

PLANT SIGNALING AND FUNCTIONAL CAPABILITIES OF PLANTS

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ABSTRACT

This study examines the signaling potential of certain plant species, particularly higher plants, as bioindicators of heavy metal (HM) and other toxicant presence in agroecosystems and technogenic soils. The work focuses on the structural-functional and physiological-biochemical characteristics of plants capable of accumulating and removing HMs and various pollutants, emphasizing their practical relevance for environmental monitoring and remediation. Specific attention is given to mechanisms of metal uptake, translocation, and detoxification, as well as to the adaptive responses of plants exposed to contaminated substrates. By integrating insights from plant physiology, biochemistry, and ecology, the research highlights the potential of using selected species as cost-effective and sustainable tools for assessing soil contamination levels and mitigating environmental risks. The findings underscore the importance of understanding species-specific traits that govern accumulation efficiency and tolerance, providing a foundation for developing targeted phytoremediation strategies. Overall, this work contributes to contemporary approaches in environmental management, offering practical guidance for employing plants as indicators and mitigators of soil toxicity.

Keywords: monitoring, signaling, testing, heavy metals, pollution, soil.

INTRODUCTION

Environmental contamination by heavy metals (HMs) and other persistent toxicants represents a major challenge to soil health, agricultural productivity, and ecosystem sustainability. When ranking environmental toxicants according to their hazard potential for specific habitat types, it is essential to consider multiple factors, including their intrinsic toxicity, persistence in the environment, spectrum of toxic effects, mobility and dispersion within ecosystems, and interactions with the abiotic and biotic components of the landscape, such as soil–plant and soil–water systems (Rashid et al., 2023). Effective monitoring of soil quality in inhabited areas and agroecosystems requires standardized approaches that target conservative ecotoxicants, including technogenic radionuclides (TRN), polycyclic

aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), toxic HMs and metalloids, persistent herbicides, and indicator organisms capable of accumulating these pollutants (Zhong, et al., 2020; Mohamed, et al., 2025).

Traditionally, soil mesofauna has served as an important group of bioindicators, with earthworms reflecting cadmium (Cd) levels, insects representing lead (Pb) accumulation, and centipedes indicating copper (Cu) presence (Iqbal et al., 2025). In areas with limited accessibility, monitoring can be complemented by pheromone trapping of click beetle adults (*Agriotes* spp.), whose larvae reside in the soil for several years, allowing subsequent analysis of PAH and TRN accumulation (Sokolov et al., 1994; Yadav et al., 2023).

Plants offer an additional, highly informative layer of monitoring due to their ability to absorb, accumulate, and translocate metals from the soil. Mechanistically, two main types of accumulation can be distinguished: barrier (non-accumulating) and non-barrier (accumulating). Barrier accumulation, typical of most higher plants, restricts metal uptake into sensitive tissues, whereas non-barrier accumulation, characteristic of mosses and lichens, allows more extensive metal uptake (Chaplygin et al., 2020). Specific examples include Sphagnum moss for cobalt (2.66 mg/kg), birch (*Betula papyrifera*), stone bramble (*Rubus saxatilis*), and lily-of-the-valley (*Convallaria majalis*) for copper (10.0 mg/kg), and bilberry (*Vaccinium myrtillus*) for manganese (Toika and Potehine, 1980). High cadmium concentrations have been documented in the sporophores of *Amanita muscaria* in birch forests (29.9 mg/kg dry weight), while the surrounding soil contained 70 times less cadmium (0.4 mg/kg) (Scheffer, 1989). Plants capable of concentrating cobalt (Boraginaceae, Brassicaceae, Myrtaceae, Fabaceae, Caryophyllaceae) demonstrate remarkable tolerance to this element. Nickel hyperaccumulators have been identified in medicinal and wild plants, including papaya (*Carica papaya*), valerian, belladonna (*Atropa belladonna*), yellow horned poppy (*Glaucium flavum*), desert heart (*Leonurus cardiaca*), passionflower (*Passiflora incarnata*), and *Thermopsis lanceolata* (Lottermoser et al., 2008; Bali et al., 2010).

