni, Fe, and Co from soils contaminated by the galvanoplastic industry. They found that *Lactuca sativa* accumulated more Ni and Co, while *Lolium perenne* was more effective at accumulating Fe. The study suggested selecting plant species based on the specific metal targeted for optimal remediation, noting that soil pH influences metal concentrations and plant survival. Pandey et al. [26] observed a positive correlation between metal accumulation in *Typha latifolia* and soil metal concentrations, indicating that higher concentrations in the soil and longer exposure durations resulted in increased accumulation of Zn, Mn, Cu, Pb, Cd, Cr, and Ni in the plant. Liu et al. [27] identified plant species such as Purple Coneflower, Aster Callistephus, Fawn, Fire Phoenix, and Alfalfa as effective for remediating petroleum-contaminated soils.

A study by Ning et al. [28] found that using a compounded activation agent derived from fruit residue enhanced the phytoextraction of Pb by *Sedum alfredii*, increasing Pb uptake in the plant's tissues and demonstrating a promising method for improving phytoremediation efficiency in Pb-contaminated soils. Plant-growth-promoting microbes with ACC (1-amino-cyclopropane-1-carboxylate) deaminase enhanced germination and growth, while arbuscular mycorrhizal fungi (AMF) improved nutrient uptake [29]. Dhaliwal et al. [30] noted that adding a chelating agent to the soil improved the phytoextraction of Cd uptake by plants, resulting in a 15 % increase in metal uptake as ethylenediaminetetraacetic acid (EDTA) levels in the soil rose from 1 to 2 mg/kg. Shinta et al. [31] concluded that citric acid was more effective than EDTA in improving soil conditions for phytoremediation by lowering the soil's pH and promoting a beneficial microbial community, which enhanced plant root growth and facilitated the uptake and accumulation of contaminants.

Water pollution is a pressing global issue that can be sustainably addressed through phytoremediation, which involves treating contaminated water bodies, wetlands, and industrial effluents. Aquatic plants such as water hyacinth [32], duckweed [33], and water lettuce [34] have demonstrated the ability to accumulate heavy metals, degrade organic pollutants, and remove excess nutrients, thereby contributing to water purification. Zhu et al. [35] emphasized that excessive nutrients, such as nitrogen and phosphorus in water bodies lead to eutrophication, causing algal blooms and oxygen depletion. They reported the effectiveness of aquatic plants like water hyacinth and duckweed in reducing nutrient levels through uptake and assimilation, which helps to mitigate the adverse effects on water quality in affected aquatic environments. According to Qin et al. [34], water hyacinth effectively mitigated carbon, water lettuce successfully reduced nitrogen, and duckweed efficiently removed phosphorus from contaminated ponds.

Ansari et al. [36] discovered that floating aquatic phytoremediators, such as Azolla, Eichhornia, Lemna, Spirodela, Wolfia, and Wolffiella significantly removed water pollutants through the bioaccumulation of heavy metals and organic contaminants in their tissues. Uysal and Taner [37] observed that metal accumulation in plants increased with initial metal concentrations ranging from 0 to 50 mg/L, but decreased when concentrations rose from 50 to 100 mg/L. This decline led to plant wilting due to metal toxicity, which may have been exacerbated by the transpiration of metal ions from the roots to the surrounding solution, and negatively impacted plant survival. Studies by Jang et al. [38] and Wang et al. [39] demonstrated that wetland plants, such as *Phragmites australis* and *Typha latifolia* marginally removed nanoparticles like Ag, Cu, and Zn from wastewater by accumulating them in their tissues, highlighting their potential for phytoremediation in treating wastewater contaminated with metallic nanoparticles. Conversely, Xu et al. [40] showed that duckweed effectively removed PAHs from water bodies, with the plant's associated microorganisms degrading PAHs in contaminated water and reducing their concentrations. *Vetiveria zizanioides*, a perennial bunchgrass, exhibited a 93 % removal rate of the textile dye Remazol Red from wastewater, while a plant consortium with *Ipomoea aquatica* further enhanced textile dye removal by increasing dye-degrading enzymes in its root and shoot tissues [41].

Air quality significantly impacts human health and ecosystem well-being, and plants can purify air by absorbing and metabolizing airborne pollutants. Schaub et al. [42] investigated the use of trees for the phytoremediation of air pollutants, examining the mechanisms of pollutant uptake and metabolism within trees. They emphasized the factors that influence the efficacy of trees in controlling air pollution, and highlighted their role in mitigating pollutants through processes such as deposition on leaf surfaces, absorption through stomata, and transformation within plant tissues. Plants can absorb and degrade pollutants, including volatile organic compounds (VOCs), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) through mechanisms such as phytovolatilization, phytofiltration, and phytodegradation [43]. Urban green spaces, phytowalls, and green roofs have been studied for their effectiveness in mitigating air pollution, despite challenges to their widespread adoption [44]. Teiri et al. [45] demonstrated that *Nephrolepis obliterata* and *Chamaedorea elegans* effectively removed formaldehyde, achieving removal rates ranging from 65 % to 100 % over prolonged exposure, thus showcasing their potential for indoor air purification. Irga et al. [46] found that plants grown in hydroculture were more effective at removing specific pollutants compared to those grown in traditional soil. They estimated that 57 m^2 of leaf area could absorb or eliminate approximately 13 % of the CO_2 produced per person in an average unventilated room, indicating that hydroculture might enhance the air purification abilities of indoor plants, with larger leaf areas leading to increased CO_2 removal. Sriprapat and Thiravetyan [47] investigated the ability of *Zamioculcas zamiifolia*'s ability to remediate benzene, toluene, ethylbenzene, and xylene from indoor air, highlighting its potential for improving indoor air quality. They determined that cuticular absorption in *Z. zamiifolia* contributed to 20 % of benzene, 23 % of toluene, 25 % of ethylbenzene, and 26 % of xylene uptake. Jeong et al. [48] assessed 18 indoor plant species for their ability to reduce indoor particulate matter levels, underscoring their potential to improve air quality and mitigate pollution.

5. Selecting plants: a strategic approach

Phytoremediation depends on the ability of plants to absorb contaminants through their roots, where these substances accumulate in the leaves until they can be removed. Nutrient uptake occurs via passive mechanisms, such as transpiration and active transport through cell membrane proteins, utilizing pathways such as the apoplast and symplast in the xylem [49]. Furthermore, plants can absorb nonessential inorganic compounds, necessitating retention mechanisms for essential nutrients like Cu, Zn, and Mn, which can be toxic at elevated concentrations [5].

Environmental factors such as soil type, pH, moisture, and climate can influence phytoremediation. Comprehensive site-specific assessments are essential for identifying suitable plants and ensuring sustainability by integrating them with the local ecosystem [50]. Laboratory and field experiments, along with small-scale pilot studies, are crucial for evaluating plant tolerance and accumulation capabilities, as well as for validating the feasibility of large-scale projects [51].

Plants commonly used in phytoremediation include hybrid poplars, willows, grasses, legumes, and hyperaccumulators. Mustard and alfalfa are effective for addressing surface soil contaminants, while hybrid poplars are particularly beneficial for groundwater remediation [52]. Although edible crops pose health risks and therefore unsuitable, medicinal and aromatic plants offer an innovative solution, as they are economically valuable and help minimize contamination in the food chain [53,54]. Aromatic plants from families such as *Poaceae, Lamiaceae, Asteraceae*, and *Geraniaceae* have demonstrated potential for heavy metal phytoremediation [54]. Additionally, ornamental plants like *Echinacea purpurea* and *Callistephus chinensis* have been shown to release compounds that facilitate the degradation of PAHs [55].

Hyperaccumulator plants are preferred for phytoextraction due to their high metal accumulation capacity and lower biomass production, making them economically viable for metal recovery and disposal. When selecting plants for phytoextraction, factors such as the ability to address specific contaminants, growth rate, pest resistance, metal tolerance, and ease of maintenance are considered. Grasses, which can be harvested multiple times during a growth period, are often more suitable for phytoremediation than shrubs and trees [1]. The symbiotic relationship between plants and rhizosphere microorganisms enhances nutrient absorption and contaminant degradation [27]. Soleymanifar et al. [56] highlighted that hyperaccumulators, which concentrate metals significantly more than non-hyperaccumulator, show consistent pollutant removal across various environments despite differing conditions. Hazotte et al. [57] compared metal concentrations in three Ni hyperaccumulators (*Odontarrhena chalcidica, Leptoplax emarginata,* and *Berkheya coddii*) at temperatures of 550 °C and 900 °C, finding higher Ni levels at 900 °C in all tissues. At 550 °C, over 95 % of the organic material was decomposed, and 99 % of carbon was eliminated from all species.

Metallophytes, including herbaceous and woody species, exhibited a greater accumulation and tolerance of heavy metals compared to non-hyperaccumulators, thereby facilitating effective phytoremediation. *Thlaspi caerulescens* and *Arabidopsis halleri* exhibited tolerance to Cd and Zn, yet the differences in metal uptake were not accounted for in the transport capacities of leaf protoplast. This suggests that regulation occurs before the plasma membrane of the leaf mesophyll protoplast [58]. *Thlaspi caerulescens* and *Thlaspi arvense* identified approximately 5,000 differentially expressed genes that were involved in the transport and compartmentalization of Zn [59].

Willow species absorb heavy metals differently across various plant parts, accumulating Cd in twigs and leaves, Pb in roots and twigs, and Zn in twigs. Notably, higher Cd accumulation occurred in soils with lower pH, and both Cd and Zn rates increased over three years [60]. Metal-accumulating trees like willow, poplar, and birch effectively absorbed Zn and Cd from contaminated sites, with *Salix caprea* exhibiting the highest accumulation of Zn and Cd in its leaves and fine roots [61]. Willows, with their deeper root systems, can reclaim greater soil depths compared to herbaceous hyperaccumulators. Additionally, walnuts and maple trees have proven effective in absorbing Pb and Cr, with walnuts, demonstrating greater efficiency in absorbing both metals [62].

Poplar trees have been extensively utilized in phytoremediation due to their rapid growth and extensive root systems, which enhance their ability to absorb and degrade organic pollutants such as trichloroethylene (TCE) and polycyclic aromatic hydrocarbons (PAHs). Similarly, willow trees have demonstrated effectiveness in removing various organic contaminants, including hydrocarbons and pesticides, owing to their high transpiration rates and robust root systems [63]. An experiment performed by Ghanem et al. [64] assessed the germination and growth of three selected plants in soil contaminated with pyrene at concentrations of 50 or 100 mg/kg dry soil for Alfalfa, Oilseed rape, and Perennial Ryegrass. Remarkably, pyrene did not hinder the germination of these species, even at the higher concentration (100 mg/kg), with Alfalfa, Oilseed rape, and Ryegrass exhibiting germination rates of 95, 90, and 86 %, respectively.

6. Phytoremediation with soil amendments

Phytoremediation with soil amendments represents an environmentally sustainable strategy that improves the ability of plants to remediate pollutants from contaminated soils by incorporating beneficial substances. These amendments significantly affect the bioavailability, uptake, translocation, and bioaccumulation of contaminants, which subsequently impact the growth and development of plants.

