International Journal of Plant & Soil Science

Volume 38, Issue 7, Page 335-353, 2026; Article no.IJPSS.160782
ISSN: 2320-7035

Phytoremediation of Heavy Metal-Contaminated Environments: A Comprehensive Review of Mechanisms, Plants, and Microbial Application

B. Kavitha [a], P. Maheshwari [b*] and D. R. Sudha [c]

[a] *Department of Environmental Science, SBACRF, Karaikudi, Tamil Nadu - 630 306, India.*
[b] *Department of Agricultural Microbiology, SBACRF, Karaikudi, Tamil Nadu - 630 306, India.*
[c] *Department of Agricultural Microbiology, DBCA, Arakkonam, Tamil Nadu– 631 151, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i76162

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/160782

Review Article

Received: 26/04/2026
Accepted: 24/06/2026
Published: 03/07/2026

Abstract

Heavy metal contamination in soil and water has increased in association with industrial development, urban expansion, mining activities, municipal waste disposal, and intensive agricultural practices. These contaminants are environmentally persistent because they are non-biodegradable and may accumulate in soil, aquatic systems, plants, and other organisms. Their movement through environmental compartments can affect soil fertility, plant growth, food quality, and ecological safety. Conventional remediation techniques, including chemical extraction, soil washing, and excavation, have been applied to contaminated sites; however, these methods may be costly, technically demanding, and disruptive to the environment. Phytoremediation provides an environmentally compatible and economically feasible alternative that uses plants and associated rhizosphere microorganisms to remove, immobilise, transform, or detoxify pollutants.

**Corresponding author: E-mail: maheshmicro77@gmail.com, maheshmicro2005@yahoo.com;*

Cite as: *Kavitha, B., Maheshwari, P., & Sudha, D. R. (2026). Phytoremediation of Heavy Metal-Contaminated Environments: A Comprehensive Review of Mechanisms, Plants, and Microbial Application. International Journal of Plant & Soil Science, 38(7), 335–353. https://doi.org/10.9734/ijpss/2026/v38i76162*

This review discusses the major mechanisms of phytoremediation, including phytoextraction, phytostabilisation, phytodegradation, phytovolatilisation, and rhizofiltration. It also summarises the roles of hyperaccumulator plants, aquatic and wetland plants, woody species, agricultural crops, and microorganisms in the management of heavy metal-contaminated environments. Plant selection, contaminant characteristics, soil properties, and plant-microbe interactions are important determinants of remediation performance. The review highlights phytoremediation as a sustainable strategy for environmental restoration while recognising the need to improve plant selection, microbial-assisted approaches, and field-level efficiency.

Keywords: Phytoremediation; heavy metals; contaminated soil; contaminated water; phytoextraction; phytostabilisation; rhizofiltration; hyperaccumulators; aquatic plants; rhizosphere microorganisms; bioremediation.

1. Introduction

The continuous rise in population, along with urban expansion and rapid industrial development, has resulted in the discharge of significant amounts of pollutants into the environment. As a result, soil and water ecosystems are increasingly contaminated with various organic, inorganic, and metallic substances, particularly in agricultural regions where industrial discharge and intensive farming practices are common. These pollutants originate from multiple sources such as industrial effluents, mining operations, municipal waste disposal, and the excessive application of fertilisers and pesticides in crop production systems (Alengebawy et al., 2021; Moghimi Dehkordi et al., 2024; Elumalai et al., 2025). Recent global and review-based assessments further indicate that heavy metal pollution remains closely linked with agricultural and human-health risks, which reinforces the need for sustainable remediation strategies (Hou et al., 2025; Rasool et al., 2023).

Among the different environmental contaminants, heavy metals are considered especially hazardous due to their persistence and non-biodegradable nature. Unlike organic pollutants, heavy metals cannot be decomposed by microbial or chemical processes and therefore remain in the environment for long periods. Over time, these metals accumulate in soil, water bodies, and biological organisms, eventually entering the food chain and posing serious risks to ecological systems and human health (Sethy & Ghosh, 2013; Ali et al., 2019). The continuous accumulation of heavy metals in agricultural soils can reduce soil fertility; negatively affect plant growth and productivity, and compromise food quality and safety (Muthusaravanan et al., 2018; Kumar et al., 2019).