The phase of vegetation strongly influences the type and intensity of phytoaccumulation. Non-barrier accumulation is particularly pronounced during germination, at the final stage of vegetation (maturation), and during winter dormancy. In these stages, excess metals may be excreted in solid form, representing an adaptive detoxification mechanism (Kovalevsky, 1991). Based on their responses to soil metal presence, vegetating plants are commonly classified into three functional groups: indicators, accumulators, and removers. This classification provides the framework for both environmental monitoring and the development of phytoremediation strategies aimed at mitigating soil contamination and enhancing ecosystem resilience (Sao and Maru, 2019; Bhat, et al., 2022; Stojanova et al., 2024a).

INDICATOR PLANTS

Indicator plants for metals include species that actively accumulate metals in their aboveground tissues, reflecting the overall content of heavy metals (HMs) in the soil. These plants exhibit tolerance to elevated metal concentrations through various physiological and biochemical adaptations. One key mechanism involves the formation of extracellular compounds, such as chelators, which bind metals and reduce their toxicity (Cakaj et al., 2024). Additionally, metals may be compartmentalized within specific cellular or tissue loci that are less sensitive to metal stress, thereby minimizing damage to essential metabolic processes. Some species also possess enhanced antioxidant systems and stress-response pathways that further mitigate the harmful effects of metal exposure (Mehes-Smith et al.,

2013). By integrating these mechanisms, indicator plants serve as reliable bioindicators, providing a measurable reflection of soil contamination levels and enabling early detection of environmental pollution. Such species are increasingly important in contemporary monitoring programs and can inform both ecological risk assessments and targeted soil remediation strategies (Mohamed et al., 2025).

Accumulator Plants

Most higher plants experience damage when soil heavy metal (HM) concentrations reach maximum levels. However, many species are capable of accumulating high concentrations of HMs, primarily in their aboveground tissues, often exceeding soil content severalfold. These traits characterize accumulator plants (El-Sappah et al., 2024). Through evolution, these species have adapted to thrive in soils with abnormal geochemical conditions, developing constitutive mechanisms of resistance to HMs and other toxic elements. Accumulation often occurs in metabolically inert organs, or metals are transformed into physiologically safe forms via chelation (Jarin et al., 2025). In recent decades, suitable accumulator species have been actively applied in the development of phytoremediation technologies for biological soil purification in HM- and toxin-contaminated areas (Polovnikova, 2010; Narayanan and Ma, 2023).

Hyperaccumulator species of toxic elements have been identified in the families *Brassicaceae*, *Euphorbiaceae*, *Asteraceae*, *Lamiaceae*, and *Scrophulariaceae*. Among these, the most studied and widely used is Indian mustard (*Brassica juncea*), a high-biomass species capable of accumulating Pb, Cr(VI), Cd, Cu, Ni, Zn, ⁹⁰Sr, and Se. In studies of various tested species, *B. juncea* showed the highest lead uptake, with HM accumulation in aboveground tissues exceeding 1.8% of dry biomass. Except for sunflower (*Helianthus annuus*) and tobacco (*Nicotiana tabacum*), plants from other families exhibited a biological absorption coefficient <1 (Dar et al., 2015; Nepal et al., 2024).

Accumulator plants have developed a suite of adaptive mechanisms that protect cellular metabolism from HM toxicity. These include metal binding by the cell wall and exudate release, reduction of metal entry into the cytoplasm with sequestration into the apoplast, cytoplasmic chelation with peptides and proteins, repair of damaged proteins, and vacuolar compartmentalization via transporters (Polovnikova, 2010). Adaptation of cultivated plants to HMs represents a form of agronomic resistance, enabling acceptable yields under adverse soil conditions. The degree of yield reduction under metal stress serves as an indicator of plant resistance and overall agronomic performance (Hall, 2002; Jarin et al., 2025).