Saengwilai et al. (2020) conducted a study examining the effects of organic amendments (cattle and pig manure) and inorganic amendments (leonardite and osmocote) on the growth of *Tagetes erecta* and its uptake of Cd. Their findings indicated a higher accumulation of Cd in the roots of the plants. In a separate investigation, Kuziemska et al. [65] explored the effects of increasing Cu doses in conjunction with cattle and chicken manure. They spent mushroom substrate on the growth of cocksfoot and their results demonstrated that cattle manure was the most effective in mitigating Cu toxicity. Taeprayoon et al. [66] found that combinations of bone meal and bat manure, as well as leonardite and bat manure, significantly enhanced the growth performance of *Acacia mangium, Jatropha curcas*, and *Manihot esculenta*, with bone meal proving particularly effective for *Jatropha curcas*. Saengwilai et al. [67] determined that cow manure resulted in optimal growth for *Oryza sativa* L., leading to an increase in growth rates. They also reported that both cow manure and leonardite reduced Cd concentrations by 3.3-fold and 1.6-fold, respectively, suggesting that a combination of organic and inorganic amendments may enhance while simultaneously reducing heavy metal accumulation in contaminated soils. Furthermore, Doichinova and Velizarova [68] noted the beneficial effects of paper waste on phytoremediation, which resulted in decreased uptake of Pb and Cd by Red oak and Austrian pine seedlings. This effect was attributed to improved plant growth and enhanced soil physical properties. The combined application of paper industry waste and fertilizers with an N-P-K ratio of 2:1:2 was found to promote both sapling growth and heavy metal accumulation.

Feng et al. [69] found that the application of sewage sludge compost improved the phytoextraction of PAHs by *Festuca arundinacea* by natural chelating agents. The study indicated that the incorporation of compost and the cultivation of vegetation could promote the dissipation of PAHs, as evidenced by a reduction in PAH concentrations after 126 days and an increase in soil dehydrogenase activities. Similarly, Scattolin et al. [70] investigated the effects of composted sewage sludge on mitigating slag toxicity and improving the nutritional value of various herbaceous species, including *Achillea millefolium, Bromus erectus, Festuca arundinacea, Melilotus officinalis*, and *Medicago sativa*. Their findings revealed that plant biomass decreased when the pH exceeded 8.6, primarily due to Cr accumulation surpassing toxic thresholds and deficiencies in Mn, Zn, and P. Conversely, when the pH was below 8.6, biomass increased, resulting in decreased Cr levels in leaf below toxicity thresholds and an elevation in Mn, Zn, and P levels exceeding deficiency thresholds.

González-Chávez et al. [71] advocated for the utilization of corn biochar due to its advantageous effects on the chemical properties of mine residue, which subsequently enhanced the growth of *Jatropha curcas* L. This enhancement was attributed to improvements in cation exchange capacity, organic matter content, essential nutrients availability, electrical conductivity, and water-holding capacity. These modifications resulted in increased plant biomass and improved nutritional and physiological performance. Namgay et al. [72] reported that the application of wood biochar in the soil led to a reduction in the concentrations of As, Cd, and Cu in the shoots of *Zea mays*, as well as a decrease in Pb levels in the soil. The application of biochar notably diminished the concentrations of As, Cd, and Cu in maize shoots, particularly at elevated rates of trace element application; however, its effects on Pb and Zn concentrations in the shoots were found to be inconsistent. Brennan et al. [73] investigated the effects of maize plant and pine-derived biochars, in addition to commercially available activated carbon, as soil amendments. Their findings indicated that these sorbent amendments improved plant growth characteristics, including chlorophyll content and the shoot-to-root biomass, while consistently reducing the uptake of contaminants into the shoots. Nonetheless, they also raised concerns regarding the environmental implications of biochar production, its potential interactions with herbicides, and the release of hydrocarbons.

Research has demonstrated that the incorporation of sugar beet residue (SBR) significantly improved the phytoextraction of various heavy metals, including Ni, Zn, Fe, B, Cr, and Cd. The application of SBR has been shown to improve phytoextraction efficiency across different plant species, such as *Trifolium repens* L., *Tetraclinis articulata*, and *Crithmum maritimum* L. This enhancement is attributed to an increase in microbial biomass within the rhizosphere and the reduction of metals by microbial activity, which subsequently leads to increased metal bioavailability [74–76].

Artificial root exudates have the potential to enhance remediation processes by lowering the pH in the rhizosphere and promoting the dissolution of metal ions. Wang et al. [77] reported that root exudates accelerated the phenanthrene degradation by the microbial community present in contaminated soil, with *Koelreuteria paniculata* showing high degradation rates. Furthermore, Lu et al. [78] demonstrated that root exudates, such as glucose, facilitated the pyrene degradation by influencing dehydrogenase activity and altering the soil microbial community, particularly the bacterial taxonomic composition, which in turn affected pyrene biodegradation. Liao et al. [79] found that root exudates initially increased the degradation of naphthalene, phenanthrene, and pyrene in soils;

however, this effect declined with concentrations of exudates. Notably, there was a significant stimulation of *Pseudomonas*, which may carry the nahAc gene essential for PAH degradation. This suggests that root exudates promote PAH biodegradation. by increasing the abundance of degrading microorganisms and the associated genetic elements.

7. Phytoremediation with chelates

Chelates are chemical compounds that bind to metal contaminants present in soil, thereby enhancing their bioavailability and absorption by plants, which facilitates the remediation process. The integration of chelating agents has been shown to increase both the accumulation and solubility of metals, even in plant species that do not exhibit hyperaccumulation traits. Natural organic chelating agents like acetic, malic, citric, and oxalic acids, are eco-friendly and biodegradable, while synthetic agents like ethylene glycol tetraacetic acid (EGTA), ethylenediaminetetraacetic acid (EDTA), and diethylenetriaminepentaacetic acid (DTPA) are also effective. Nonetheless, the high mobility of chelating agents in the soil can lead to the dispersion of contaminants and the formation of persistent metal-chelate complexes, necessitating careful management to mitigate the risks of excessive metal uptake and potential phytotoxicity. The effectiveness of remediation is enhanced by both synthetic and natural chelating agents, particularly organic acids.

Plants treated with 1 mM EDTA exhibited higher Pb concentrations in their shoots compared to control groups. Furthermore, treatments with 5 mM and 10 mM nitrilotriacetic acid (NTA) resulted in elevated Pb levels in the foliage of switchgrass when compared to the 1 mM and 2 mM treatments. The combination of NTA with Triton X-100 more than doubled the Pb concentrations, indicating an enhancement in phytoextraction efficiency [80]. Hosseinniaee et al. [81] studied the effects of EDTA on the phytoextraction of Pb, Cd, and Zn in species such as *Marrubium cuneatum, Stipa arabica,* and *Verbascum speciosum*. Their findings revealed that higher doses of EDTA led to a reduction in chlorophyll content and biomass due to oxidative stress, while simultaneously increasing the activity of antioxidant enzymes, including superoxide dismutase (SOD), glutathione peroxidase (GPx), and catalase (CAT). Specifically, a 5 mmol/kg EDTA dose resulted in decreased plant biomass, and the study observed high bioconcentration factor (BCF) values for Cd across all plant species, as well as for Zn and Pb in *M. cuneatum* and *S. arabica*. Additionally, high accumulation factors for Cd were noted in all species, and for Pb in *S. arabica*, thereby demonstrating the effectiveness of EDTA in the phytoextraction of Cd, Zn, and Pb from contaminated soils. Similarly, EDTA was found to enhance Pb uptake and root-to-shoot translocation in Pb-contaminated soils, significantly increasing shoot Pb concentrations in corn and pea plants from less than 500 mg/kg to over 10,000 mg/kg. This indicates superior capacity of EDTA for Pb desorption compared to other chelating agents such as hydroxyethyle-thylenediaminetriacetic acid (HEDTA), diethylenetriamine-pentaacetic acid (DTPA), ethylene glycol tetraacetic acid (EGTA), and ethylenediamine-N,N′-bis (o-hydroxyphenyl) acetic acid (EDDHA). Notably, the Pb concentration in corn xylem sap increased 140-fold, and net Pb translocation rose 120-fold within 24 h [82]. EDTA was shown to enhance Pb uptake in *Zea mays, Sedum alfredii, Vetiveria zizanioides*, and *Canavalia ensiformis* L. [83]. In contrast, EGTA was found to improve Cd uptake and accumulation in *Althea rosea* [84], *Mirabilis jalapa* [85], and *Calendula officinalis* [86], while also increasing Pb accumulation in the above-ground parts of *Cicer arietinum* [87].

At a concentration of 25 μM, citric acid (CA) was found to enhance Cd uptake and translocation in *Halimione portulacoide*, while simultaneously inhibiting Ni absorption. Remarkably, an increase in CA concentration resulted in a reduction of Ni absorption, yet it also led to an increase in the root uptake of Cd [88]. Hosseini et al. [89] studied the effects of EDTA and CA on Pb accumulation and enzyme activities. Their findings indicated that EDTA reduced overall plant growth and increased Pb concentration in the shoots. In contrast, CA was observed to enhance plant growth, increase Pb accumulation in the roots, and elevate enzyme activities in the rhizosphere, although it did not facilitate translocation to the shoots. Additionally, synthetic surfactants like sodium dodecyl sulfate, were shown to enhance the solubility of heavy metals, thereby promoting Cd accumulation in both the roots and shoots of *Althaea rosea* [90] and in the shoots of *Calendula officinalis* [86].

8. Nanoparticles and phytoremediation

Nanomaterials possess significant potential in phytoremediation, attributed to their superior absorption and pollutant degradation properties. These capabilities are influenced by their nanoscale structure, high surface area-to-volume ratio, and reactivity, which can have both positive and negative effects on plant physiology.

Biosynthesis using plant extracts facilitates sustainability and cost-effective production of nanoparticles (NPs). For instance, *Bacillus subtilis* has been shown to biosynthesize silver nanoparticles (AgNPs) by reducing aqueous silver ions (Ag^+) to AgNPs within 18 h [91]. The synthesis of NPs derived from plant sources like AgNPs from *Capsicum annuum* and TiO_2-NPs from Aloe vera extract, presents environmentally friendly alternatives. Aloe vera extracts have demonstrated efficacy in reducing TiO_2-NPs, with the concentration of the extract influencing both the size and bioactivity of the nanoparticles. Furthermore, the green synthesis of TiO_2-NPs has been associated with enhanced biocompatibility and a reduction in cytotoxicity towards HepG2 cells [92].

Numerous nanoparticles, including iron oxide, titanium oxide, and carbon-based types, have been shown to promote plant growth, enhance pollutant bioavailability, and facilitate the uptake and accumulation of contaminants within plant systems. Specifically, iron oxide NPs, combined with PGPR, have been effective in improving the removal of heavy metals from contaminated soils. In a study, *Providencia vermicola* and FeO-NPs mitigated As toxicity, promoting growth and biomass in *Trachyspermum ammi* seedlings. This effect was attributed to the scavenging of reactive oxygen species and the reduction of oxidative stress. Higher levels of As were found to have adverse effects on plant growth, biomass, photosynthetic pigments, gas exchange, sugar content, and nutrient levels while also causing damage to membrane-bound organelles. On the other hand, increased As concentration led to heightened indicators of oxidative stress, including malondialdehyde, hydrogen peroxide, electrolyte leakage, and organic acid exudation in the root of *T. ammi*. Both *P. vermicola* and FeO-NPs alleviated As toxicity, enhancing plant growth and reducing oxidative stress by lowering As content in roots and shoots [93]. Similarly, the integration of carbon-based NPs with microbial agents has been shown to enhance degradation of organic pollutants in both soil and water environments [94].