Several conventional techniques such as chemical extraction, soil washing, and excavation have been used to remediate contaminated sites. However, these methods are often costly, technically demanding, and may cause further environmental disturbance. In recent times, phytoremediation has attracted increasing interest as a green and sustainable approach for addressing environments contaminated with heavy metals. This approach utilises plants and their associated rhizosphere microorganisms to remove, stabilise, or detoxify contaminants present in soil and water systems (Lone et al., 2008; Yan et al., 2020). Phytoremediation is considered a green technology because it is cost-effective, environmentally compatible, and suitable for large-scale remediation programs (Amanullah et al., 2016). Thus, phytoremediation is gaining attention as a sustainable and efficient method for addressing heavy metal contamination and supporting the rehabilitation of degraded ecosystems. Recent reviews and experimental studies also suggest that phytoremediation outcomes depend on plant selection, contaminant characteristics, and mechanistic understanding of metal uptake and tolerance (Islam et al., 2024; Saa-Aondo et al., 2024). Despite these advances, the manuscript indicates a need for an integrated synthesis of phytoremediation mechanisms, candidate plants, and microbial applications for heavy metal-contaminated environments.

1.1 Objective

The present review focuses on the fundamental principles, mechanisms, and practical applications of phytoremediation and highlights its significance in the remediation of toxic heavy metals from polluted environments.

2. Phytoremediation and its Mechanisms

Phytoremediation is an environmentally friendly and economically feasible technology that utilises plants to remove, stabilise, or detoxify pollutants present in soil, water, and even the atmosphere. This approach relies on the natural ability of plants and their associated rhizospheric microorganisms to absorb, accumulate, or transform contaminants into less harmful forms. The efficiency of phytoremediation is influenced by several factors, including the type and concentration of contaminants, their bioavailability, and soil characteristics such as pH, texture, and organic matter content, as well as microbial activity in the rhizosphere (Cunningham et al., 1995; Cunningham et al., 1997). The remediation of heavy metals from polluted environments through phytoremediation generally occurs through several distinct mechanisms as discussed below.

1. Phytoextraction
2. Phytostabilization
3. Phytodegradation
4. Phytovolatilization
5. Rhizofiltration

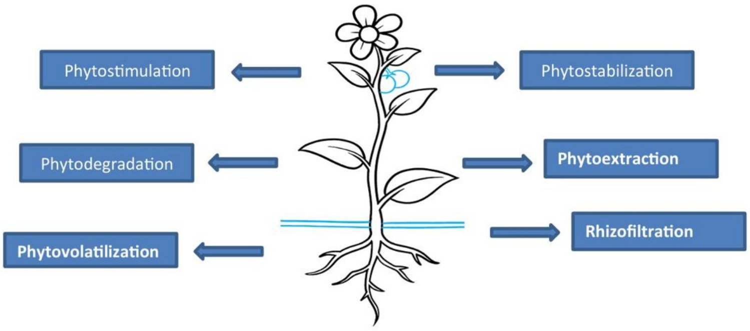

Fig. 1. Schematic representation of phytoremediation tactics

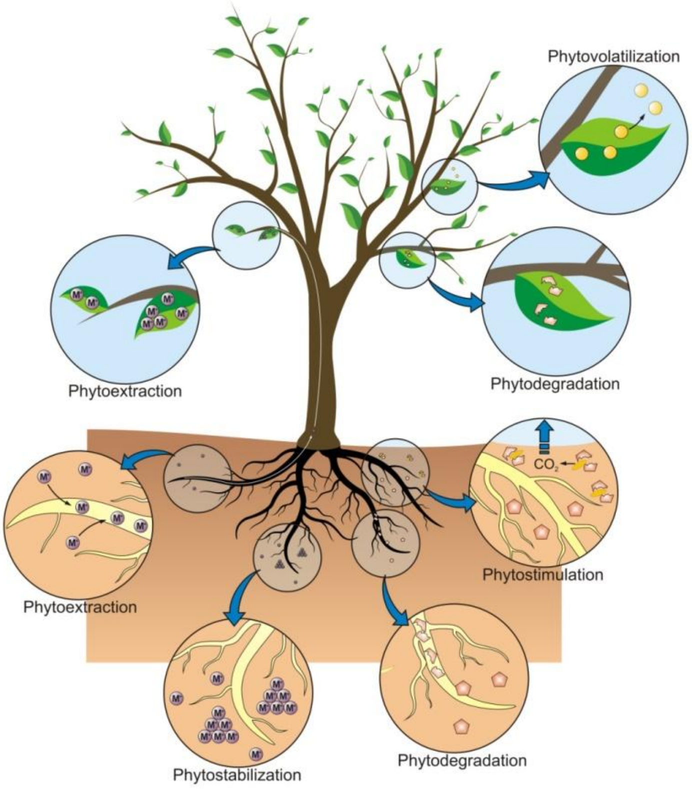

Fig. 2. Phytoremediation mechanisms used by plants to remove, stabilize, degrade, or volatilize contaminants

