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**PHYTOREMEDIATION POTENTIAL OF PLANTS IN THE UPTAKE AND
STABILIZATION OF HEAVY METALS: A REVIEW****Qilichev Shohjahon Shomurod ugli**Junior Researcher, Institute of Botany, Academy of
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Abstract: In this scientific review, the phytoremediation potential of various plant species for the remediation of soils and water bodies contaminated with heavy metals is analyzed based on published research data. A wide range of plant species, including *Amaranthus spinosus*, *Brassica juncea*, *Malva rotundifolia*, *Sedum alfredii*, *Linum usitatissimum*, *Medicago sativa*, and several other taxa, have been reported to exhibit the ability to accumulate, stabilize, or translocate metals such as Cd, Pb, Zn, Cu, Ni, As, Mn, and Fe. Recent studies indicate that the effectiveness of phytoremediation can be enhanced through the application of soil amendments, including biochar and multi-walled carbon nanotubes, which promote plant growth and improve metal uptake and distribution. In addition, several investigations demonstrate that the utilization of contaminated plant biomass for the production of essential oils or other value-added products may increase the economic feasibility of phytoremediation.

Keywords: phytoremediation, hyperaccumulating plants, ecological restoration, phytostabilization

Introduction

Under the combined influence of natural processes and anthropogenic activities, the degradation and contamination of land resources are accelerating on a global scale (Wang et al., 2023). Numerous studies indicate that large areas of land worldwide are affected by heavy metal contamination, often at concentrations exceeding internationally accepted regulatory limits (Akansha et al., 2024; Li et al., 2025; Hou et al., 2025). This situation represents a serious threat to environmental safety, ecosystem stability, food chain integrity, and human health.

Soil contamination by heavy metals is considered one of the major environmental challenges of the 21st century. Heavy metals play an important role in natural geochemical cycles and are essential for the normal functioning of living organisms at trace levels. Elements such as copper, zinc, manganese, and iron are necessary for plant metabolism and growth (Rai

et al., 2021). However, excessive accumulation of these elements can lead to toxic effects, disrupting physiological processes and impairing the functional balance of biological systems (Ali et al., 2021).

The rapid development of industrial activities, mining and metallurgical operations, oil and gas extraction, intensive agricultural practices, and urbanization has significantly disturbed the natural circulation of heavy metals in the environment. In particular, mining activities are among the primary sources of soil contamination, as large amounts of toxic elements such as cadmium, lead, mercury, and arsenic are released into surrounding ecosystems (Dehkordi et al., 2024; Fulke et al., 2024). These pollutants may migrate through soil, water, and air, enter the food chain, and accumulate in the human body, contributing to the development of chronic health disorders.

Therefore, the systematic assessment, monitoring, and development of effective strategies aimed at mitigating the negative impacts of heavy metal pollution are of both scientific and practical importance. In recent years, various remediation technologies have been proposed, including chemical stabilization, physical removal, and bioremediation approaches (Santos et al., 2025). However, many conventional methods are associated with high costs and potential secondary environmental impacts, which limits their large-scale application (Dhaliwal et al., 2020).

Heavy metals occur in the environment in different physicochemical forms, such as dissolved ions, suspended particles, and mineral complexes. These forms determine their mobility, bioavailability, and ecological impact within soil–water–air systems (Mishra et al., 2023). Consequently, understanding the behavior of heavy metals in different environmental compartments is essential for selecting appropriate remediation strategies.

Among the available remediation approaches, phytoremediation has been increasingly recognized as an effective and environmentally sustainable method for reducing heavy metal contamination (Sharma et al., 2023; Aryal, 2024; Kumar et al., 2024). This technology involves the use of selected plant species capable of absorbing, accumulating, or immobilizing metals in contaminated environments. Depending on plant characteristics and metal properties, phytoremediation may proceed through phytoextraction or phytostabilization mechanisms (Zhang et al., 2024). Compared with conventional remediation methods, phytoremediation is relatively low-cost, causes minimal disturbance to ecosystems, and contributes to soil quality improvement.

The concept of phytoremediation emerged in the 1990s and is primarily based on the use of hyperaccumulator plants capable of tolerating and accumulating high concentrations of heavy metals. In addition to contaminant removal, phytoremediation can enhance soil fertility, reduce erosion risk, and support ecosystem recovery (Reeves et al., 2018). Consequently, this approach is now regarded not only as a remediation technique but also as a component of sustainable land management (Fiorentino et al., 2018).