In coastal ecosystems, *Suaeda glauca* showed a greater capacity for the removal of nanomaterials like TiO_2 and ZnO in comparison to *Brassica campestris*. This species showed a higher ZnO-NP concentration and maintained superior levels of Zn and Ti compared to *B. campestris* at a treatment concentration of 100 mg/kg. Notably, *S. glauca* was the only species to survive at a treatment concentration of 1000 mg-ZnO-NP/kg, thereby illustrating its enhanced remediation potential [95]. Fernandes et al. [96] demonstrated that *Phragmites australis* accumulated Ag exclusively in belowground tissues, particularly within the roots, in the absence of rhizome sediment. The accumulation of Ag was found to be greater accumulation when exposed to Ag-NPs compared to ionic Ag. Andreotti et al. [97] investigated the interactions of Cu-NP with *Halimione portulacoides* and *Phragmites australis*, revealing that both plant species accumulated lower levels of Cu in their roots from NPs. *P. australis* was capable of translocating Cu in both ionic and NP forms, whereas *H. portulacoides* did not translocate Cu from NPs, resulting in Cu accumulation in the roots being 4 to 10 times lower in NP form. Tabande et al. [98] found that co-inoculation with *Serendipita indica* alleviated the phytotoxic effects of ZnO-NP on *Medicago sativa* L. This co-inoculation led to an enhanced growth rate, a reduction in Zn translocation from roots to shoots, and an increase in shoot dry weight compared to plants inoculated solely with *Sinorhizobium meliloti*. Specifically, co-inoculation resulted in an 18.33 % and 8.05 % increase in shoot dry weight at 400 and 800 mg-ZnO/kg, respectively. Furthermore, root inoculation was associated with a reduction in the Zn translocation factor by 60.2 % and 44.3 % at 800 mg-ZnO-NP/kg compared to *S. meliloti* alone.

9. Microbial stimulation

Microorganisms such as plant growth promoting rhizobacteria (PGPR), endophytic bacteria, mycorrhizal fungi, and microbial consortia, play a significant role in enhancing plant growth, nutrient uptake, and stress tolerance. This is particularly relevant in the context of challenges like low plant biomass and slow pollutant uptake. The application of these microorganisms, in conjunction with organic amendments, has been shown to enhance soil microbial activity and support phytoremediation efforts. This is achieved by strengthening plant defenses against pathogens, increasing tolerance to heavy metals, improving nutrient uptake, and producing beneficial compounds including organic acids, siderophores, antibiotics, enzymes, phytohormones, and ACC (1-aminocyclopropane-1-carboxylate) deaminase, which aids plant growth by reducing ethylene production [99].

The introduction of *Trichoderma harzianum* to heavy metal-contaminated soil has been shown to enhance the biomass and metal uptake of *Brassica juncea*. This treatment resulted in increased levels of potassium, phosphorus, nitrogen, and organic matter in the soil, which in turn elevated the activity of plant glutathione and peroxidase enzymes, as well as soil urease and sucrase enzymes. Dominant soil bacteria (*Firmicutes*) and fungi (*Ascomycota*) exhibited a positive correlation with soil nutrients and the presence of toxic elements in plants [100]. Furthermore, the combination of *Trifolium repens* with the *Pseudomonas putida* strain RE02 improved growth, reduced Cd, Cr, and Pb toxicity, increased soil fertility, and boosted plant N-P-K concentrations by 16.72 %, 30.55 %, and 3.81 %, respectively. Total heavy metal uptake increased by 30.03–574.58 % [101]. The application of biochar and arbuscular mycorrhizal fungi (AMF) to *Medicago sativa* resulted in enhanced Cr accumulation and growth by regulating genes associated with reactive oxygen species and proline metabolism, while also raising soil pH, increasing phosphorus in soil, and reducing Cr in soil by 40 % [102]. A microbial consortium of PGPR, rhizobia, and AMF improved growth and Cd accumulation in legumes in Cd-contaminated soil. A Cd-tolerant pea mutant with *V. paradoxus* 5C-2, R. *leguminosarum* bv. *viciae* RCAM1066, and *Glomus* sp. 1Fo achieved Cd tolerance and accumulation levels comparable to *Indian mustard* [103]. The addition of organic matter, followed by bioaugmentation with an *Actinobacteria* consortium and *Brassica napus*, facilitated the transformation of Cr(VI) to Cr(III) and detoxified lindane [104]. Multi-metal-resistant bacteria that produce indole-3-acetic acid (IAA), siderophores, and solubilize phosphate reduced Cr(VI) toxicity and supported plant growth in Cr-contaminated soil. *Cellulosimicrobium* sp. NF2 promoted alfalfa growth and metal uptake under metal stress [105]. Soil treated with switchgrass and *Burkholderia xenovorans* LB400 showed the highest PCB removal rate of 47.3 %, with switchgrass enhancing the survival of LB400 [106]. AMF formed mutualistic relationships with most terrestrial plants, enhancing resilience to various stresses by stabilizing and transforming Cr, improving nutrient uptake, and regulating physiological processes [107]. Contrary to expectations, non-pathogenic fungal strains such as *Trichoderma harzianum, Penicillium simplicissimum, Aspergillus flavus, Aspergillus niger*, and *Mucor* spp. have been found to improve soil properties and increase Pb availability. Among these, *A. niger* exhibited the highest Pb tolerance, while *A. flavus* and *Mucor* spp. increased Pb solubility and lowered soil pH. Additionally, *A. flavus* also enriched soil organic matter content, and *A. niger* produced both IAA and siderophores, facilitating plant growth. *P. simplicissimum* contributed to phosphate solubilization, whereas *Mucor* spp. demonstrated significant potential for Pb phytoextraction in *Pelargonium hortorum* L. [108].

10. Genetically modified bacteria

Genetically modified bacteria (GMB) provide enhanced capabilities for phytoremediation by either extracting or degrading pollutants, and they are specifically designed to interact effectively with plants to improve remediation efforts in contaminated areas [109]. Despite their potential benefits, GMB faces challenges such as horizontal gene transfer and uncontrolled proliferation. Mitigating these risks requires the implementation of strategies like antisense RNA and suicidal genes [110]. Furthermore, to prevent the unintended transfer of antibiotic resistance to native soil microorganisms, it is crucial to avoid using antibiotic genes as selectable markers and to adopt safer alternatives [111].

GMB effectively removes toxins from soil, groundwater, and activated sludge that indigenous bacteria cannot degrade. By introducing specific genes, GMB are transformed into novel strains capable of rapidly eliminating pollutants such as heavy metals, pesticides, and petroleum hydrocarbons. These customized GMB express genes that facilitate metal sequestration or transformation into less toxic forms, making them particularly useful for soils contaminated with heavy metals [112]. Engineered bacteria improve nutrient cycling and plant health by enhancing nutrient solubilization and mobilization. They also assist in pollutant uptake and microbial degradation in the rhizosphere. Introduced through bioaugmentation, these bacteria complement the natural microbial community or add functionalities to optimize remediation [109].

11. Genetic engineering plants: transgenic plants

Genetically engineered plants, modified to express specific traits or enzymes, hold significant promise for phytoremediation by enhancing the absorption, accumulation, and detoxification of pollutants in soil and water. Transgenic plants enhance phytoremediation by influencing the rhizosphere microbial community and fostering beneficial plant-microbe interactions through root exudates that stimulate pollutant-degrading microorganisms. By genetically engineering hyperaccumulator plants with substantial biomass, these plants can extract heavy metals from contaminated areas while simultaneously increasing their tolerance to environmental stresses like salinity and drought, thereby expanding the range of environments suitable for phytoremediation [113]. Another strategy involves breeding plants with superior phytoremediation potential and high biomass production; however, this approach is complex due to the numerous genes involved in overall plant productivity, making it difficult to achieve through single-gene insertion [114]. Genetic and molecular techniques improve plant selection for remediation by identifying and manipulating genes associated with phytoremediation traits, while traditional breeding and genetic engineering improve the growth and biomass of hyperaccumulators or introduce these traits into fast-growing plants [5].

Brassica juncea was genetically engineered with the gshl gene from *E. coli* to enhance the production of glutathione and phytochelatin. The transgenic seedlings expressing gamma-glutamylcysteine synthetase (γ-ECS) exhibited increased tolerance to Cd tolerance and demonstrated higher levels of phytochelatins, γ-L-Glutamyl-L-cysteine (γ-Glu-Cys), glutathione, and total non-protein thiols compared to wild-type plants [115]. Furthermore, genetic modifications can improve a plant's ability to degrade organic pollutants by enabling the expression of specific enzymes that facilitate the breakdown of complex compounds like pesticides and hydrocarbons [116]. Approaches include manipulating metallothionein and phytochelatin genes, cloning metal chelator genes, altering oxidative stress mechanisms, modifying roots structures and biomass, and cloning metal transporter genes. The transfer of the Metallothionein-II gene has resulted in increased tolerance to Cd [117].

Liu et al. [118] transferred the *Streptococcus thermophilus* γ-Glutamyl-cysteine synthetase-glutathione synthetase (GCS-GS) operon into *Beta vulgaris* plants, enhancing their tolerance to and accumulation of Cd, Zn, and Cu. The metal concentrations in the shoots of transgenic plants were significantly higher (400, 270, and 300 μg/mg) compared to wild-type controls (100, 80, and 90 μg/mg). Similarly, Pomponi et al. [119] found that the expression of *Arabidopsis thaliana* Phytochelatin synthase PCS1 in *Nicotiana tabacum* increased Cd tolerance and accumulation, with transgenic plants achieving 700 mg-Cd/kg, compared to 400 mg-Cd/kg in controls. When Cd was provided in conjunction with glutathione (GSH), the accumulation in transgenic plants exceeded 2000 mg-Cd/kg. Dhankher et al. [120] studied the transfer of *E. coli* γ-ECS and arsenate reductase (arsC) to *Nicotiana tabacum* and *Arabidopsis thaliana*, resulting in enhanced Cd tolerance and accumulation. The shoot concentrations of Cd in transgenic plants reached 480 μg-Cd/g, compared to 300 μg-Cd/g in wild-type plants. He et al. [121] transferred γ-ECS to *Populus tremula* × *P. alba*, leading to increased Cd tolerance and accumulation. After 80 days of exposure to 100 μM Cd, the Cd levels in the aerial parts of transgenic plants were 69–82 % higher than those in wild-type plants, with total Cd removal reaching up to 5000 μg/plant in transgenics compared to 3000 μg/plant in wild types. Additionally, transgenic *Arabidopsis thaliana* exhibited increased As tolerance and accumulation [122], while modified tobacco plants demonstrated significant degradation of TNT [123].

12. Metagenomics/proteomics/metabolomics approaches

Metagenomics involves the analysis of genetic material directly extracted from environmental samples, providing a comprehensive view of microbial communities engaged in phytoremediation. By using DNA sequencing and analysis, metagenomics enables the identification and characterization of functional genes within these communities. The field has evolved from early sequencing techniques to next-generation sequencing, which produces more accurate DNA profiles free from chimeric sequences, thus improving data quality [124]. Metagenomic studies reveal diverse microbial populations that contribute to phytoremediation through processes such as contaminant degradation, nutrient cycling, and plant-microbe interactions. These studies highlight the genetic diversity and functional capabilities of root-associated microbial communities in contaminated environments, revealing dominant bacterial phyla like *Proteobacteria, Actinobacteria, Chloroflexi, Bacteroidetes, Acidobacteria*, and *Cyanobacteria*. A comparison of taxonomic and functional attributes across different biomes indicates that microbiomes cluster by biome and matrix type, with core metabolic functions remaining consistent, suggesting functional resilience across varying conditions [125].

Proteomics requires a comprehensive analysis of proteins, offering insights into the dynamic changes in protein expression and modifications that occur during plant-microbe interactions [126]. This approach helps in identifying crucial proteins involved in processes like contaminant uptake, transport, and detoxification in plants and their associated microorganisms [127]. Proteomic studies have revealed the specific proteins and pathways activated in response to contaminant stress, deepening our understanding of the molecular mechanisms utilized by plants and microbes in phytoremediation.