Source: (Favas ET AL., 2014)

2.1 Phytoextraction

Phytoextraction, also known as phytoaccumulation, is a phytoremediation process in which plants absorb heavy metals from contaminated soil through their root systems and translocate them to above-ground parts such as stems and leaves. These metals accumulate in the plant biomass, which can later be harvested and removed from the contaminated site, thereby gradually reducing the concentration of toxic elements in the soil. Certain plant species, including *Brassica juncea, Helianthus annuus, Pteris vittata, Thlaspi caerulescens, Alyssum murale* and *Sedum alfredii* are known as hyperaccumulators and possess the ability to accumulate exceptionally high levels of metals such as cadmium, nickel, zinc, and lead without showing toxicity symptoms. This technique is particularly useful for the remediation of moderately contaminated soils because it is environmentally friendly and relatively cost-effective (Chaney et al., 1997; Ali et al., 2013).

2.2 Phytostabilization

Phytostabilization is a phytoremediation strategy that reduces the mobility and bioavailability of contaminants in soil through the action of plant roots. In this process, plants immobilise heavy metals in the rhizosphere by mechanisms such as adsorption onto root surfaces, precipitation, or complex formation with soil components. Rather than removing metals from the site, phytostabilization prevents their movement into groundwater or their uptake by plants and other organisms. Several plant species, including *Vetiveria zizanioides, Festuca arundinacea, Agrostis capillaris, Populus deltoides, Salix viminalis*, and Atriplex halimus, have been widely used for phytostabilization because of their extensive root systems, high tolerance to heavy metals, and ability to reduce contaminant mobility in soil. This method is particularly suitable for highly contaminated soils where metal removal is difficult but stabilization can effectively limit environmental and health risks (Johnston et al., 2005; Kumpiene et al., 2008; Ali et al., 2013; Cunningham & Berti, 2000).

2.3 Phytodegradation

Phytodegradation, also referred to as phytotransformation, involves the breakdown of organic contaminants through metabolic processes within plants or through the activity of enzymes produced by plant-associated microorganisms in the rhizosphere. In this mechanism, pollutants are absorbed by plants and then converted into less toxic or less harmful compounds through biochemical reactions. Several plant species, including *Populus deltoides, Populus nigra, Salix viminalis, Medicago sativa, Brassica juncea,* and *Typha latifolia*, have demonstrated significant potential for phytodegradation because of their ability to absorb, transform, and stimulate microbial degradation of contaminants. This process is particularly effective for the remediation of organic pollutants such as pesticides, hydrocarbons, and industrial chemicals present in soil and water environments (Salt et al., 1998; Newman and Reynolds, 2004; Saier & Trevors, 2010).

2.4 Phytovolatilization

Phytovolatilization is a process in which plants take up pollutants from soil or water and convert them into volatile forms that are subsequently released into the atmosphere through transpiration. This mechanism is commonly associated with elements such as mercury, selenium, and arsenic. After uptake, plants chemically transform these substances into gaseous compounds, which are then emitted from the leaves. Several plant species, including *Brassica juncea, Populus deltoides, Populus nigra, Salix viminalis, Arabidopsis thaliana, have* demonstrated the ability to absorb and volatilize contaminants such as selenium, mercury, and arsenic. Consequently, phytovolatilization can contribute to the remediation of contaminated soils and water bodies by reducing pollutant concentrations in the environment (Zayed et al., 1998; Lee, 2013; Limmer & Burken, 2016).

2.5 Rhizofiltration

Rhizofiltration is a phytoremediation technique used mainly for the treatment of contaminated water. In this process, plant roots absorb, adsorb, or precipitate pollutants such as heavy metals from aqueous solutions. Several plant species, including *Helianthus annuus* (sunflower), *Eichhornia crassipes* (water hyacinth), *Lemna minor* (duckweed), *Pistia stratiotes* (water lettuce), *Typha latifolia* (broadleaf cattail), and *Vetiveria zizanioides* (vetiver grass), have been widely used in rhizofiltration. The contaminants accumulate on the root surface or within root tissues. Plants used for rhizofiltration are often grown hydroponically and then introduced into polluted water bodies to remove dissolved contaminants (Dushenkov et al., 1995; Banerjee & Roychoudhury, 2022; Biswal, 2025).

