

Plants as Bioindicators of Heavy Metal Pollution: A Synthetic Viewpoint from Measurement to Mechanistic Understanding

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Abstract The use of vegetation as a diagnostic tool for environmental contamination has evolved from descriptive practices. Plants have long been used as bioindicators of environmental contamination, particularly heavy metals. While analytical advances have greatly improved our ability to quantify trace elements in plant tissues, interpreting these data remains a critical challenge. This viewpoint argued that plants should not be considered as passive recorders of environmental pollution, but as dynamic systems that integrate, transform, and redistribute metals according to species-specific physiology and environmental conditions.

Key words bioindicator; heavy metal pollution; environmental pollution; plant and soil interactions

植物作为重金属污染的生物指示物—— 从测量到机理理解的综合观点

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摘要 植被作为环境污染诊断工具已从描述性实践中不断发展和应用。植物长期被用作环境污染(尤其是重金属污染)的生物指示物。尽管分析技术的进步显著提升了我们对植物组织中微量元素的定量能力,但解析这些数据仍面临重大挑战。本文观点认为,植物不应被视为环境污染的被动记录者,而应理解为基于物种特异性生理机制和环境条件整合、转化并重新分配金属的动态系统。

关键词 生物指示物;重金属污染;环境污染;植物与土壤互作

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The natural concentration of heavy metals such as Cd, Cr, Cu, Ni, Pb, Zn, and Hg in the environment tends to remain low to ensure optimum ecological equilibrium. However, due to human activities, heavy metal (HM) concentrations frequently increase^[1-3]. Indeed, problems related to the presence

of HMs due to anthropogenic activities (mining, smelting, fossil fuel combustion, industrial emissions, and agricultural inputs) are well known^[4-8]. Plant tissues integrate exposure over time, often reflecting contamination events. Vegetation provides a unique interface between the atmosphere and soil, al-

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lowing the integration of multiple metal input pathways (Fig. 1). However, the interpretation of plant metal concentrations requires careful consideration of

species-specific physiology, environmental context, and the chemical behaviour of each element.

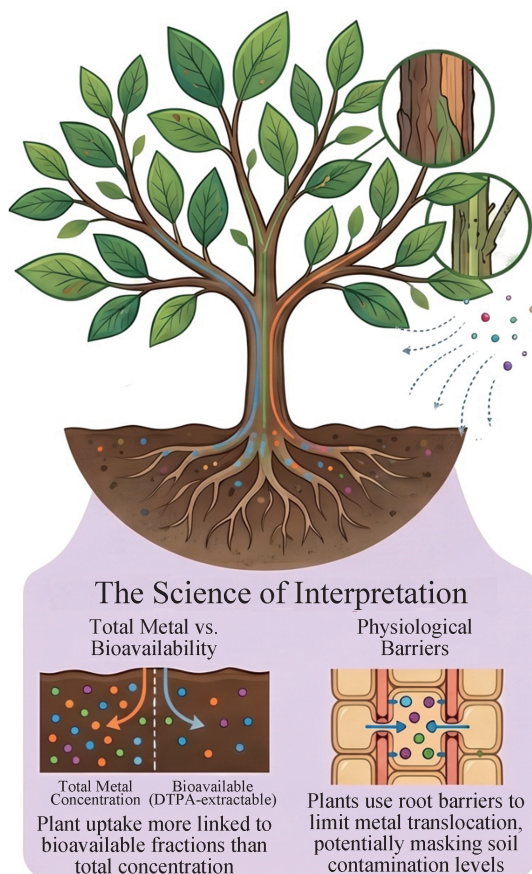


Fig.1 Main pathways of heavy metal uptake, transformation and accumulation in plants

In addition, plants are not only capable of accumulating heavy metals, but also of actively transforming and detoxifying them once absorbed. Several elements can undergo valence changes within plant tissues, altering their mobility and toxicity—for example, the reduction of Cr (VI) to the less toxic Cr (III). Concurrently, plants deploy a range of detoxification mechanisms, including chelation by phytochelatins and metallothioneins, sequestration in vacuoles, and compartmentalization in specific tissues such as bark^[9]. These physiological processes not only mitigate toxic effects but also influence internal metal distribution, often decoupling tissue concentrations from external exposure. Importantly, these mechanisms underpin the dual role of plants as both bioindicators and potential agents for the rehabilita-

tion of heavy metal-contaminated soils.

Plants as integrators of environmental pollution

Vegetation can function as a natural archive of atmospheric inputs, capturing and storing chemical signals from the air. Plants incorporate atmospheric constituents into their leaves, bark, wood, and other tissues through processes such as gas absorption, particle deposition, and nutrient uptake. This integrative capacity is particularly evident in long-term studies. Herbarium-based retrospective analyses offer a unique window into historical pollution trends. Herbarium specimens are preserved under controlled conditions and retain their elemental signatures for decades or centuries.

One of these studies was conducted in Spain, which analysed herbarium specimens collected in 1941 from the Valencia Botanical Garden and compared them with contemporary samples from the same species trees^[10]. Their results showed that over seven decades of urban expansion, industrialisation, and increased vehicular traffic, foliar concentrations of Cd, Cr, and Ni increased dramatically by factors of 10 to 16, reflecting intensified atmospheric emissions. In contrast, Pb concentrations declined sharply, mirroring the phase-out of leaded gasoline in Spain. These temporal patterns underscore the sensitivity of evergreen species, particularly *Quercus ilex*, to airborne metal deposition and confirm their value as long-term indicators of bioactivity.