Metabolomics systematically analyzes metabolites within cells, providing insights into the metabolic processes involved in plant-microbe interactions [128]. In both plants and their associated microbes, metabolite profiles can be assessed to identify the metabolic pathways that are activated or modulated in response to contaminants. Metabolomic studies have been significant for understanding the chemical transformations of contaminants and how plants allocate resources to endure stress, thereby enhancing the effectiveness of phytoremediation [129]. Plant metabolism is broadly categorized into primary and specialized metabolism, which includes compounds essential for growth, development, reproduction, and adaptation to abiotic and biotic stresses [128].

13. Phytoremediation of pollutants

Hyperaccumulators possess low biomass but exhibit high tolerance to pollutants and significant accumulation capabilities. In contrast, non-hyperaccumulators have greater biomass and growth rates, indicating the diversity of phytoremediation strategies. The removal of heavy metals and organic contaminants from soil, water, and air is achieved through various phytoremediation mechanisms, including phytostabilization, rhizofiltration, phytoaccumulation, phytoextraction, phytovolatilization, phytodegradation, and rhizodegradation.

13.1. Phytoextraction

Phytoextraction is highly effective in areas with diffuse pollution characterized by low concentrations of pollutants, including heavy metals, radionuclides, and organic contaminants. Factors like growth rate, element selectivity, disease resistance, and harvesting techniques significantly influence its efficacy. The process involves mobilizing metals in the soil, increasing metal

Table 1
Phytoextraction of pollutants.

Plant	Contaminant	Remark	Reference
Amaranthus spinosus	Cu, Zn, Pb, & Cd	The rate of heavy metal removal was faster in the soil from the mechanic workshop than in the soil from the dump site. The trend of the rate of heavy metal removal was Cu > Zn > Pb > Cd for vegetated soil and Zn > Cu > Pb > Cd for non-vegetated soil.	Njoku & Nwani [130]
Arundo donax L.	Se	The giant reed (*Arundo donax* L.) ecotypes STM (Hungary), BL (USA), and ESP (Spain) exhibited significant ability in selenium accumulation within their stems and leaves. Notably, the ESP ecotype accumulated 1783 μg/g in the leaf, followed by BL with 1769 μg/g, and STM with 1606 μg/g in the 5.0 mg-Se/kg treatment.	Domokos-Szabolcsy et al. [131]
Chromolaena odorata	Fuel oil	*C. odorata* with *M. luteus* exhibited the highest Pb accumulation at 513.7 mg/kg and 7.7 mg/plant uptake. Additionally, it demonstrated the greatest reduction percentage of TPHs at 52.2 %, suggesting enhanced TPH degradation in vegetated soils due to the interaction between rhizosphere microorganisms and plants.	Jampasri et al. [132]
Corchorus capsularis L.	Cu,	Elevated soil Cu levels reduced plant growth, biomass, chlorophyll, gas exchange, and fiber yield, increasing ROS levels and oxidative stress. Despite this, *C. capsularis* fiber quality remained largely unaffected, with greater Cu accumulation reported in shoots compared to roots.	Saleem et al. [133]
Pelargonium hortorum, & *Mesembryanthemum criniforum*	Pb	In pot experiments, *P. hortorum* showed higher Pb uptake than *M. criniflorrum*, with a 1.9-fold increase in plants inoculated with the NCCP–1848 strain, followed by a 1.8-fold increase with the NCCP–1862 strain. In Pb-contaminated soils, *P. hortorum* inoculated with *Mucor* spp. exhibited the potential to enhance Pb phytoextraction and boost biomass production through plant growth–promoting activities.	Manzoor et al. [108]
Ipomoea carnea, Lantana camara, & Solanum surattense	Cd, Pb, Cu, Cr, Mn, & Ni	The plants effectively removed Cd, Pb, Cu, Cr, Mn, and Ni from the fly ash deposits, with *L. camara* and *I. carnea* showing significant translocation from root to shoot for most metals, except Mn and Pb.	Pandey [6]
Pelargonium hortorum, & *Pelargonium zonale*	Pb, & Cd	EDTA enhanced the solubility of Pb and Cd in the soil, resulting in higher concentrations accumulating in both roots and shoots, with *P. hortorum* and *P. zonale* showing a 50.9 and 42.2 % increase in Pb accumulation in shoots at 1500 mg/kg when 5 mmol/kg EDTA was used.	Gul et al. [134]
Sedum alfredii	Pb	In Pb-contaminated soils, *S. alfredii* demonstrated a higher capacity to accumulate elevated concentrations of lead (Pb) in its tissues, with a 52 % increase in biomass and doubled Pb accumulation with 15 mL of CAA.	Ning et al. [28]
Spartina alterniflora	Cr, Cu, Pb, Fe, & Zn	Metal concentrations in plant tissues exhibited variability across polluted sites and between aboveground and belowground tissues. Translocation factors were below 1 for Fe and often over 1 for Mn, but uncalculable for Cd.	Negrin et al. [135]
Tithonia diversifolia	Zn, & Pb	*T. diversifolia* effectively removed Pb and Zn from potted contaminated soil, with more Pb in roots than shoots regardless of AM fungus (*Glomus clarum*) injection. At the same time, Zn accumulation favored shoots with AM and roots without it.	Kekere et al. [136]
Typha domingensis, T. latifolia, & T. angustifolia	Al, As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, & Zn	All *Typha* species accumulated higher levels of Cd, Cu, and Pb in their roots, while Cr, Ni, and Zn were more prevalent in their stems and leaves.	Bonanno & Cirelli [137]
Zea mays	Pb, & Ti	The use of EDTA increased the concentration of Pb and Tl in the shoots of *Z. mays*, with extraction efficiency of Pb and Tl from Pb-Tl-contaminated soil increasing by 86 and 43 % in the presence of oxalic acid.	Huang et al. [138]

bioavailability, capturing metals by root cells, and transporting and sequestering metals within the plant [74]. Table 1 outlines an overview of the phytoextraction process for metals.

Metal uptake into root cells is facilitated by transport systems and intracellular binding sites. Once inside the plant, metals often precipitate, becoming immobilized in apoplastic and symplastic compartments. The transport of metals into the xylem is regulated, and influenced by factors such as membrane potential, competition between essential and non-essential heavy metals for transporters, and the presence of metal chelate complexes [11]. Strategies involved in this mechanism include exclusion, accumulation, and enhancement of metal uptake. These strategies aim to prevent pollutants from entering plant tissues, store pollutants, and modify plant properties to increase metal uptake, respectively [49].

Soil amendments, such as chelators and organic materials, improve pollutant uptake by plants, thereby enhancing phytoextraction and promoting both soil health and plant growth. Microbial inoculation with non-pathogenic fungi or plant growth-promoting bacteria (PGPB) further increases phytoextraction by modifying soil properties and enhancing metal availability to plants [139]. The addition of biochar or sugar beet residue to the soil boosts microbial biomass in the rhizosphere, which enhances metal availability and the phytoextraction of heavy metals [74,140].

Corchorus capsularis demonstrated significant phytoremediation potential in Cu-contaminated soil. High levels of Cu adversely affected growth, biomass, chlorophyll content, gas exchange, and fiber yield, while simultaneously increasing the production of reactive oxygen species and oxidative stress. Antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and ascorbate peroxidase (APX) were shown to mitigate this stress to prevent the accumulation of reactive oxygen species (ROS) and resulting cell damage [133]. Despite the accumulation of Cu, the quality of the fiber remained unaffected, with a greater

Table 2
Phytostabilization of metals.

Plant	Contaminant	Remark	Reference
Achillea millefolium, Bromus erectus, Festuca arundinacea, Melilotus officinalis, & Medicago sativa	Cr	Plant biomass decreased above pH 8.6 due to Cr toxicity and Mn, Zn, and P deficiencies, but increased below pH 8.6 with reduced leaf Cr and improved Mn, Zn, and P levels.	Scattolin et al. [70]
Agrostis capillaris, Arrhenatherum elatius, & Calamagrostis epigeios	Zn, Pb, As, & Cd	The highest concentrations were found for Pb in the *A. capillaris* rhizosphere at 3417 mg/kg and for Zn in *A. elatius* at 3876 mg/kg. At the same time, $CaCl_2$-extractable Zn was lowest in the rhizosphere of *C. epigeios*, and Pb was lower in *A. elatius*.	Teodoro et al. [143]
Arundo donax L., *Hordeum vulgare* L., & *Lupinus albus* L.	Pb, Sb, Cd, & As	Municipal solid waste compost (MSWC) increased the metal accumulation efficiency of *A. donax* and partially that of *L. albus*, but not of *H. vulgare*, especially in soils amended with 4 % MSWC from metal-contaminated sites.	Garau et al. [144]
Atriplex halimus, Nicotiana glauca Graham, *Cynara cardunculus, Brassica juncea* Czern, *Salvia rosmarinus* Spenn., & *Retama sphaerocarpa* Boiss.	As, Cd, Cu, Pb, & Zn	The combination of *C. cardunculus* and *B. juncea* was the most effective in reducing metal extractability and stimulating microbial activity in agricultural soil, whereas in mining soil, compost-assisted phytostabilization decreased $CaCl_2$-extractable Cd by 12–50 % and Zn by 71–76 %.	Lacalle et al. [145]
Eupatorium cannabinum	As	*E. cannabinum* showed high tolerance to As stress across pH levels and accumulated significant amounts of As in its roots, the addition of 20 mg/L of citric acid enhanced biomass, As accumulation, and stabilization at acidic pH.	González et al. [146]
Festuca rubra, & Heterocypris incongruens	Cu, Pb, Zn, & Cr	*Festuca rubra* accumulated more heavy metals in roots than above-ground parts, while limestone and chalcedonite boosted *H. incongruens* growth.	Radziemska et al. [147]
Helianthus annuus	Tetracycline & oxytetracycline	The root system degraded tetracycline and oxytetracycline from the water system, indicating its potential for in vivo antibiotic phytoremediation. Additionally, *Helianthus* spp. root-secreted compounds facilitated the breakdown and removal of these antibiotics.	Gujarathi et al. [142]
Lolium perenne	As, & Pb	Biochars derived from pig manure, Japanese knotweed, and a mixture demonstrated the potential to enhance plant growth, reduce Pb and As levels, and limit Pb and As movement in soil over time.	Qiu et al. [148]
Salix viminalis, & Salix purpurea	As, Sb, & Pb	As, Sb and Pb accumulated mainly in the *Salix* rhizosphere, with *S. purpurea* more efficient at accumulating As in its upper parts than *S. viminalis*, while *S. viminalis* transferred Pb and Sb to its shoots, unlike *S. purpurea*.	Sylvain et al. [149]
Setaria pumila, Pennisetum sinese, Sedum plumbizincicola, & Elsholtzia splendens	Cu, & Cd	All plants combined with limestone elevated soil pH and decreased Cu and Cd fractions; the bioavailability and mobility of Cu and Cd in *P. sinese* treatments were lower than in the other treatments.	Cui et al. [150]
Solanum nigrum	Cu, Zn, & Cd	The combination of 10 % attapulgite (MA2) and 10 % biochar (MB2) was optimal for amendments, exhibiting a synergistic effect with *S. nigrum* L. and achieving superior metal phytostabilization, particularly with MA2.	Li et al. [151]

concentration of Cu stored in the shoots compared to the roots. *Amaranthus spinosus* effectively enhanced the accumulation of Cu, Zn, Pb, and Cd from soils, particularly those contaminated by mechanical workshops. This process influenced soil pH, organic matter content, and cation exchange capacity, with its rapid uptake indicating effective soil remediation primarily through phytoaccumulation [130].