3. Plants Involved in Phytoremediation

Phytoremediation involves the use of specific plant species that are capable of tolerating, accumulating, stabilising, or transforming toxic heavy metals present in contaminated soil and water. These plants are typically characterized by rapid growth, high biomass production, extensive root systems, and an enhanced capacity for the uptake and translocation of heavy metals (Bhat et al., 2022; Sabreena et al., 2022).

Based on their remediation mechanisms, plants used in phytoremediation can be broadly classified into hyperaccumulators, aquatic plants, woody plants, and crop plants. Hyperaccumulator plants possess the remarkable ability to accumulate exceptionally high concentrations of heavy metals in their tissues without exhibiting phytotoxic effects. Aquatic plants including *Eichhornia crassipes, Pistia stratiotes, Lemna minor, Spirodela polyrhiza, Typha latifolia, Phragmites australis,* and *Vetiveria zizanioides* are particularly useful for the remediation of contaminated water bodies through processes such as absorption and rhizofiltration. In contrast, woody plants such as *Populus deltoides, Populus nigra, Salix viminalis, Salix alba, Betula pendula, Eucalyptus camaldulensis,* and *Robinia pseudoacacia, together with* crop species such as *Brassica juncea, Helianthus annuus, Zea mays, Oryza sativa, Triticum aestivum, Sorghum bicolor,* and *Ricinus communis* play a significant role in stabilising contaminants within the soil or extracting heavy metals through phytoextraction (Xu et al., 2024).

The effectiveness of phytoremediation largely depends on the careful selection of plant species, which should be based on the nature of the contaminants, environmental conditions of the site, and the intended remediation goals. Choosing plants that are well-adapted to specific pollutants and local conditions ensures better survival and contaminant removal. In addition, combining these plants with beneficial microorganisms and adopting proper agronomic practices can greatly improve the overall performance and success of the phytoremediation process (Salt et al., 1998; Pilon-Smits, 2005; Jan et al., 2016; Ashraf et al., 2019).

The ability of certain plants to accumulate and tolerate high levels of heavy metals has been widely documented, making them important tools in phytoremediation. More than 500 plant species, distributed across approximately 40–45 families, have been identified as hyperaccumulators. These plants can absorb and concentrate significant amounts of metals such as nickel (Ni), zinc (Zn), cadmium (Cd), lead (Pb), copper (Cu), cobalt (Co), and arsenic (As) in their tissues without showing visible signs of toxicity (Saha et al., 2021; Sharma et al., 2025; Li et al., 2026). Their unique physiological and biochemical adaptations enable them to survive in contaminated environments. These plants are widely utilized in remediation strategies like phytoextraction and phytostabilization, where they help remove, immobilise, or neutralise contaminants present in soil and water. Numerous plant taxa across different families have been documented for their capacity to either accumulate or withstand heavy metal stress, highlighting their significance in environmental clean-up efforts and various plants are listed in Table 1.

Table 1. Plants used for phytoremediation of heavy metals

S. No.	Common name	Plant species	Type of plant	Heavy metals removed	Reference
1.	Indian mustard	*Brassica juncea*	Hyperaccumulator	Pb, Cd, Cr	Cunningham and Ow, 1996)
2.	Chinese brake fern	*Pterisvittata*	Hyperaccumulator	As	Ma et al., 2001; Irshad et al., 2021
3.	Sunflower	*Helianthus annuus*	Crop plant	Pb, U	Dushenkov et al., 1995; Awa, &Hadibarata, 2020
4.	Water hyacinth	*Eichhorniacrassipes*	Aquatic plant	Cd, Pb	Wolverton & McDonald 1979;Rezania et al., 2015
5.	Vetiver grass	*Vetiveriazizanioides*	Grass plant	Pb, Zn, Cd	Danh et al., 2009; Suelee et al., 2017
6.	Poplar tree	*Populus spp.*	Woody plant	Cd, Zn, Ni	Pulford & Watson (2003);

