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Phytoremediation of Heavy Metals in Soil and Water: (Turning Flowers and Green Landscapes into Living Environmental Clean-Up Tools)

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Abstract

Due to increased industrialization, urbanization, mining operations, wastewater irrigation, and overuse of agrochemicals, heavy metal poisoning of soil and water has become a major global environmental and agricultural concern. Lead, cadmium, chromium, arsenic, mercury, and nickel are examples of persistent, non-biodegradable, and bioaccumulative toxic metals that pose major threats to human safety, crop productivity, and ecosystem health. According to recent global assessments, heavy metal pollution affects a large percentage of freshwater systems and agricultural land, including some areas of India. A sustainable, economical, and environmentally beneficial substitute for traditional mechanical and chemical remediation techniques is phytoremediation, a plant-based remediation technology. The concepts and processes of phytoremediation, such as phytoextraction, phytostabilization, and rhizofiltration, are reviewed in this article with a focus on the function of aquatic, flowering, decorative, and fruit plants. In contaminated habitats, species like water hyacinth, marigold, chrysanthemum, gladiolus, Indian mustard, sunflower, and Typha have shown a great deal of promise for heavy metal uptake and stability. Contaminated sites can be converted into useful green spaces that boost biodiversity, improve environmental quality, and increase aesthetics by combining phytoremediation with floriculture and landscape management. The essay emphasizes phytoremediation as a viable green technique for sustainable soil and water management by highlighting current data, case studies, and useful considerations.

Keywords: Phytoremediation; Heavy metal pollution; Soil and water contamination; Floriculture; Ornamental plants; Sustainable remediation; Environmental horticulture

Introduction

Rapid industrialization, urbanization, excessive fertilizer use, sewage irrigation, mining, and the indiscriminate disposal of waste have resulted in alarming levels of heavy metal contamination in soil and water. Metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), mercury (Hg), copper (Cu), and zinc (Zn) are persistent, non-biodegradable, and toxic even at low concentrations. According to a major global assessment published in *Science*, an estimated 14–17% of the world's cropland, about 242 million hectares, is contaminated with at least one heavy metal above safety thresholds. This translates to 900 million to 1.4 billion people living in high-risk polluted areas worldwide and reveals the deeply worrying extent to which these natural poisons are polluting our soils, entering our food and water, and affecting our health and our environment [American Association for the Advancement of Science (AAAS)].

In India, heavy metal contamination is widespread. A government report revealed that 81 rivers and their tributaries have dangerously high concentrations of toxic metals (Central Water Commission). 328 monitoring stations analyzed nationwide were observed during January-December 2022, 2023, and 2024 (Table 1), 43% showed alarming levels of one or more toxic heavy metals and places upto 1.4 billion people at risk from soil heavy metal exposure.

For floriculture, nursery production, landscaping, and peri-urban horticulture, heavy metals not only reduce plant growth and flower quality but also pose serious ecological and human health risks. Conventional remediation methods like soil excavation, chemical washing, or vitrification are expensive, disruptive, and impractical for large areas.

Phytoremediation harnesses plants' natural ability to absorb, stabilize, or transform heavy metals, transforming contaminated sites into safer environments without the intensive energy or chemical inputs of conventional remediation (Bhat *et al*., 2022).

Why heavy metals matter to soil, water, and plants?

Heavy metals are persistent, **non-degradable**, and often **bioaccumulative**. Unlike biodegradable pollutants, once heavy metals enter soil or water, they can remain for decades, penetrating plant roots and leaching into groundwater. Their presence:

- Reduces crop yield and soil fertility
- Compromises plant health and flower quality
- Threatens animal and human health via food and water exposure

What is Phytoremediation?

Phytoremediation is a plant-based technology that utilizes the natural ability of plants to absorb, accumulate, immobilize, or transform heavy metals present on contaminated soils and water bodies.