Soil contamination with Pb and Zn reduced plant growth and biomass production, with the extent of these effects varying based on metal type, concentration, specific growth parameters, and soil conditions, including the presence of arbuscular mycorrhiza. Plants exhibited improved performance when associated with arbuscular mycorrhiza, which facilitated increased metal accumulation in plant tissues. *Tithonia diversifolia* showed significant potential for the remediation of Pb- and Zn-contaminated soils, with bioaugmentation using *Glomus clarum* further enhancing its effectiveness [136]. A study revealed that three species of cattail (*Typha domingensis*, *T. latifolia*, and *T. angustifolia*) in a metal-contaminated wetland exhibited similar levels of metals in their roots, rhizomes, and leaves. These species showed comparable metal mobility from sediments to roots and from roots to leaves, indicating a high tolerance to metal contamination and limited translocation [137].

13.2. Phytostabilization

This technique employs plants to stabilize pollutants, reducing their mobility through root accumulation or immobilization in the rhizosphere. The mechanisms involved include sorption, precipitation, complexation, and metal valence reduction [141]. Phytochemical exudates and root surface transport proteins help the immobilization of contaminants, while sequestration processes store these substances within vacuoles. Heavy metals and organic contaminants are transformed into non-toxic forms through conjugation with sugars, proteins, and amino acids [142], mitigating their harmful effects. Table 2 shows the process of metal phytostabilization during phytoremediation.

Hammond et al. [152] studied that plants immobilized As in the rhizosphere through binding to ferric sulfate, forming a trivalent complex of As-tris-thiolate [152]. Campos et al. [153] found that in *Pistia stratiotes*, the concentration and coordination of glutathione and related enzymes were important for As(III) tolerance. Additionally, research indicated that the addition of chelating agents like citric acid (CA) enhanced As absorption by plants. The findings suggested that these thiolic compounds were crucial for As detoxification, as the presence of CA reduced the amount of thiols required to manage As toxicity [146].

Recent studies indicate that biochar-treated soils can decrease Pb availability while enhancing As mobility. Certain biochars, such as P1J1, effectively stabilize Pb without mobilizing As, resulting in lower concentrations of both As and Pb in plants compared to soils

Table 3
Phytodesalination of metals during phytoremediation.

Plant	Metal	Remark	Reference
Alternanthera philoxeroides, Ipomoea aquatica, & Ludwigia adscendens	Na^+	*A. philoxeroides* had the highest Na + accumulation at 145.63 g/kg in its roots, while *I. aquatica* demonstrated superior desalination capacity (130 kg/ha) due to its higher productivity compared to both *A. philoxeroides* (105 kg/ha) and *L. adscendens* (80 kg/ha).	Islam et al. [159]
Atriplex nummularia Lindl	Na^+	Chemical (gypsum and anionic polymer) and organic conditioner (bovine and sheep manure) treatments decreased both the Na + adsorption ratio and the exchangeable Na + percentage. *Atriplex nummularia* resulted in 60, 41, and 37 % in exchangeable Na^+ and reductions of 10, 38, and 40 % in soluble Na^+ across the 0–10, 10–30, and 30–60 cm layers.	Miranda et al. [160]
Carex pseudocyperus, C. riparia, & Phalaris arundinacea	Cl^-	Wetland plants grown hydroponically removed up to 7 kg-Cl^-/m^2 from water, indicating the potential of species like *C. riparia* and *P. arundinacea*, with their high tolerance, substantial biomass, and significant accumulation abilities.	Schück & Greger [161]
Cyperus alternifolius, Amaranthus retroflexus, Closia cristata, & Bambusa vulgaris	Na^+	*Bambusa vulgaris* exhibited approximately 32.62 % efficiency in desalination in water containing NaCl concentrations ranging from 1000 to 2000 mg/L, while *C. alternifolius*, known for its rapid growth in polluted water, demonstrated pollutant absorption.	Siahouei et al. [162]
Fimbristylis ferruginea, & Fimbristylis tenuicula	Na^+	Bioconcentration factor and translocation factor values suggested *F. ferruginea* for phytostabilization and *F. tenuicula* for phytoextraction, with *F. ferruginea* storing up to 50 % of Na+ in its biomass.	Manasathien & Khanema [163]
Lonicera japonica Thunb	Na^+	The increase in root respiration triggered by salt enhances the plant's salt resistance by promoting Na^+ extrusion, facilitating Na^+ leaching, and assisting in the desalinization of saline soil by replacing Na^+ at the exchange site with Ca^{+2}.	Yan et al. [164]
Puccinellia nuttaliana, & Typha latifolia	Na^+, & Cl^-	Alkaligrass and cattail accumulated 6.85 and 7.00 g Na^+/kg biomass, respectively, and exhibited Cl^- accumulation rates of 120.14 % and 94.47 % from irrigated landfill leachate.	Xu et al. [165]
Sesuvium portulacastrum L.	Na^+	The roots of *S. portulacastrum* and their accumulation in above-ground biomass reached 872 mg/plant and 4.36 g/pot, which subsequently alleviated the negative growth effects on the test culture of *H. vulgare* due to decreased salinity and sodicity of the desalinized soil.	Rabhi et al. [166]
Sesuvium verrucosum	Na^+, K^+, Ca^{+2}, & Mg^{+2}	*S. verrucosum* exhibited rhizosphere desalination, notably enhanced when combined with $CaSO_4{\cdot}2H_2O$, leading to increased biomass and significant Na^+ accumulation in its aerial parts.	Lastiri-Hernández et al. [158]

without biochar, despite an increase in soil Pb release over time [148]. The combination of *Brassica juncea* and *Cynara cardunculus* improved the health of mine soils by reducing extractable Cu and Zn levels, while also boosting soil pH, microbial biomass, activity, and diversity [145]. Compost showed varied effects on metal concentrations in different plant species, with municipal solid waste compost showing potential for the phytostabilization of metal-contaminated soils [144]. Additionally, lowering pH of slag below 8.6 reduced Cr toxicity and improved Mn, Zn, and P uptake, while composted sewage sludge was proposed to aid phytostabilization of slag dumps [70].

Arbuscular mycorrhizal fungi (AMF) plays an integral role in phytostabilization by forming polyphosphate complexes that sequester heavy metals in plant roots and fungi, enhancing plant stress adaptation [141]. Inoculating AMF with *Robinia pseudoacacia* accelerated the removal rate of heavy metals by increasing plant biomass and Pb accumulation, while also improving soil characteristics [154]. AMF enhanced plant resilience against Cu toxicity by boosting photosynthesis, increasing antioxidant enzyme activity, and promoting overall growth [155,156]. They have demonstrated the ability to degrade high-molecular-weight PAHs like benzo(α) pyrene, improving the removal efficiency of phenanthrene and pyrene, and elevating the levels of enzymes essential for PAH

Table 4
Rhizofiltration during phytoremediation.

Plant	Metal	Remark	Reference
Azolla, Pistia, & Eichhornia	As, Cu, Pb, Ni, & F^-	The presence of organic acids, such as citric and malic acids, in root exudates facilitated the scavenging, absorption/adsorption by roots, and sedimentation of pollutants.	Banerjee & Roychoudhury [168]
Coleus Scutellarioides, & Portulaca Oleracea	TSS, TDS, BOD, COD, phosphorus, phosphate, & total nitrogen	*C. scutellarioides* and *P. oleracea*, grown hydroponically with aeration, showed reductions in TSS (79.43 %), TDS (64.36 %), BOD (82.36 %), and COD (81.86 %) from dairy wastewater. Additionally, *P. oleracea* accumulated nutrient contents such as total phosphorus (75.55 %), phosphate (74.24 %), and nitrogen (74.67 %), with nutrient accumulation attributed to the growth of both plants.	Das & Paul [169]
Lactuca sativa, Brassica campestris L., *Raphanus sativus* L., & *Oenanthe javanica*	U	Higher concentrations of U in groundwater led to increased accumulation in plant roots, resulting in a higher bioconcentration factor, as uranium adsorbed onto root surfaces as a solid phase.	Han et al. [170]
Eichhornia crassipes, Pistia stratiotes, & Spirodela polyrhiza	Fe, Cr, Cu, Cd, Zn, Ni, & As	During the 15-day experiment in microcosms, there was a high removal (>79 %) of different metals. *E. crassipes* exhibited the highest effectiveness in removing heavy metals, followed by *P. stratiotes* and *S. polyrhiza.*	Rai [171]
Juncus acutus	Cr	*J. acutus* filtrated Cr(VI) from contaminated water with up to 140 μg/L concentrations. Compared to *Ochrobactrum* sp. strain R24, *Pseudomonas* sp. strain R16 completely reduced 100 mg/L Cr(VI) after 150 h of incubation.	Dimitroula et al. [172]
Phaseolus vulgaris L. var. *vulgaris*	U, & Cs	In 72 h, bean roots accumulated U, & Cs to concentrations 317–1019 times higher than the initial 100–700 μg/L in contaminated solutions.	Yang et al. [173]
Phragmites australis	NH_3	Ammonium removal in the rhizofiltration system occurred via nitrification, and an average temperature increase of 5.2 °C in warmer months increased ammonium removal efficiency by 7.5 % on the planted side and by 2.4 % on the control side, with 60.4 % nitrate removal on the planted side and 45.4 % denitrified on the control side, while nitrate removal efficiency dropped to 32.2 % on the planted side and to 26.1 % on the control side in colder months.	Sikhosana et al. [174]
Pistia stratiotes	Pb, Zn, Co, & bacteria	The rhizofiltration for the three heavy metals removed from the drainage water by *P. stratiotes* tissues was higher in summer for Pb and Co (219.4 and 17.2 g/m^2/year) and autumn for Zn (102.7 g/m^2/year), whereas the lowest rhizofiltration value for Pb was in the spring (161.6 g/m^2/year), in the winter and summer (66.6 and 67.4 g/m^2/year) for Zn, and in autumn (4.5 g/m^2/year) for Co. The highest counts of coliform, fecal coliform, fecal streptococci, and *Salmonella* spp were at 168.3×10^6, 161.3×10^6, 139×10^6 CFU/mL, and 8.8×10^5 CFU/100 mL) during the summer, and the lowest counts were at 1.0×10^5, 9.0×10^4, 1.2×10^5 CFU/mL, and 8.0×10^3 CFU/100 mL in winter.	El-Liethy et al. [175]
Scirpus grossus	Ibuprofen, & paracetamol	Plant accumulated ibuprofen and paracetamol in its roots and shoots, enhancing their removal by 39–45 and 5–33 % in wetland systems after 21 days of exposure to water initially containing 600 and 60 μg/L of these pharmaceuticals.	Falahi et al. [176]
Typha angustifolia, Acorus calamus, & Pandanus amaryllifolius	Cd, & Zn	*T. angustifolia* had a 100 % survival rate, no toxicity symptoms, high dry biomass (11.5–20.8 g), and substantial Cd and Zn uptake (4941.1–14,109.4 mg/plant and 14,039.3–59,360.8 mg/plant), while *P. amaryllifolius* showed phytotoxicity at 40 mg/L Zn, indicating *T. angustifolia* is an excluder species for Cd and Zn with BCF >100 and TF < 1 for all treatments.	Woraharn et al. [177]

biodegradation [102].