S. No.	Common name	Plant species	Type of plant	Heavy metals removed	Reference
					Salehi & Shariat, 2024
7.	Indian pennywort	*Centellaasiatica*	Herbaceous plant	Cd, Pb	Zayed et al., 1998; Mazumdar &Das, 2021
8.	Alpine pennycress	*Thlaspicaerulescens*	Herbaceous plant / Hyperaccumulator	Zn, Cd	Baker et al., 1994; Satapathy et al., 2025
9.	Willow	*Salix* spp.	Trees or shrubs	Cd, Pb, Zn	Pulford & Watson (2003); Kaur et al., 2024
10.	Duckweed	*Lemna minor*	Aquatic plant	Cd, Pb, Hg	Zayed et al., 1998; Ahmed & Kareem, 2025
11.	Maize	*Zea mays*	Crop plant	Pb, Cd	Anjum et al., 2015;Chen et al., 2024
12.	Rice	*Oryzasativa*	Crop plant	As, Cd	Meharg & Zhao (2012);Wu, et al., 2024
13.	Cattail	*Typhalatifolia*	Aquatic plant	Pb, Cd, Zn	Raskin et al., 1997; Liu et al., 2025
14.	Reed	*Phragmitesaustralis*	Aquatic /Wetland plant	Pb, Cd, Zn	Pulford & Watson (2003);Al-Homaidan et al., 2020
15.	Barley	*Hordeum vulgare*	Crop plant	Cd, Pb	Chen et al., 2010; Wang et al., 2025
16.	Wheat	*Triticum aestivum*	Crop plant	Cd, Pb, Zn	McGrath & Zhao, 2003;Yousuf, 2026
17.	Tomato	*Solanum lycopersicum*	Crop plant	Cd, Pb	Peralta-Videa, 2002; Lopes, 2018; Romero-Estévez et al., 2020.
18.	Spinach	*Spinaciaoleracea*	Crop plant	Cd, Pb, Zn	Clemens, 2006; Khosa et al., 2023
19.	Mustard greens	*Brassica rapa*	Crop plant	Pb, Cd	Chaney et al., 2004; Rizwan et al., 2018
20	Rapeseed	*Brassica napus*	Crop plant	Pb, Zn, Cu	Salt et al., 1998
21.	Radish	*Raphanus sativus*	Crop plant	Cd, Zn, Ni	Kumar et al., 1995; Ahmad et al., 2018.
22.	Amaranthus	*Amaranthus* spp.	Crop plant	Cd, Pb, Zn	Vamerali et al., 2010; Sharma et al., 2024
23.	Pumpkin	*Cucurbita pepo*	Crop plant	Pb, Cd	White et al., 2003; Flores-Iga et al., 2023
24.	Flax	*Linumusitatissimum*	Crop plant	Cd, Pb	Saleem et al., 2020
25.	Kenaf	*Hibiscus cannabinus*	Fiber crop	Cd, Pb	Cleophas et al., 2023
26.	Jerusalem artichoke	*Helianthus tuberosus*	Energy crop	Cd, Zn, Pb	Chen et al., 2011; Mohamed et al., 2025
27.	Marigold	*Tageteserecta*	Ornamental plant	Pb, Cd	Liu et al., 2006; Meeinkuirt et al., 2024
28.	Alyssum	*Alyssum murale*	Hyperaccumulator	Ni	Reeves & Brooks, 1983; Reeves, 2024
29.	*Azolla*	*Azolla pinnata*	Aquatic fern	Cd, Pb	Rai et al., 1995; Zeid, et al., 2024

3.1 Hyperaccumulator Plants

Hyperaccumulator plants are specialized species capable of absorbing and storing exceptionally high concentrations of heavy metals in their aerial parts without exhibiting toxic effects. Metals such as zinc (Zn) and cadmium (Cd) can accumulate in these plants at levels far higher than those tolerated by most other species. This ability is supported by distinct physiological and biochemical mechanisms, including efficient uptake from the soil, enhanced translocation to shoots, and compartmentalization of metals within plant tissues to avoid toxicity (Asare et al., 2023; He et al., 2026).