In contrast, conifer needles have long been used in European monitoring programs because of their multi-year lifespan, high surface area, and waxy cuticles that efficiently trap airborne particles^[11-12]. Needles accumulate metals from both atmospheric deposition and root uptake, although the relative contribution of each pathway varies with species, age, and environmental conditions. For example, in industrial areas (especially near smelters or coal-fired power plants), Pb and Zn often accumulate predominantly through foliar deposition, whereas Cd and Ni may be absorbed through soil uptake^[13].

Tree rings as archive of atmospheric inputs

Dendrochemical analysis has long been proposed as a method for reconstructing historical pollution trends^[14-15]. However, plant metal concentrations in tree rings cannot be directly interpreted as simple proxies for environmental contamination. Species-specific physiology introduces substantial variability in the uptake, translocation, and storage of these elements.

The case of mercury is especially illustrative for *Pinus canariensis*. The Hg content in tree rings has been studied in trees that survived a volcanic eruption in 1949 in La Palma (Spain)^[9]. In this study, the Hg concentration in the covering of wounds left on the tree was approximately ten times higher than

that of the tree rings before and after the eruption. Their results revealed elevated Hg concentrations in pyroclastic wound tissues, whereas tree-ring records showed no consistent temporal signal. This pattern suggests that Hg is actively redistributed within the plant, with preferential allocation to the bark and phloem rather than long-term storage in the xylem. Instead, Hg was preferentially translocated to the phloem and bark, suggesting active detoxification pathways and compartmentalisation in non-living tissues. This finding challenges the assumption that tree rings reliably record Hg deposition and highlights the need to understand internal metal mobilities. However, other heavy metals, such as Pb and Cd, tend to be relatively immobile once incorporated into the xylem, and Hg and Zn can be redistributed through phloem transport, or remobilized during heartwood formation^[16-18]. Thus, dendrochemical bioindication must be species-specific and element-specific. These observations underscore a fundamental point: plant tissues not only record environmental inputs but also reflect the outcome of intricate physiological processes^[13].

Bioindication in mining and industrial landscapes

Mining regions provide some of the most dramatic examples of heavy metal contamination, and vegetation often reflects these gradients with high fidelity^[19]. One of these studies was carried out in the Migori-Transmara gold mining district of Kenya^[20], where extreme Hg concentrations in soils, tailings, and river sediments due to artisanal amalgamation practices showed Hg levels up to 1 000 $\mu\text{g} \cdot \text{kg}^{-1}$ in lichens and mosses. Lichens and mosses, which lack roots and rely primarily on atmospheric deposition, provide direct measures of airborne contamination. In contrast, vascular plants integrate both soil and atmospheric sources, offering a more complex and comprehensive signal.

In arid environments, where vegetation is sparse, additional challenges arise. Desert-adapted species show physiological adaptations, including

deep-rooting systems and tolerance to abiotic stress, influencing their performance as bioindicators. In Iran, *Haloxylon ammodendron* and *Artemisia persica* accumulated higher concentrations of Cd, Cr, and Pb than non-desert species^[21]. These species can reveal contamination associated with mining, dust deposition, and agricultural inputs in drylands. Urban systems highlight the value of long-lived species as integrators of diffuse, low-intensity contamination^[10]. In summary, the effectiveness of plants as bioindicators is strongly dependent on the environmental context.

Soil-plant interactions and metal bioavailability

The utility of plants as bioindicators depends not only on atmospheric deposition but also on the availability of metals in the soil. The relationship between soil contamination and plant uptake is mediated by bioavailability rather than the total metal concentration^[22]. For example, Carbonell et al.^[22] showed that different soil amendments influence both the total metal concentrations and plant uptake patterns. While municipal solid waste compost increased Cu, Pb, and Zn levels in the soil, their uptake remained largely confined to the roots, suggesting limited translocation to aerial tissues.

At the root level, plants actively regulate metal uptake through selective transporters, rhizosphere interactions, and sequestration mechanisms^[23-24]. This biological control can decouple plant metal concentrations from bulk soil chemistry, complicating interpretation but also providing insights into plant adaptive strategies. Given the complexity outlined above, plant-based bioindication must move beyond isolated measurements toward integrative frameworks. Such approaches should combine plant data with soil chemistry, atmospheric deposition, and a mechanistic understanding of internal metal dynamics.

Conclusion

Plant-based bioindication offers a powerful and ecologically meaningful approach for assessing heavy metal pollution. However, its effectiveness depends

on understanding the biological and environmental processes that govern metal uptake, retention, and redistribution. Plants integrate contamination over time, respond to both atmospheric and edaphic inputs, and reveal spatial patterns that are difficult to detect through soil sampling alone. However, not all species accumulate metals proportionally to environmental concentrations, and some redistribute metals internally, complicating chronological interpretation. Nevertheless, plant-based bioindication is constrained by species-specific physiology, environmental variability, and the mobility of different metals within plant tissues.

In summary, plants remain indispensable tools for assessing heavy metal pollution. However, their true potential lies not in their use as simple indicators but in their capacity to reveal underlying processes. To fully exploit this potential, we must embrace the complexities of plant-environment interactions. As global pressures on ecosystems intensify, vegetation remains an indispensable ally in monitoring and understanding heavy metal pollution.

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