The mechanisms by which hydrophobic organic contaminants bind to plant structures show intriguing variations. Hussain et al. [157] emphasized the role of hemicellulose and the lipid bilayer of the plasma membrane in facilitating the binding of these contaminants to the cell wall. Additionally, glutathione, produced by enzymes like glutathione synthetase, acts as a conjugating agent, detoxifying organic contaminants by forming complexes. Gujarathi et al. [142] further elucidated that compounds secreted by the roots of *Helianthus* spp. roots aid in the breakdown and removal of tetracycline and oxytetracycline, respectively.

13.3. Phytodesalination

Phytodesalination uses halophytes to mitigate soil and water salinity through mechanisms such as salt exclusion, excretion, and compartmentalization. These plants, which thrive in saline soils or utilize saline water, accumulate salts in their tissues, thereby enhancing soil productivity. However, saline conditions can adversely affect sensitive plants and soil organisms [158]. Halophytes provide an environmentally friendly solution by improving soil quality and porosity through salt leaching facilitated by their extensive root systems. The process of phytodesalination during phytoremediation is illustrated in Table 3.

Halophytic legumes and rhizospheric bacteria enhance Na $^+$ ion leaching by catalyzing the dissolution of $CaCO_3$, which releases Ca^{+2} ions that replace Na $^+$ ions, increasing leaching rates [166]. Miranda et al. [160] assessed *Atriplex nummularia* under various treatments and observed no changes in pH but significant reductions in electrical conductivity, Na^+ adsorption ratio, and exchangeable Na $^+$ percentage. This suggests that *A. nummularia* and organic conditioners were viable options for managing soil degradation caused by salinization. Lastiri-Hernández et al. (2020) found that *Salsola verrucosum*, particularly when combined with $CaSO_4{\cdot}2H_2O$ and Polisul-C, improved the physicochemical properties of moderately saline, clay-textured soil. $CaSO_4{\cdot}2H_2O$ was more effective than Polisul-C for heavy-textured saline soil, highlighting *S. verrucosum*'s potential for land rehabilitation and food security in saline regions. Islam et al. [159] discovered that halophytes such as *Ipomoea aquatica, Alternanthera philoxeroides*, and *Ludwigia adscendens* exhibited high bio-concentration factors (56.10–80.29) and translocation factors greater than 1, making them effective Na^+ accumulators and improving water quality for irrigation. Schück & Greger [161] revealed that wetland plants could accumulate up to 10 mg-Cl^- $(gDW)^{-1}$ while tolerating moderate Cl^- levels, with variations among species. *Phalaris arundinacea* exhibited the highest removal capacity and shoot tissue concentration, while *Carex riparia* showed the greatest Cl^- tolerance and biomass production, suggesting criteria for selecting suitable candidates for phytodesalination. Zorrig et al. [167] conducted a phytodesalination study in arid and semi-arid regions of China using four halophytic plants, revealing decreases in Na^+ and Cl^- ion concentrations following the growth of these halophytic plants in salt-affected soils.

13.4. Rhizofiltration

Rhizofiltration uses plant roots to filter and remove toxic substances, as well as excess nutrients like nitrogen and phosphorus, from contaminated water. In this process, contaminants are absorbed and adsorbed by metal-tolerant aquatic plants through their roots and submerged structures. Table 4 shows the rhizofiltration of metals during phytoremediation.

Some endophytic bacteria residing on the root surface assist in the rhizofiltration process. Specific strains of *Pseudomonas* and *Ochrobacterium* within plant roots can reduce Cr(VI) to Cr(III), which then precipitates inside the roots, thereby purifying the water [172]. Zure et al. (2024) found that embryophytes and macrophytes exhibited higher in vitro antiviral activity (43–62 %) compared to grasses (21–26 %). Notably, *Ocimum basilicum* and *Pistia stratiotes* demonstrated the highest activity (57–62 % and 59–60 %, respectively), along with significant in vivo virus reduction (>60 %) in culture solutions attributed to rhizofiltration (66–74 %) and phytoinactivation/phytodegradation (63–84 %). These findings highlight the antiviral capabilities of these plants and propose a novel approach for controlling waterborne viruses.

In rhizofiltration experiments, *Raphanus sativus* L. accumulated the highest uranium (U), followed by *Brassica campestris* L., *Lactuca sativa*, and *Oenanthe javanica*. The root U levels were consistently two orders of magnitude higher than those in shoots. At pH 3, *R. sativus* and *B. campestris* demonstrated BCF values over four times higher than at pH 5, and more than 25 times higher than at pH 7 and 9 [170]. Sunflowers and beans effectively removed U from contaminated groundwater, achieving removal efficiencies exceeding 90 % [178]. Sunflower and mustard facilitated specific mechanisms for treating Pb-contaminated water, involving Pb-phosphate precipitation [179]. *Azolla*, *Pistia*, and *Eichhornia* exhibited the highest rhizofiltration capacities for As, Pb, and F^- [168]. In an aerated system, *Portulaca oleracea* significantly reduced biochemical oxygen demand (BOD) chemical oxygen demand (COD) total suspended solids (TSS), and total dissolved solids (TDS) by accumulating total phosphorus, phosphate, and total nitrogen, achieving reduction rates of 82.36 % for BOD, 81.86 % for COD, 79.43 % for TSS, and 64.36 % for TDS. The growth of *Coleus scutellarioides* and *Portulaca oleracea* facilitated the accumulation of total phosphorus (75.55 %), phosphate (74.24 %), and total nitrogen (74.67 %) [169]. *Pistia stratiotes* also demonstrated potential for heavy metal rhizofiltration, despite its susceptibility to metal toxicity. Seasonal variations influenced the physicochemical and bacterial parameters of drain water, with summer showing the highest bacterial counts [175]. *Thalia angustifolia* showed improved survival, biomass production, and metal uptake for Cd and Zn rhizofiltration compared to *Acorus calamus* and *Pandanus amaryllifolius* [177]. *Phragmites australis* exhibited increased ammonium removal during warmer months due to enhanced nitrification and denitrification; however, complete nitrogen removal was not achieved under colder conditions, highlighting the seasonal variability in nitrogen removal efficacy [174].

Woraharn et al. [177] evaluated the rhizofiltration capabilities of *Typha angustifolia, Acorus calamus,* and *Pandanus amaryllifolius* in hydroponic experiments focusing on Cd and Zn. *T. angustifolia* exhibited 100 % survival, the highest biomass (11.5–20.8 g), and significant uptake of Cd and Zn (4941.1–14,109.4, and 14,039.3–59,360.8 mg/plant). In contrast, *P. amaryllifolius* showed phytotoxicity at a concentration of 40 mg-Zn/L, while *T. angustifolia*, acting as an excluder species, primarily accumulated Cd and Zn in its roots, achieving a BCF exceeding 100 and a translocation factor below 1. Sikhosana et al. [174] observed that a temperature increase of 5.2 °C during warmer months enhanced the NH_3 removal efficiency of *Phragmites australis* by 7.5 % on the planted side, compared to 2.4 % on the control side. This increase was attributed to higher rates of nitrification and denitrification, resulting in a 60.4 % removal of NO_3^- removal on the planted side versus 45.4 % on the control side. However, during colder months, the NO_3^- removal efficiency had decreased to 32.2 % for the planted side and 26.1 % for the control, underscoring the influence of temperature on nitrogen removal, although complete nitrogen removal was not achieved.

13.5. Phytovolatilization

Phytovolatilization is a process in which plant roots absorb contaminants, convert them into gaseous forms, and release them into the atmosphere through evapotranspiration. This method is particularly effective for contaminants that become less harmful when transitioning from soil to air; however, it is essential to ensure that the volatilized contaminants pose minimal risk to the atmosphere. Table 5 presents the phytovolatilization of metals during phytoremediation.

This method is effective for addressing organic contaminants and volatile metals such as mercury and selenium. However, releasing transformed substances into the atmosphere poses risks, as mercury and selenium can form toxic compounds like methylmercury and dimethylselenide ([187]; [188]). Guarino et al. [139] studied the combined use of *Arundo donax* L. with a consortium of PGPB for the remediation of As pollution. They found that As and/or PGPB slightly boosted plant biomass, with *A. donax* accumulating low levels of As, which were primarily volatilized through transpiration. Sitarska et al. [182] investigated *Lemna minor* and *Salvinia natans* for the phytoremediation of Hg using contaminated Hoagland's solution (0.15–0.30 mg-Hg/dm^3). They observed increased growth rates in Hg-exposed monocultures (0.12 g/gday), peak BCF values ranging from 216 to 856 by day 7, and achieved a 96 % Hg removal efficiency. Total protein content increased by 34 % in *L. minor*, 84 % in *S. natans,* and up to 99 % in mixed cultures. Total chlorophyll content rose by 14 % in *L. minor* and up to 60 % in mixed cultures, but decreased by 53 % in *S. natans*. In contrast, Zhang et al. [183] found that 2,4-DBA exhibited stronger volatilization and higher bioaccumulation in rice tissues compared to 2,4-DBP. Phytovolatilization significantly contributed to their emissions, with 2,4-DBA and 2,4-DBP accounting for 6.78 and 41.7 %, respectively, of atmospheric emissions. However, VOCs can react with NO_x to form ozone, posing risks to human health and the environment.

13.6. Phytodegradation

Phytodegradation employs enzymes to convert organic contaminants into less harmful substances, thereby reducing pollutants through processes such as transformation, decomposition, stabilization, and volatilization in soil and groundwater. Key enzymes involved in this process include nitroreductases, glycosyltransferases and glutathione transferases, oxidases, phosphatases, nitrilases,

Table 5
Phytovolatilization during phytoremediation.

Plant	Pollutant	Remark	Reference
Arundo donax L.	As	*A. donax* took up and volatilized As(III), achieving over 50 % removal efficiency, with DNA methylation implicated in *Arundo*'s response to As stress.	Guarino et al. [139]
Crotalaria juncea, Zinnia violacea Cav., & *Tagetes erecta* L.	Styrene	At 28 days, all three plants showed full styrene removal with 1 g/kg of nZVI-AC (T-nZVI-AC or B-nZVI-AC), but without it, *C. juncea, Z, violacea, & T. erecta* L. had removal efficiencies of 30 %, 67 %, and 56 %, respectively.	Kambhu et al. [180]
Juncus effuses	NH_3	Methane emissions occurred alongside the absorption of 44.5 % of the total ammonium–nitrogen load by growing plants, affecting both ammonium removal and methanogenesis in constructed wetlands.	Wiessner et al. [181]
Lemna minor, & Salvinia natans	Hg	The efficiency of mercury removal reached 96 %, with total protein increasing by 34 % for *L. minor*, 84 % for *S. natans*, and up to 99 % in mixed culture, alongside a total chlorophyll increase of 14 % for *L. minor* and up to 60 % for the mixed culture, while decreasing by 53 % for *S. natans*.	Sitarska et al. [182]
Oryza sativa Japonia. cv. Nipponbare	2,4-dibromophenol, & 2,4-dibromoanisole	2,4-DBA showed higher bioaccumulation than 2,4-DBP in rice leaf sheath and leaf, while rice plants enhanced the volatilization of both compounds, with demethylation of 2,4-DBA exceeding methylation of 2,4-DBP, and efficient volatilization of metabolites helping to decrease the bioaccumulation of both.	Zhang et al. [183]
Phragmites australis	Organochlorines	1,4-dichlorobenzene (DCB), 1,2,4-trichlorobenzene (TCB), and γ-hexachlorocyclohexane (γHCH) translocated from roots to shoots and volatilized from foliar surfaces.	Miguel et al. [184]
Polypogonmon speliensis	As	Dimethylchloroarsine ($AsCl(CH_3)_2$) and pentamethylarsine ($As(CH_3)_5$) were volatilized, but more toxic organic forms of arsenic such as AsH_3, AsH_2CH_3, $AsH(CH_3)_2$, and $As(CH_3)_3$ were not released during volatilization from the plant-soil system.	Ruppert et al. [185]
Salix nigra, and *Populus deltoides × nigra,* DN34	*N*-nitrosodimethylamine	In radiolabeled NDMA experiments, 46.4 % of the total 14C-activity was recovered in plant tissues, with 47.5 % phytovolatilized, and the distribution in plants was around 18.8 % in leaves, 15.9 % in stems, 7.6 % in branches, and 3.5 % in roots.	Yifru & Nzengung [186]

and dehalogenases, which are secreted by plants and microorganisms [189]. The effectiveness of phytodegradation is influenced by factors such as soil pH, temperature, and moisture content. The degradation of some pollutants during phytoremediation is detailed in Table 6.