These metal-tolerant plants including *Noccaea caerulescens* (Zn, Cd), *Alyssum murale* (Ni), *Pteris vittata* (As), *Brassica juncea* (Pb, Cd, Cr), *Sedum alfredii* (Zn, Cd, Pb), *Arabidopsis halleri* (Zn, Cd), and *Helianthus annuus* (Pb, U, Cd are of great importance in phytoremediation, particularly in techniques such as phytoextraction and phytostabilization. In phytoextraction, hyperaccumulators absorb contaminants from polluted soils and concentrate them in harvestable plant parts, thereby facilitating the removal of toxic metals. In phytostabilization, they help reduce the mobility and bioavailability of contaminants, contributing to environmental stabilization. A wide variety of plant families have been reported to contain species capable of accumulating or tolerating heavy metals, demonstrating their ecological significance (Nedjimi, 2021).

Furthermore, hyperaccumulator plants serve as valuable model systems for understanding the processes of metal uptake, transport, tolerance, and detoxification in plants. Research on these species has contributed significantly to improving phytoremediation technologies and developing sustainable strategies for managing contaminated environments (Rasheed et al., 2024) and are summarised in Table 2.

Table 2. Hyperaccumulator plants used for clean-up of heavy metals

S.No.	Common name	*Scientific name*	Heavy metals	Authors name
1.	Alpine pennycress	*Thlaspicaerulescens*	Zn, Cd	Brooks et al., 1977
2.	Nickel alyssum	*Alyssum murale*	Ni	Brooks et al., 1998; Dehghani et al., 2021; Konakci et al., 2023.
3.	Chinese brake fern	*Pterisvittata*	As	Ma et al., 2001; Zhao et al., 2023; Han et al., 2024
4.	Sedum stone crop	*Sedum alfredii*	Zn, Cd	Yang et al., 2004; Chen et al., 2025
5.	Indian mustard	*Brassica juncea*	Pb, Cd, Cr	Salt et al., 1997; Ali, et al., 2021; Mohapatra&Mohanty, 2024
6.	Alpine pennycress relative	*Arabidopsis halleri*	Zn, Cd	Bert et al., 2000; Geng et al., 2021

Table 3. Aquatic and wetland plants used for clean-up of heavy metals

S. No.	Common name	*Scientific name*	Heavy metals	Authors name
1.	Water hyacinth	*Eichhorniacrassipes*	Pb, Cd, Hg	Wolverton & McDonald, 1979; Churko et al., 2023; Monroy-Licht et al., 2024.
2.	Duckweed	*Lemna minor*	Cu, Zn, Pb	Zayed et al., 1998; Ajiboye et al., 2024
3.	Water lettuce	*Pistiastratiotes*	Cd, Pb	Rai et al., 1995; Rizvi et al., 2024
4.	Cattail	*Typhalatifolia*	Cr, Pb, Zn	Raskin et al., 1997; Rizvi et al., 2024

3.2 Aquatic and Wetland Plants used for Clean-up of Heavy Metals

Aquatic macrophytes including *Eichhornia crassipes, Pistia stratiotes, Lemna minor, Spirodela polyrhiza, Typha latifolia, Phragmites australis,* and *Vetiveria zizanioides* are extensively utilized in rhizofiltration, a phytoremediation technique designed to remove heavy metals from contaminated water bodies and wastewater. These plants possess dense and well-developed root systems that effectively absorb and accumulate toxic metal ions from the surrounding water, and in some cases, they can also aid in converting them into less harmful forms. Their rapid growth rate, high biomass production, and strong tolerance to polluted environments make them particularly suitable for water purification applications. Consequently, aquatic and wetland plant species are considered highly efficient in removing heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and zinc (Zn) from aquatic systems (Aryal, 2024; Satapathy et al., 2025) and are listed in Table 3.

3.2.1 Woody Plants

Woody plant species including *Populus deltoides, Populus nigra, Salix viminalis, Salix alba, Betula pendula, Eucalyptus camaldulensis,* and *Robinia pseudoacacia* have been widely recognised for their effectiveness in phytoremediation, particularly in phytostabilization and long-term restoration of contaminated soils. Their deep and extensive root systems enable them to access pollutants present in deeper soil layers while simultaneously stabilising contaminants within the soil. In addition, their large biomass and perennial growth habit allow continuous interaction with contaminated environments over extended periods, enhancing remediation efficiency (Pulford & Watson, 2003; Acharya et al., 2023).

Woody plants also contribute significantly to environmental protection by reducing soil erosion and limiting the spread of contaminants through leaching and runoff. Their root networks improve soil structure and prevent the dispersion of polluted particles to surrounding areas. Moreover, their high biomass production enables greater accumulation of heavy metals, and their non-edible nature reduces the risk of contaminants entering the food chain, making them suitable for large-scale remediation projects (Suman et al., 2018; Alliluev et al., 2026) and are presented in Table 4.