Given the growing body of research in this field, a comprehensive synthesis of existing studies is necessary to evaluate plant performance, remediation mechanisms, and technological advancements. Therefore, this review aims to analyze recent research on phytoremediation of heavy metal–contaminated soils and water bodies, with particular emphasis on hyperaccumulator plants, enhancement strategies, and the potential ecological and economic benefits of this approach.

Materials and methods

In this review, published scientific studies on phytoremediation conducted in different geographical regions and ecological settings were systematically analyzed. The review is based

on peer-reviewed articles and conference papers that investigated the use of plants for the remediation of soils and water bodies contaminated with heavy metals. Various ecosystem types were represented in the reviewed literature, such as mining-affected areas, industrial zones, agricultural lands, and river sediments. This diversity allowed for a comparative evaluation of phytoremediation performance under different environmental and climatic conditions.

Both field-based and controlled experimental studies were considered in order to provide a balanced overview of phytoremediation potential. Field studies offered insights into plant performance under realistic environmental conditions, while greenhouse and laboratory experiments contributed to a better understanding of physiological and molecular mechanisms involved in metal tolerance and accumulation. Data from these different study types were synthesized qualitatively to identify general trends, species-specific characteristics, and methodological limitations.

Discussion

Mechanisms of heavy metal accumulation and tolerance in plants

The uptake, translocation, and accumulation of heavy metals and metalloids by plants represent complex physiological and molecular processes that vary considerably among plant species. While most conventional plant species exhibit sensitivity to elevated metal concentrations, hyperaccumulator plants have evolved specific adaptive mechanisms that allow them to tolerate and accumulate unusually high levels of toxic elements without severe physiological damage (Pasricha et al., 2021). These mechanisms are closely associated with the enhanced expression of metal transporter proteins, efficient chelation through metal-binding ligands, compartmentalization of metals within vacuoles, and effective translocation from roots to aerial tissues (Sitar et al., 2021).

As a result, hyperaccumulator plants serve not only as valuable tools for environmental remediation but also as important biological models for understanding metal tolerance and homeostasis. Integrating knowledge derived from naturally occurring hyperaccumulator species with biotechnological and agronomic approaches is considered a key strategy for improving phytoremediation efficiency in contaminated environments.

Diversity and distribution of hyperaccumulator species

Over the past three decades, extensive research has been conducted to identify plant species capable of accumulating heavy metals. According to the global database compiled by Reeves et al. (2018), hyperaccumulator plants are distributed across more than 52 plant families, 130 genera, and over 720 species. This diversity highlights the broad evolutionary adaptation of plants to metal-rich environments and underscores the potential for selecting species suited to different ecological and climatic conditions.

Continuous efforts are being made to identify new hyperaccumulator species, particularly in regions affected by mining and industrial activities. Such research expands the range of plant candidates available for site-specific phytoremediation applications.

Phytoremediation potential of selected plant species

Several studies have demonstrated the effectiveness of specific plant species in remediating soils contaminated with heavy metals. Africa et al. (2024) reported that *Amaranthus spinosus* exhibits a high capacity for the phytoextraction of copper and zinc from tropical soils. The addition of biochar significantly enhanced plant growth and metal uptake, indicating that soil amendments can play a crucial role in improving remediation efficiency. The study showed that metals were predominantly absorbed through the roots and accumulated in stem tissues, suggesting the suitability of *A. spinosus* for phytoextraction strategies.

Wu et al. (2018) investigated the phytoremediation potential of several ornamental plant species under cadmium stress. Among the tested species, *Malva rotundifolia* demonstrated the highest tolerance and accumulation capacity, with substantial concentrations of cadmium detected in both root and shoot tissues. High bioaccumulation and translocation factors confirmed the plant's ability to absorb cadmium efficiently and transfer it to aerial parts, making it a promising candidate for the remediation of cadmium-contaminated soils. However, the authors noted that the results were obtained under specific soil and climatic conditions, which may limit broader applicability.

The nickel hyperaccumulator *Sedum alfredii* has been widely studied for its exceptional metal tolerance. Ge et al. (2020) reported that this species maintained normal growth even under elevated nickel concentrations and accumulated large amounts of nickel, particularly in root tissues. Micro-XRF imaging revealed that nickel was primarily localized in vascular tissues, especially the xylem. The high nickel tolerance of *S. alfredii* was attributed to efficient metal homeostasis mechanisms in root cells, which mitigate metal toxicity and support sustained growth under stress conditions.