Lupinus luteus, in association with endophytic bacteria, effectively remediated PAH-contaminated landfill soils, such as benzo(a) pyrene, without exhibiting toxicity. This process benefited from bacteria that enhance plant growth and metabolize contaminants, including diesel and PCBs [199]. *Cyperus papyrus* demonstrated the ability to metabolize neonicotinoids, with concentrations decreasing over time, likely due to enzymatic activity. This process involved absorption by the roots, upward translocation, and accumulation in the shoots, resulting in minimal concentrations by day 28. The metabolism of neonicotinoids included processes such as nitro reduction, hydroxylation, and demethylation. Toxicity assessments of neonicotinoids were conducted through peroxidase and catalase activity measurements, while transcriptomic analysis revealed differentially expressed genes, including P450s, peroxidase, and glutathione S-transferase [194]. On the contrary, *Azolla filiculoides* removed organic compounds from water with over 95 % efficiency, influenced by factors such as reaction time, contaminant concentration, water weight, pH, and temperature [191]. Similarly, *Alternanthera philoxeroides* degraded Remazol Red dye within 72 h at a concentration of 70 mg/L using enzymes found in its roots, stems, and leaves. This degradation process resulted in slight reductions in chlorophyll and carotenoids levels, suggesting a phytotransformation pathway [190]. Additionally, hairy roots of *Sesuvium portulacastrum*, induced by *Agrobacterium rhizogenes*, achieved 98 % degradation of Reactive Green 19A HE4BD dye within 5 days. Leaf explants showed a higher induction frequency and root production compared to stems, as confirmed by T-DNA amplification [197].

Transgenic *Arabidopsis thaliana* has been shown to effectively degrade the herbicide isoproturon through the expression of human Cytochrome P450-1A2 and plant-mediated microbial degradation [200]. In contrast, weeds like *Alopecurus* sp., *Sinapis* sp., *Brassica* sp., and *Chenopodium* sp. exhibited sensitivity to isoproturon. Sunflowers, on the other hand, demonstrated high tolerance, likely due to factors such as low root uptake, root conjugation (possibly with glutathione), minimal xylem transfer from root to shoot, and the crystallization of aclonifen on the root surface at elevated concentrations [201].

Table 6
Phytodegradation of pollutants during phytoremediation.

Plant	Pollutant	Remark	Reference
Alternanthera philoxeroides Griseb	Sulfonated Remazol Red dye, & textile effluents	*A. philoxeroides* Griseb., a macrophyte, completely degraded the highly sulfonated textile dye Remazol Red within 72 h at a concentration of 70 mg/L.	[190]
Azolla Filiculoides	BisphenolA	*Azolla* demonstrated a high BPA removal capacity from water, achieving rates of 60–90 %, with efficiency exceeding 90 % at a BPA concentration of 5 ppm and biomass of 0.9 g, and generally improving with lower BPA concentrations and higher biomass.	Zazouli et al. [191]
Brassica campestris, Festuca arundinacea, & Helianthus annuus	Total petroleum hydrocarbons	The addition of humic acid increased the removal of TPH from the soil in pots planted with *B. campestris, F. arundinacea,* and *H. annuus*, enhancing percentage degradation to 86 %, 64 %, and 85 % from 45 %, 54 %, and 66 %, respectively, with its effect also observed in the degradation of n-alkanes within 30 days.	Park et al. [192]
Chlorella pyrenoidosa	Pentachlorophenol	PCP degraded over time under controlled lab conditions, including photolysis, biodegradation, and direct phytodegradation, with or without the presence of algae. The degradation of PCP primarily depended on photolysis, following pseudo-first-order kinetics with rate constants ranging from 6.4 to 7.7 h^{-1}.	Headley et al. [193]
Pontederia crassipes	Sodium dodecyl sulfate	Water hyacinth removed SDS from water, controlled by *Chromolaena odorata* L. extract, with SDS efficiently absorbed by both root and aerial parts.	Gong et al. [32]
Cyperus papyrus	Neonicotinoids	*C. papyrus* decreased neonicotinoid concentrations, which gradually reached low levels over 28 days. Major metabolic processes, such as nitro reduction, hydroxylation, and demethylation, responded to neonicotinoids within wetland ecosystems.	Liu et al. [194]
Limnobium laevigatum	Sulfamethoxazole & & Trimethoprim	The SMX and TRI content in water decreased by 96.0 % and 75.4 %, respectively, after 14 days, with SMX primarily undergoing photolysis and hydrolysis processes for removal, while TRI was predominantly absorbed by the plant.	Stando et al. [195]
Phragmites australis	Ibuprofen	After 21 days, *P. australis* completely degraded IBP from the liquid medium, showing a half-life of 2.1 days, and contained four intermediates in its plant tissues including hydroxy-IBP, 1,2-dihydroxy-IBP, carboxy-IBP, and glucopyranosyloxy-hydroxy-IBP.	He et al. [196]
Sesuvium portulacastrum L.	Reactive green 19A-HE4BD	Hairy roots, induced from the *A. rhizogenes* NCIM 5140 in *S. portulacastrum*, degraded Reactive green 19A HE4BD by up to 98 % within 5 days of incubation, and the extracted metabolites showed a non-toxic nature.	Lokhande et al. [197]
Spirodela polyrhiza	Ofloxacin	High concentrations of OFX led to a 93.73–98.36 % reduction, resulting in decreases in biomass (4.8–41.3 %), relative root growth, protein (4.16–11.28 %), and photopigment contents.	Singh et al. [33]
Urticaceae urtica dioica	Polychlorinated biphenys	PCBs from contaminated soil were transferred to the aboveground parts of the plant, with degradation reaching up to 33 % within four months.	Viktorova et al. [198]

13.7. Rhizodegradation

Rhizodegradation refers to the biodegradation of organic contaminants within plant root systems, particularly in the rhizosphere soil region. Plants release compounds such as sugars and organic acids through their roots, which provide nutrients for bacteria [202]. These bacteria then metabolize pollutants into less harmful substances, including carbon dioxide and water. Various combinations of plants and bacteria can effectively degrade contaminants like hydrocarbons, pesticides, and dyes. The mechanism involves complex interactions between plants and soil microbes, with both aerobic and anaerobic pathways contributing to the breakdown of contaminants [203]. Table 7 illustrates the rhizodegradation of organic contaminants.

A combination of lindane-tolerant *Withania somnifera* and *Staphylococcus cohnii* subspecies *urealyticus* successfully reduced pesticide levels in soils [209]. Ren et al. [205] demonstrated that resuscitation-promoting factors enhanced alfalfa growth in PCB-contaminated soil by increasing antioxidant enzymes, detoxification metabolites, and PCB-degrading genes (bphA and bphC). *Zea mays* exposed to *Pseudomonas qingdaonensis* ZCR6 and crude oil achieved a 76.52 % reduction in hydrocarbon content over four weeks, with ZCR6's genome revealing genes for various beneficial functions, including nitrogen fixation and heavy metal resistance [208]. *Acinetobacter junii, Pseudomonas indoloxydans*, and *Rhodococcus* sp. in conjunction with *Phragmites australis*, achieved 95 % degradation of the azo dye Reactive Black 5 in a floating treatment wetland system, producing non-toxic metabolites [210]. *Rhodococcus fascians* strain L11 promoted the growth of *Lolium perenne* L. and facilitated petroleum hydrocarbon degradation, demonstrating capabilities such as phosphate solubilization (62 %), cellulolytic enzyme production (62 %), motility (55 %), siderophore production (45 %), ammonium production (41 %), and hydrogen cyanide synthesis (38 %). Additionally, five endophytes produced biosurfactants, and ten strains harbored the 1-aminocyclopropane-1-carboxylate deaminase (ACCD) gene (acdS), which helps modulate ethylene levels for enhanced plant growth. Notably, *Rhodococcus fascians* strain L11 uniquely possessed the hydrocarbon degradation genes alkB and pah, with four other endophytic bacteria, including *Microbacterium* sp. and *Rhodococcus* sp. (L7, S12, S23, S25), also testing positive for the alkB gene, indicating their potential for hydrocarbon degradation [203]. Similarly, *Pseudoarthrobacter phenanthrenivorans* (MS2) and *Azospirillum oryzae* (MS6), isolated from oil-contaminated soil, were noted for their plant growth-promoting characteristics and biosurfactant production, particularly beneficial for *Zea mays* and *Salix* sp. in phyto-rhizoremediation due to their production of salicylic acid and related compounds [202]. Studies on *Kandelia candel* marginally enhanced phenanthrene (47.7 %) and pyrene (37.6 %) degradation in contaminated sediment, with the highest degradation rates observed near the root zone, indicating that plant-promoted biodegradation played a major role in remediation [211].

Table 7
Rhizodegradation of organic contaminants.

Plant	Bacteria	Pollutant	Remark	Reference
Liriope muscari	*Bacillus aryabhattai* VITNNDJ5	Monocrotophos	Incorporating VITNNDJ5 into the root zone enhanced plant growth and expedited the degradation of up to 93 % of MCP within 5 days, yielding non-hazardous end products.	Dash & Osborne [204]
Medicago sativa L.	*Mycolicibacterium* sp. PAM1	Fluoranthene, anthracene, fluorene, & phenanthrene	PAM1, which produced indole acetic acid, promoted alfalfa growth and displayed degradation rates when exposed to various PAHs as the sole carbon sources, indicating a decreasing availability of pollutants in the sequence of phenanthrene > fluorene > fluoranthene ~ pyrene > anthracene.	Golubev et al. [18]
Medicago sativa L.	Pseudomonas, s Rhizobium pp., *Streptomyces, & Bacillus* spp.	PCBs	*Pseudomonas* and *Rhizobium* spp. boosted PCB degradation, while *Streptomyces* and *Bacillus* spp. enhanced alfalfa growth. Rpf presence in PCB-contaminated soil promoted alfalfa growth by promoting antioxidant enzymes and detoxification metabolites, increasing removal rates for five selected PCBs by 0.5–2.2 times after 40 days of treatment.	Ren et al. [205]
Nicotiana tabacum	*Pseudomonas putida* strain KT. DNT & *P. putida* KT2440	2,4-dinitrotoluene	Plant-associated 2,4-DNT-degrading bacteria showed great potential for rapidly degrading 2,4-DNT in contaminated soil when planted either alone or together with *P. putida* KT2440 or *P. putida* KT.DNT. In soils contaminated with 1 mM and 1.5 mM of 2,4-DNT, the maximum degradation rates of 98 % and ~93 % were determined at the end of 14 days by KT.DNT-inoculated tobacco plants.	Akkaya [206]
Phragmites australis	*Bacillus, Lysibacillus, & Pseudomonas*	Reactive Black 5, & Blue S2G dyes	Bacteria colonizing plant roots degraded dye, showing potential for enhanced azo-dye phytodepuration in constructed wetlands facilitated by *P. australis*.	Riva et al. [207]
Zea mays	*Pseudomonas qingdaonensis* ZCR6	Crude oil	ZCR6 produced indole acetic acid, siderophores, and ammonia, solubilized $Ca_3(PO_4)_2$, exhibited surface-active properties, and showed cellulase activity along with very high 1-aminocyclopropane-1-carboxylic acid deaminase activity. The strain degraded 76.52 % of the initial petroleum hydrocarbon content and was resistant to Cd, Zn, and Cu, with minimal inhibitory concentrations of 5, 15, and 10 mM, respectively.	Chlebek et al. [208]

14. Integrating phytoremediation and bioenergy production

The integration of phytoremediation with bioenergy production represents a promising strategy for achieving sustainable environmental remediation and renewable energy generation. As the demand for alternative energy sources continues to increase, plants have the capacity to simultaneously remediate contaminated soil and water while supplying biomass for bioenergy applications. This biomass can be converted into renewable energy, thereby rendering the process particularly advantageous. Biofuels serve as a sustainable alternative to fossil fuels and can significantly enhance the efficacy of phytoremediation initiatives [212]. Table 8 presents data on phytomass generated from phytoremediation for bioenergy production.