Table 4. Woody plants used for clean-up of heavy metals

S. No.	Common name	*Scientific name*	Heavy metals	Authors name
1.	Poplar	*Populus* spp.	Cd, Zn, Pb	Pulford& Watson, 2003; Tőzsér et al., 2023; Li et al., 2025.
2.	Willow	*Salix* spp.	Cd, Cu, Zn	Pulford& Watson, 2003; Cao et al., 2022; Jiang et al., 2024
3.	*Eucalyptus*	*Eucalyptus* spp.	Pb, Cd	Robinson et al., 2000; Negrini et al., 2024

Table 5. Agricultural crops used for clean-up of heavy metals

S.No.	Common name	*Scientific name*	Heavy metals	Authors
1.	Sunflower	*Helianthus annuus*	Pb, Cd, Zn	Dushenkov et al., 1995; Zhong et al., 2024; Zhao et al., 2023
2.	Maize	*Zea mays*	Pb, Cd	Ebbs &Kochian, 1997; Elik&Gül, 2025; Chen et al., 2024
3.	Rice	*Oryza sativa*	As, Cd	Meharg& Zhao, 2012; Wang et al., 2024
4.	Mustard	*Brassica napus*	Cd, Pb	Salt et al., 1998; Zhao et al., 2023

3.2.2 Agricultural Crops

Agricultural crops such as maize, sunflower, mustard, and rice have shown potential in phytoremediation. These crops can absorb and accumulate certain heavy metals from contaminated soils, particularly under controlled conditions. Although their accumulation capacity is generally lower than that of hyperaccumulators, their rapid growth, high biomass production, and economic value make them useful for phytoextraction and phytostabilization. However, precautions must be taken to prevent the entry of accumulated metals into the food chain (Deng et al., 2024; Kumar et al., 2022) are shown in Table 5.

3.3 Microbes Used for Clean-up of Heavy Metals

Microorganisms play a crucial role in the detoxification of heavy metal-contaminated environments through a range of biological mechanisms. Diverse groups such as bacteria, fungi, algae, and cyanobacteria have developed the ability to survive in metal-stressed conditions and remove toxic elements from soil and water. They employ processes such as biosorption, bioaccumulation, biomineralization, biotransformation, and bioleaching, which collectively help reduce the mobility, bioavailability, and toxicity of heavy metals, thereby contributing to ecosystem restoration (Gadd, 2004; Wang & Chen, 2009; Rajkumar et al., 2012; Agrawal et al., 2024).

Bacteria are among the most extensively studied microorganisms for heavy metal remediation due to their adaptability and metabolic versatility. Genera such as *Pseudomonas*, *Bacillus*, *Arthrobacter*, and *Alcaligenes* are known to remove metals by binding them to cell surfaces or converting them into less toxic forms. These bacteria produce extracellular polymeric substances (EPS), siderophores, and metal-binding proteins that enhance the immobilisation and removal of metals like lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) from contaminated environments (Nies, 1999; Volesky, 2001; Verma et al., 2023; Patil et al., 2025).

Fungi also serve as effective agents for heavy metal remediation due to their high tolerance to toxic conditions and significant biomass production. Species such as *Aspergillus niger*, *Penicillium chrysogenum*, and *Trichoderma viride* exhibit strong metal-binding capacity because of functional groups like carboxyl, hydroxyl, phosphate, and amino groups present in their cell walls. These groups facilitate the adsorption and sequestration of heavy metals from polluted environments (Gadd, 1994; Kapoor & Viraraghavan, 1995; Baldrian, 2003).

Fungi also serve as effective agents for heavy metal remediation due to their high tolerance to toxic conditions and significant biomass production. Species such as *Aspergillus niger*, *Penicillium chrysogenum*, and *Trichoderma viride* exhibit strong metal-binding capacity because of functional groups like carboxyl, hydroxyl, phosphate, and amino groups present in their cell walls. These groups facilitate the adsorption and sequestration of heavy metals from polluted environments (Gadd, 1994; Kapoor & Viraraghavan, 1995; Baldrian, 2003; Mishra et al., 2021).