Remover Plants

In indicator plants, the metal content in cells and tissues approximately reflects the concentration present in the soil. In remover plants, however, the aboveground tissues maintain consistently low levels of toxicants even when soil heavy metal (HM) concentrations are elevated. In such cases, the root system and root collar act as effective barriers against pollutant translocation, preventing excessive metal accumulation in sensitive aerial tissues (Hall, 2002). Remover plants predominantly sequester metals in roots, thereby protecting photosynthetically active organs and other metabolically important tissues from potential damage. These plants are believed to possess adaptive mechanisms that include modulation of membrane permeability, enhancement of the metal-binding capacity of cell walls, and inhibition of chelate transport, effectively limiting the movement of toxicants to

the shoots (Leppetal, 1987; Toika and Potehina, 1980). In addition, some species may actively compartmentalize metals within root vacuoles or bind them to intracellular ligands, further reducing metal bioavailability and toxicity. Such traits make remover plants critical for stabilizing contaminated soils, preventing leaching or transfer of metals into the food chain, and supporting sustainable environmental management practices (Jarin et al., 2025). Table 1 presents the structural-functional characteristics that underlie the unique properties of each of the three plant groups discussed. The data indicate that the specific mechanisms of metal translocation and localization in roots largely determine a plant's capacity to accumulate toxicants in either underground or aboveground organs. These traits make remover plants particularly valuable for stabilizing contaminated soils and preventing the spread of heavy metals into the food chain, contributing to sustainable soil management and environmental protection.

Table 1. Comparative characteristics of Ni remover plants and hyperaccumulators (Seregin, 2009).

Feature	Remover Plants	Hyperaccumulators
Metal accumulation primarily occurs	in underground organs	in aboveground organs
Barrier tissues in the root	present	absent
Accumulator tissues in the root	present (cortex, endodermis, pericycle)	absent
Accumulator tissues in the shoot	absent	present
Endogenous chelator (histidine) level in the root	low	high
Endogenous chelator (histidine) level in the shoot	low	low
Rate of metal entry into the xylem	low	high

LOCALIZATION OF HEAVY METALS IN PLANTS AND THEIR NEGATIVE EFFECTS

The accumulation of heavy metals (HMs) in underground organs, characteristic of remover plants and hyperaccumulators, is strongly dependent on the structural-functional and physiological-biochemical properties of root tissues and cells. Structural-functional traits include, for example, the presence of functional barriers that restrict metal entry into the root stele and, consequently, into the vascular system. As a result, HMs are sequestered in specialized root tissues that act as sinks or storage compartments, reducing the translocation of toxicants to aboveground organs (Dar et al., 2015; Stojanova et al., 2024b; Stojanova et al., 2026).

The ability of remover plants to accumulate nickel (Ni) in underground organs, as demonstrated in the case of field pennycress (*Thlaspi arvense*), is associated with significantly lower endogenous histidine content and, likely, a limited capacity for <<histidine + Ni>> transport into the xylem. At the same time, Ni entry into root cell

vacuoles remains unrestricted, leading to its accumulation in specific root tissues that function as metal-accumulating sites. However, the limited accumulation capacity of remover plants also correlates with less efficient detoxification mechanisms, rendering these species more susceptible to HM toxicity (Fig. 1; Seregin, 2009).

According to Seregin (2009), the role of plant tissues in HM translocation and accumulation varies not only among different metals but also between remover plants and hyperaccumulators. In hyperaccumulator roots, functional barrier tissues and dedicated accumulator tissues are absent. Consequently, unlike remover plants, the root system of hyperaccumulators does not restrict metal entry into the shoot. For example, Ni hyperaccumulators exhibit limited retention of toxicants in root cells and enhanced translocation into the xylem. In alpine pennycress (*Thlaspi caerulescens*), this process is strongly influenced by intracellular histidine content.