The selection of appropriate plant species, such as poplars, willows, and castor beans, is crucial for successful remediation of contaminated sites, as these species are capable of accumulating heavy metals and producing biomass for biofuels. In contrast, herbaceous plants like elephant grass, silvergrass, and switchgrass exhibit rapid growth and the ability to regenerate after harvest, rendering them effective for continuous phytoremediation and bioenergy production [222,223]. The enhancement of this process through plant-microbe interactions, particularly those involving mycorrhizal fungi and endophytic bacteria, has been shown to improve plant growth, contaminant uptake, and biomass yield. These interactions facilitate nutrient absorption, boosting stress resistance, and promote overall plant health, thereby optimizing the efficiency of both phytoremediation and bioenergy production [224]. The utilization of energy crops for metal extraction not only addresses contamination issues but also adds economic value by generating biofuels, biogas, or biochar, thus providing financial incentives for remediation efforts [225]. Further, it is essential to assess the quality of the produced biofuels and evaluate the suitability of energy crops for both biofuel production and the phytoremediation of metal-contaminated sites prior to their application on a field scale [226]. Pogrzeba et al. [227] investigated the potential of *Sida hermaphrodita*, an energy crop, phytoextraction of heavy metals from soil and its calorific value following gasification. Their findings indicated that while *S. hermaphrodita* effectively accumulated heavy metals, its efficiency was contingent upon the bioavailability of these metals. Additionally, the application of fertilizers was found to reduce metal accumulation, with contaminated plants exhibiting a slight decrease in calorific value compared to their non-contaminated counterparts.

Valorization refers to the process of converting biomass into energy fuels and other valuable materials through various methods, including combustion, gasification, and pyrolysis. Combustion is characterized by the thermal decomposition of fuel in the presence of oxygen, whereas gasification involves thermal decomposition to generate synthesis gas (syngas). The direct combustion of metal-rich biomass produces heat that can be converted into electrical power; however, metals such as Zn and Cd may volatilize at elevated temperatures, leading to their concentration in the volatile fractions [228]. Gasification, on the other hand, converts biomass into clean-burning syngas suitable for electricity generation and heating [10]. Pyrolysis, which involves the thermal decomposition of organic material in the absence of oxygen, transforms compounds such as cellulose and lignin into combustible gases and char. This

Table 8
Utilization of phytomass to produce bioenergy.

Plant	Pollutant	Energy	Remark	Reference
Pteris vittata	As	Bioethanol	The recombinant bacteria yeast co-culture demonstrated optimal bioethanol production from phytomass derived from As-hyperaccumulators.	Tusher et al. [213]
Nicotiana tabacum L.	Zn, Fe, & Mn	Bioethanol	Plants could accumulate trace elements while producing substantial biomass, demonstrating their potential for both remediation and bioenergy.	Asad et al. [214]
Sorghum bicolor	Cu, Zn, Cd, & Pb	Bioethanol	Cellulase hydrolyzed and fermented biomass to ethanol with *Saccharomyces cerevisiae*, raising metal concentration in solids due to solubilization, while some metals, particularly Zn, were found in the liquid phase.	Vintila et al. [215]
Brassica juncea L.	Cd	Bioethanol	Cd-accumulated rapeseed stalks greatly improved biomass saccharification and bioethanol production by enhancing cellulose accessibility and lignocellulose porosity, while completely releasing Cd.	Wu et al. [216]
Elsholtzia haichowensis, Sedum alfredii, Solanum nigrum, Phytolacca americana, & Pteris vittata	Cu, Pb, Zn, Cd, Mn, & As	Biogas	Anaerobic digestion showed potential for disposing of trace metal-contaminated plants and energy production.	Wang et al. [217]
Lepidium sativum L. & *Mentha spicata*	Hg	Biogas	Biogas production was demonstrated by elevated Hg contamination in anaerobic feedstocks.	Rollinson et al. [218]
Zea mays L., *Brassica napus* L., *Elsholtzia splendens Nakai* ex *F. Maekawa, & Oenothera biennis* L.	Cu	Biogas	Anaerobic digestion had great potential for disposing of contaminated plants and provided a solution for biogas production.	Cao et al. [219]
Miscanthus sinensis OPM-10	Pb, Fe, Cu, Cr, Ni, As & Cd.	Biorefinery	Valorization possibilities were explored for integrating highly metal-contaminated biomass into biorefining.	Hennequin et al. [220]
Silybum marianum, Piptatherum miliaceum, Nicotiana glauca, & Helianthus annuus	Pb & trace elements	Compost, biogas, & thermal energy	Plants proved suitable for biogas production through anaerobic digestion.	Bernal et al. [221]
Sorghum bicolor	Cd	Bioethanol, and organic fertilizer	Plants showed potential to merge soil phytoremediation with bioethanol, safe grains, and forage production.	Liu et al. [101]

process yields bio-oils, biochar, and syngas with reduced emissions compared to conventional incineration, thereby stabilizing metals within the biochar fraction and ensuring that the oil, tar, and gas fractions remain free of heavy metals [229].

15. Challenges of phytoremediation

Phytoremediation presents a promising sustainable and cost-effective approach for environmental remediation; however, several challenges impede its widespread implementation and efficacy. A significant limitation is the protracted duration of the process. This method typically necessitates multiple growing seasons to attain substantial reductions in contaminants, providing it less appropriate for urgent remediation needs in comparison to more rapid methods such as excavation or chemical treatments.

A notable challenge in phytoremediation is the limited rooting depth of most plant species. Typically, plant roots extend only 1–3 m into the soil, rendering contaminants located at greater depths inaccessible. This limitation constrains the effectiveness of phytoremediation in addressing pollutants situated deeper within the soil profile. Furthermore, it is confronted with the issue of contaminant specificity, as different plant species demonstrate varying efficiencies in the removal of specific pollutants. Certain plants might be competent at extracting heavy metals, while others may show limited efficacy at addressing organic contaminants of emerging pollutants, such as pharmaceuticals. Consequently, no single plant species possesses the capability to effectively remediate complex sites characterized by multiple contaminants.

The survival of plants in environments with high levels of pollution presents a significant concern. Elevated concentrations of pollutants, including heavy metals and toxic organic compounds, can adversely affect plant growth and, in severe instances, hinder plant survival altogether. Deteriorated soil conditions can further intensify these challenges, resulting in diminished efficiency of phytoremediation processes. Moreover, once plants have absorbed or accumulated contaminants, the appropriate disposal of this contaminated biomass becomes crucial. The development of safe and cost-effective disposal methods for pollutant-laden plant material is essential to prevent the reintroduction of toxins into the environment; however, such disposal solutions are frequently inadequate.

The effectiveness of phytoremediation is also influenced by climatic and geographical factors. In colder climates, the growth of plants can be substantially hindered, while in arid regions, the scarcity of water may completely impede the remediation process. These environmental conditions restrict the selection of suitable plant species and diminish the overall efficacy of phytoremediation in specific areas. Furthermore, large-scale phytoremediation initiatives may compete for valuable agricultural land, particularly in densely populated regions or areas where there is a high demand for farmland. This competition can lead to conflicts regarding land-use priorities, thereby complicating the broader implementation of phytoremediation strategies.

Phytodegradation is a process through which plants decompose organic pollutants, but its inherent unpredictability represents another significant technical challenge. This process can exhibit variability in both speed and effectiveness, and in certain cases, the byproducts of degradation may possess toxic properties, thereby requiring further treatment interventions. Additionally, issues related to regulatory compliance and public acceptance pose considerable obstacles, particularly in instances involving genetically modified organisms. Concerns regarding safety, coupled with the prolonged time frames necessary for effective phytoremediation, can adversely affect both regulatory approval processes and public endorsement of such initiatives.

16. Future prospects

The future of phytoremediation presents great promise as researchers, scientists, and innovators work to increase its efficiency, expand its applications, and address emerging environmental issues. Various trends and breakthroughs are guiding its trajectory towards a more comprehensive and impactful role in sustainable environmental stewardship. One notable trend is the exploration of genetic engineering, which offers potential for the refinement of phytoremediation by genetically modifying plant traits to improve their ability to accumulate, withstand, and detoxify contaminants tailored to specific remediation goals.

A significant trend is the integration of phytoremediation with other remediation techniques, such as microbial remediation and chemical treatments. By leveraging the complementary strengths of multiple approaches, these integrated strategies are well-positioned to effectively address complex contaminant mixtures and challenging environmental conditions. Furthermore, nano-phytoremediation is gaining prominence, utilizing nanotechnology to enhance the efficacy of phytoremediation. Nanoparticles, in particular, have the potential to improve the uptake and sequestration of contaminants by plants, thereby facilitating more precise and efficient remediation strategies.

Given the significant impacts of climate change on ecosystems, the identification and cultivation of climate-resilient plant species for phytoremediation are essential endeavors. These resilient plants possess the ability to thrive in the face of changing environmental conditions, thereby broadening the applicability of phytoremediation across various regions and contributing to adaptive strategies. Furthermore, in urban environments, phytoremediation is emerging as a sustainable approach to mitigate urban pollution, transforming contaminated brownfields into green spaces, supporting urban renewal initiatives, and enhancing the overall quality of urban life. As the effectiveness of phytoremediation becomes increasingly evident, the need for robust policy and regulatory frameworks is also highlighted, necessitating support from governmental and environmental agencies through incentives or regulations to promote its widespread adoption. Additionally, community engagement and awareness are critical to the successful implementation of phytoremediation projects, requiring the involvement of local communities and the dissemination of information regarding its benefits to foster acceptance and support, particularly in contexts where public perception may influence project outcomes.

17. Conclusion

Phytoremediation is recognized as a promising and environmentally sustainable strategy for mitigating the effects of environmental toxicants. This approach leverages the inherent capabilities of plants, particularly hyperaccumulators, while optimizing environmental conditions to effectively address pollution across various sites, thereby facilitating ecosystem restoration. The use of plants as self-renewing agents diminishes the dependence on costly infrastructure and energy-intensive remediation processes. Furthermore, the versatility of phytoremediation in tackling a range of contaminants, including heavy metals, organic pollutants, and emerging contaminants, underscores its adaptability to diverse environmental challenges. This method is consistent with principles of ecological balance and conservation, as it minimizes the need for additional chemical interventions and reduces the risk of unintended consequences. Additionally, phytoremediation contributes to ecological benefits by enhancing biodiversity and promoting the resilience of ecosystems.

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The data used in this study is confidential.

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The author has declared no conflicts of interest.

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