In tropical ecosystems, Castañares and Lojka (2020) examined plant species growing in metal-contaminated soils of the Philippines. Their findings showed that acidic soil conditions significantly enhanced metal uptake by plants. Species such as *Cratogeomys sumatranum*, *Syngramma alismifolia*, *Pneumatopteris laevis*, *Mitragyna speciosa*, and *Pneumatopteris glabra* were found to accumulate high concentrations of metals including aluminum, chromium, cadmium, iron, and manganese. Particularly notable was the elevated manganese concentration in the leaves of *Mitragyna speciosa*, exceeding global reference values and indicating strong accumulation potential.

Cao et al. (2022) evaluated the phytoremediation performance of flowering plants in soils contaminated with cadmium, arsenic, and lead near mining areas. Among the tested species, *Tagetes patula* exhibited the highest accumulation efficiency for cadmium and lead. An important outcome of this study was the demonstration that essential oils extracted from plant biomass after remediation did not contain hazardous metal concentrations, highlighting the potential for combining environmental remediation with economic value generation.

Guo et al. (2020) assessed the cadmium phytoremediation capacity of eighteen flax (*Linum usitatissimum*) cultivars grown in contaminated soils. The results revealed significant variation among cultivars, with certain varieties showing high bioaccumulation coefficients and efficient translocation of cadmium to aerial tissues via the phloem. These findings support the use of flax as a non-food crop for phytoremediation purposes, although the authors emphasized the need for further research on long-term ecological effects and multi-metal contamination scenarios.

Phytostabilization by local and stress-tolerant species

In contrast to hyperaccumulators, several plant species primarily function as phytostabilizers by retaining metals in root tissues and limiting their mobility. Siyar et al. (2022) demonstrated that native plant species growing near a copper smelting facility in Iran exhibited varying remediation strategies. *Artemisia* species were identified as effective phytoextractors, while *Launaea acanthodes* and *Cousinia congesta* were more suitable for phytostabilization, particularly for arsenic and molybdenum.

Similarly, Sojitra et al. (2024) investigated vegetation along the Uben River and found that many monocotyledonous species retained heavy metals predominantly in their roots. This characteristic reduces metal transport to aerial parts and limits dispersion through aquatic systems, making these plants effective stabilizers in contaminated riverine environments.

Enhancement strategies and nanotechnology applications

Recent advances in phytoremediation research emphasize the use of soil amendments and nanomaterials to enhance remediation efficiency. Chen et al. (2021) demonstrated that the application of multi-walled carbon nanotubes at optimal concentrations significantly improved plant growth and increased cadmium and arsenic accumulation in *Solanum nigrum*. The study also showed a reduction in metal bioavailability in the rhizosphere, suggesting improved detoxification mechanisms.

Physiological and molecular responses to metal stress

At the molecular level, plants activate various defense mechanisms in response to heavy metal stress. Gutsch et al. (2018) reported that *Medicago sativa* exhibits increased expression of proteins involved in cell wall modification and lignification under cadmium exposure, enhancing root barrier function and limiting metal translocation. Proteomic analyses further revealed shifts in metabolic pathways aimed at maintaining cellular energy balance under stress.

Malecka et al. (2019) confirmed that *Brassica juncea* exhibits strong hyperaccumulation capacity, while *Medicago sativa* and other species display adaptive strategies that balance metal tolerance and growth. These findings collectively demonstrate that plant responses to heavy metals are species-specific and involve complex physiological and biochemical regulation.

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Conflict of interest

The authors declare that there is no actual or potential conflict of interest related to this article.

Conclusion

The synthesized data demonstrate that phytoremediation represents a scientifically sound, environmentally sustainable, and economically feasible approach for the restoration of soils and water bodies contaminated with heavy metals. Numerous plant species, including *Amaranthus spinosus*, *Malva rotundifolia*, *Sedum alfredii*, *Tagetes patula*, *Brassica juncea*, *Medicago sativa*, and various flax (*Linum usitatissimum*) cultivars, have shown considerable phytoremediation potential under diverse environmental conditions. Some of these species primarily perform phytostabilization by immobilizing metals within root tissues, whereas others are capable of phytoextraction through efficient translocation of metals to above-ground plant parts.

Nevertheless, the universal applicability of many reported results remains limited, as a substantial proportion of studies have been conducted under site-specific conditions or within controlled laboratory and greenhouse environments. This highlights the necessity for comparative and long-term field experiments across different soil types, climatic zones, and ecosystem contexts. In addition, the integration of enhancement strategies such as biochar application, nanotechnology-based approaches, and the utilization of contaminated plant biomass for the production of value-added products may further improve both the efficiency and economic viability of phytoremediation.

Overall, phytoremediation holds significant promise as an innovative nature-based solution that offers not only ecological benefits but also socio-economic advantages for the sustainable restoration of heavy metal-contaminated soil and water systems.

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