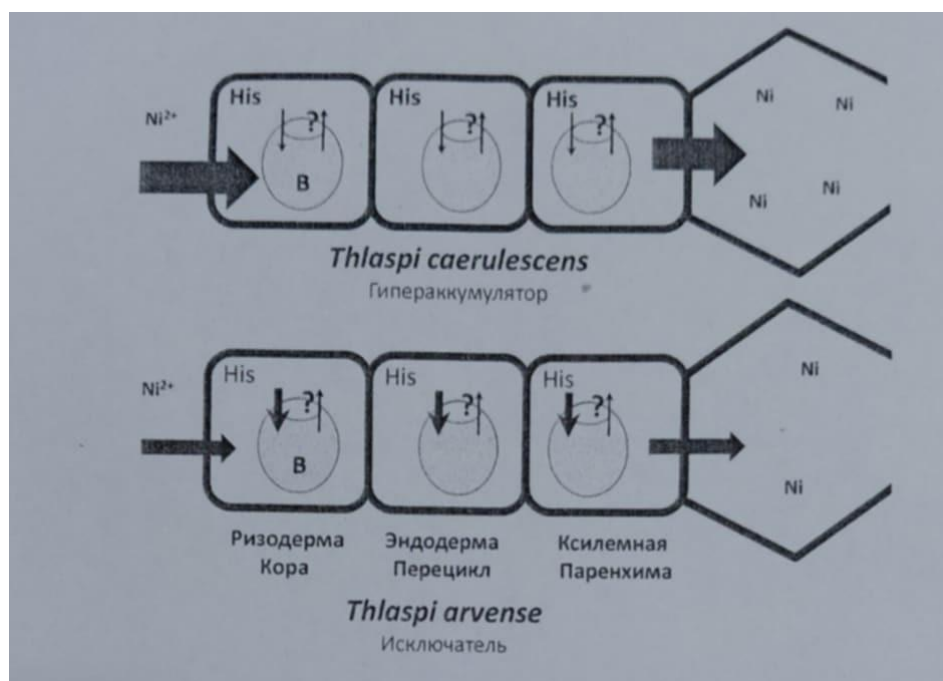


Figure 1. The role of histidine in the accumulation and transport of Ni in excluders and hyperaccumulators; a schematic representation of Ni movement in the root of the hyperaccumulator *T. caerulescens* and the excluder *T. arvense*. The pathways of Ni movement are indicated by arrows, with arrow thickness conditional representing the overall magnitude of Ni flow; V – vacuole, His – histidine.

The specificity of certain HMs on plant growth processes depends both on the physicochemical properties of the metal cations and on their tissue-specific translocation and localization patterns. As illustrated in Fig. 1, differences in Ni translocation between *T. caerulescens* and *T. arvense* are pronounced. In *T. caerulescens*, the absence of functional barriers, accumulator tissues, and collector sites in the roots, combined with a higher endogenous histidine level, facilitates enhanced metal uptake from the environment and minimal vacuolar sequestration in root cells. Histidine forms complexes with Ni, promoting its efficient entry into the xylem in *T. caerulescens*, whereas in *T. arvense*, the Ni–histidine complex is largely retained within root cell vacuoles. Notably, endogenous histidine levels

do not increase following plant incubation in Ni-containing solutions. The putative tonoplast transporter, and Ni in the xylem can exist both as free ions and as complexes, including Ni-histidine (Seregin, 2009; Dar et al., 2015).

These mechanistic insights illustrate the contrasting strategies employed by remover plants and hyperaccumulators. While remover species rely on root sequestration and barrier mechanisms to limit aboveground metal exposure, hyperaccumulators facilitate rapid translocation into the shoot, enabling both enhanced uptake and potential utilization in phytoremediation applications. Understanding these processes is critical for the development of effective strategies for managing metal-contaminated soils and mitigating ecological risks.

CONCLUSION

This review highlights the potential of plants to serve as bioindicators, reflecting the presence and levels of heavy metals (HMs) and other environmental toxicants in agroecosystems and technogenic landscapes. In addition to traditional zoological indicators, phytotests have emerged as essential components of soil-ecological monitoring programs. Higher plants, in particular, can function as indicators, accumulators, or removers of HMs and other toxic elements, providing a valuable tool for assessing soil contamination and ecosystem health.

The paper emphasizes the structural-functional and physiological-biochemical traits of plant root cells and tissues, particularly in hyperaccumulators and remover species. These traits, including metal compartmentalization, chelation, and barrier mechanisms, underpin the plants' capacity to tolerate, sequester, and selectively translocate metals, determining both their ecological role and practical utility. Understanding these mechanisms is critical not only for evaluating contamination levels but also for developing effective phytoremediation strategies, ensuring sustainable soil management, and maintaining sanitary and environmental standards in both agricultural and urban soils.

Moreover, the application of plants as bioindicators and bioremediators offers an integrative approach to environmental monitoring, bridging the gap between basic ecological research and practical land management. By selecting appropriate species based on their accumulation patterns and tolerance mechanisms, it is possible to design targeted interventions for polluted areas, reduce human and ecological exposure to toxicants, and support long-term soil fertility and ecosystem resilience. Thus, the insights gained from studying indicator, accumulator, and remover plants hold significant implications for environmental protection, agricultural sustainability, and urban ecological planning.

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