Table 1: List of permissible limits and maximum concentration of different heavy metals was observed in water quality of various rivers in India

Contaminant	**Acceptable limit**	**Maximum concentration recorded through Water quality monitoring station (WQMS)**		
		January – December 2022	**January – December 2023**	**January – December 2024**
As	10 µg / L	River Rind at Kora WQMS was 19.47 µg / L.	Sengar River (Tributary of River Yamuna WQMS) was 17.59 µg / L.	26.63 µg / L, was recorded at Palla WQMS on Yamuna River
Cd	3 µg / L	Lucknow WQMS on River Gomti observed 5.542 µg / L, or twice the permissible limit.	Thevur WQMS on Sarabenga River observed 10.59 µg / L.	6.54 µg / L observed at Singasadanapalli WQMS on Ponnaiyar River.
Cr	50 µg / L	River Brahmaputra River recorded 87.575 µg / L of chromium at Udaipur WQMS.	84.61 µg / L at Biligindulu WQMS on Cauvery River.	Hogenakkal WQMS on Chinnar River recorded 248.90 µg / L.
Cu	50 µg / L	Avarankuppam WQMS on River Palar had a copper concentration reading of 98.097 µg / L or twice the permissible limit.	At Nellithurai WQMS, 107.01 µg / L Cu was recorded.	At Singasadanapalli WQMS on Ponnaiyar River observed 160.41 µg / L.
Fe	1,000 µg / L	Kirtinagar D/S WQMS on Alakananda River recorded iron levels of 11.387 mg/L or 11 times the permissible limit.	Murappanadu WQMS observed 5.99 mg / L at Tambraparani River.	21.21 µg / L Fe was recorded at Kudlur WQMS on Cauvery River.
Pb	10 µg / L	The lead concentration in Seetha River at Avershe WQMS was 63.483 µg / L or six times the permissible limit.	75.51 µg / L was observed at Kudige WQMS on Cauvery River.	117.90 µg / L was observed at Hogenakkal WQMS on Chinnar River.
Hg	1 µg / L	Palla U / S Delhi WQMS on the River Yamuna River indicated mercury levels of 8.903 µg / L or nine times the permissible limit.	4.79 µg / L recorded on Godavari River at Rajahmundry WQMS.	At Koggedoddi WQMS on Arkavathi River 3.83 µg / L.

Ni	20 µg / L	Madamon WQMS on River Pamba showed a nickel concentration of 69.01 µg / L or thrice the permissible limit.	Musiri WQMS on Cauvery River observed 66.64 µg / L.	At Kudlur WQMS on Cauvery River 72.11 µg / L.

**Source of table: Report on Status of Trace and Toxic Metals in Rivers of India, 2022, 2023, and 2024, CWC, Department of Water Resources River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Govt. of India.*

Phytoremediation Mechanisms

1. **Phytoextraction (Phytoaccumulation):** Plants uptake metals through roots and translocate them to shoots, leaves, or flowers, which is harvestable and safely disposed. These plants (often hyperaccumulators) allow metal removal when biomass is harvested. Best suited for sunflower, Indian mustard, marigold, and chrysanthemum.
2. **Phytostabilization:** Plants reduce metal mobility by retaining them in roots or soil, minimizing leaching or erosion. Ornamental grasses, shrubs, and trees are suitable for this technique.
3. **Rhizofiltration:** Root systems absorb or adsorb metals directly from water, effective in treating contaminated surface waters and effluents. Water hyacinth, Typha, and Duckweed are suited for the rhizofiltration technique.
4. **Phytovolatilization:** Some plants convert metals into volatile forms that are released into the atmosphere in less toxic forms (a rare mechanism).
5. **Phytodegradation:** Breakdown of metal-organic complexes in soil via root secretions or microbial partners.

Role of flowers and ornamental plants in phytoremediation: *Beauty with a purpose*

Gladiolus and Chrysanthemum: A controlled study examining Cu and As showed that *Gladiolus grandiflorus* and *Chrysanthemum* accumulated significant amounts of Cu and As in roots, stems, leaves, and flowers under contaminated conditions. Notably, chrysanthemum showed a higher ability to translocate both metals into aerial parts than gladiolus, making it a promising candidate for phytoextraction in ornamental landscapes (Haseeb *et al*., 2024).

In decorative beds near industrial sites or contaminated parks, flowering ornamentals could serve dual roles: beautification and phytoremediation (Swetha *et al*., 2023).