Algae and cyanobacteria are widely utilized in wastewater treatment systems for their ability to remove heavy metals through biosorption and intracellular accumulation. Microalgae such as *Chlorella vulgaris* and filamentous algae like *Spirogyra* can efficiently accumulate metals including copper (Cu), cadmium (Cd), and mercury (Hg). Similarly, cyanobacteria such as *Anabaena* species are capable of removing metals like chromium (Cr) and nickel (Ni) through adsorption and metabolic processes (Mehta & Gaur, 2005; Wang & Chen, 2009; Markou et al., 2018).

The integration of plants and microorganisms, commonly referred to as microbial-assisted phytoremediation or rhizoremediation, significantly enhances the efficiency of heavy metal removal. Plant growth-promoting rhizobacteria (PGPR) improve plant tolerance to metal stress by producing siderophores, organic acids, and exopolysaccharides that increase metal availability and uptake. This synergistic interaction between plants and microbes has been widely recognised as an effective and sustainable approach for remediating contaminated environments (Dotaniya et al., 2018; Sharma et al., 2023) and are listed in Table 6.

Table 6. Microbes used for clean-up of heavy metals

S.No.	Microorganisms	Type	Heavy metals removed	Reference
1.	*Pseudomonas putida*	Bacteria	Pb, Cd, Cr	Volesky, 2001; Tasleem et al., 2023; Zhang et al., 2024
2.	*Bacillus subtilis*	Bacteria	Pb, Cu, Cd	Nies, 1999; Jhariya et al., 2025
3.	*Arthrobacter spp.*	Bacteria	Cr, Ni	Nies, 1999; Nnaji et al., 2023
4.	*Aspergillus niger*	Fungus	Pb, Cd, Zn	Kapoor &Viraraghavan, 1995; Alabssawy& Hashem, 2024
5.	*Penicillium chrysogenum*	Fungus	Cu, Zn	Gadd, 1994; Alabssawy&Hashem, 2024
6.	*Trichoderma viride*	Fungus	Pb, Cd	Baldrian, 2003; Syed et al., 2023
7.	*Chlorella vulgaris*	Algae	Cu, Cd, Hg	Wang & Chen, 2009; Fitri et al., 2024
8.	*Spirogyra spp.*	Algae	Pb, Cd	Mehta & Gaur, 2005; Machado et al., 2024
9.	*Anabaena spp.*	Cyanobacteria	Cr, Ni	Rai & Dubey, 1989; Aslam et al., 2025

4. Conclusion

Heavy metal contamination of soil and water has become a major environmental problem due to rapid industrialisation, urbanisation, and intensive agricultural activities. Because heavy metals are non-biodegradable and persistent in nature, they accumulate in ecosystems and enter the food chain, posing serious risks to human health and environmental sustainability. Conventional remediation technologies are often costly, energy-intensive, and may cause further environmental disturbances. In this context, phytoremediation has emerged as a promising, eco-friendly, and cost-effective approach for the remediation of heavy metal-contaminated environments.

Phytoremediation utilises the natural ability of plants to absorb, accumulate, stabilise, or detoxify pollutants through several mechanisms such as phytoextraction, phytostabilization, phytodegradation, phytovolatilization, and rhizofiltration. Various plant species including hyperaccumulators, aquatic plants, woody plants, and agricultural crops have demonstrated significant potential for the removal or stabilization of toxic metals such as Cd, Pb, Zn, Ni, Cu, and As. In addition, the involvement of rhizosphere microorganisms such as bacteria, fungi, algae, and cyanobacteria further enhances the efficiency of phytoremediation through processes like biosorption, bioaccumulation, and biotransformation.

Although phytoremediation offers several advantages such as low cost, environmental compatibility, and aesthetic value, its practical application may be limited by factors such as slow plant growth, low biomass production, and limited metal uptake capacity under certain conditions. Therefore, future research should focus on identifying highly efficient hyperaccumulator plants, improving plant–microbe interactions, and applying advanced biotechnological approaches such as genetic engineering and microbial-assisted phytoremediation to enhance remediation efficiency. Overall, phytoremediation represents a sustainable and environmentally friendly strategy for the management and restoration of heavy metal-contaminated ecosystems and has significant potential for large-scale application in environmental clean-up programs.

5. Limitations

The review is limited by its reliance on previously published evidence rather than experimental data generated within the manuscript. Phytoremediation efficiency may also vary across field conditions, contaminant concentrations, soil properties, plant species, and microbial communities. Therefore, site-specific validation is necessary before large-scale application.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

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

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