African Marigold (*Tagetes erecta*) and Organic Partners: Research demonstrates that the use of marigolds with beneficial soil bacteria enhances biomass, chlorophyll production, and metal removal in contaminated soils. These bio-assisted plants show improved heavy metal uptake and greater stress tolerance, suggesting a new frontier for combined biological and phytoremediation strategies. Urban green space restoration using marigolds could help detoxify small patches of contaminated soil while adding visual appeal and habitat value (Khilji *et al*., 2024).

Ornamental Amaranthus Tricolor: Amaranthus tricolor, an ornamental and leafy decorative plant, showed improved Pb and Zn uptake when soils were amended with organic materials, particularly vinasse sugarcane, enhancing the soil's remediation factor. This suggests that pairing ornamental with soil amendments can significantly boost phyto-extraction potential (Awad *et al*., 2021).

Sunflower (*Helianthus annuus*): Sunflowers are among the most widely studied phytoremediation species. They are effective in absorbing Pb, Cd, and other heavy metals from contaminated soils and even from wastewater. Higher biomass and an efficient root system make them effective for large-scale decontamination projects. In agricultural lands near industrial zones, sunflowers have been successfully used to reduce soil lead levels before planting food crops (Pillai and Ayyanar, 2025).

Brassica Species (Mustards and Canola): Plants in the *Brassica* genus, including Indian mustard (*Brassica juncea*), contain robust root systems and high metal uptake capacity, especially for Cd and Pb. Studies show that *B. juncea* accumulates significant Cd in shoots even under stress, representing a practical phytoextractor for contaminated agricultural soils. Many brassicas are edible; thus, careful management and biomass disposal are required to avoid food chain contamination (Aoun *et al*., 2008).

Ferns and Hyperaccumulators: Ferns like *Pteris vittata* (brake fern) and *Athyrium yokoscense* thrive in heavy metal–rich soils, concentrating arsenic, zinc, lead, and copper in their fronds without suffering toxicity. These species are excellent candidates for phytoextraction in industrial and mining landscapes.

Water Hyacinth (*Pontederia crassipes*): Water hyacinth effectively absorbs cadmium, chromium, cobalt, nickel, lead, and mercury from polluted water. Its dense root system supports heavy metal uptake and can dramatically improve water quality in eutrophic and contaminated systems. Urban ponds or irrigation canals with heavy metal pollution can be treated with floating aquatic plants like water hyacinth before linking to crops or natural streams.

Typha (*Typha latifolia*) and Eichhornia (*E. crassipes*): Common reeds and water plants such as *Typha latifolia* and water hyacinth have shown high bio-concentration factors for heavy metals, making them suitable for constructed wetlands and wastewater treatment systems (Zhang *et al*., 2018).

Practical Considerations in Phytoremediation

- **Biomass Management:** Plants that accumulate heavy metals must be harvested and properly disposed, otherwise the contaminants can return to the soil upon plant senescence or composting. Safe disposal includes controlled incineration with heavy metal capture, secure landfill burial, or extraction of metals from plant biomass.
- **Soil Conditions and Amendments:** Soil pH, organic matter content, and microbial communities influence heavy metal bioavailability. Soil amendments like organic mulch or biochar can improve root growth and metal mobilization (Awad *et al*., 2021).
- **Ecological Integration:** Integration phytoremediation with landscaping and agriculture requires careful planning, edible crops should be planted only after contaminants are reduced below safe thresholds, and ornamental phytoremediators should be managed to prevent human or animal contact with contaminated tissues.

Conclusion

Phytoremediation represents a sustainable, scalable, and cost-effective alternative to traditional cleanup methods for heavy metal contamination in both soil and water. With the right plant selections, from ornamental marigolds and gladiolus to sunflowers and water hyacinths. Appropriate management, landscapes and water bodies can be detoxified while enhancing aesthetics and biodiversity.

As research continues, the integration of biotechnological tools (e.g., microbial assistance, genetic improvement) with traditional phytoremediation will further enhance plant efficiency and expand deployment in urban, agricultural, and industrial settings.

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