

Green Catalysts at Work: Phytoremediation Trends Using Nature's Own Detoxifiers

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Abstract

Heavy metal contamination in terrestrial ecosystems presents a profound challenge to environmental integrity, agricultural resilience, and biotic health. Conventional remediation techniques, while effective, are often economically prohibitive and ecologically intrusive, necessitating sustainable alternatives. Phytoremediation—a plant-based, green biotechnological intervention—has emerged as a low-cost, eco-compatible strategy for detoxifying metal-laden soils. This study delves into contemporary trends in phytoremediation with an emphasis on the deployment of botanical green catalysts such as *Medicago sativa*, *Tagetes erecta*, *Helianthus annuus*, *Brassica juncea*, and *Bambusa vulgaris*. These species exhibit diverse metal remediation capacities through mechanisms like phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration. Notably, *M. sativa* demonstrates exceptional Cd and Pb uptake due to its prolific root architecture and biomass yield, while synergistic applications with co-catalysts or amendments have shown promise in enhancing remediation kinetics. The inclusion of fast-growing, fibrous-rooted *B. vulgaris* further broadens the scope of phytotechnological interventions in multi-metal contaminated matrices. This synthesis underscores the evolving paradigm of phytoremediation as a viable, integrative approach for sustainable soil restoration in heavy metal-polluted environments.

Keywords: Metal, Phytoremediation, Soil, Detoxification, Catalysts, *Medicago sativa*, *Tagetes erecta*, *Helianthus annuus*, *Brassica juncea* and *Bambusa vulgaris*

Introduction

Recently heavy metal is a global concern due to its impact on human health, and it has harsh effect on Soil and water both. Anthropogenic activities like factories and urbanization continue to grow, hence, toxins are released into the environment unchecked and have no known cure. Among many environmental contaminants, heavy metals are significant because human activity is constantly raising their quantities in the soil and water. Both

natural weathering processes of parent materials and man-made sources, including waste disposal, industrial and energy production, traffic emissions, vehicle exhaust, and the fertilizers used in agriculture denature land area and the crops associated to it. (Fig 1). Overabundance of metal contaminants that are deposited on soils can change and travel to flora, where they can make their way up the food chain to animals and humans.

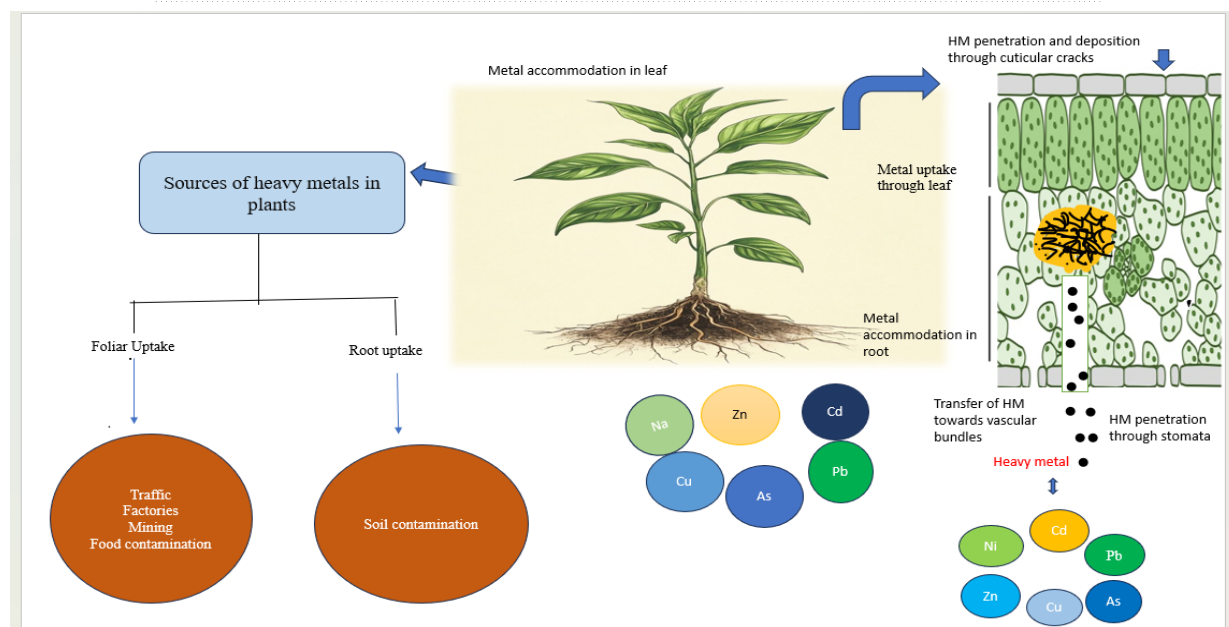
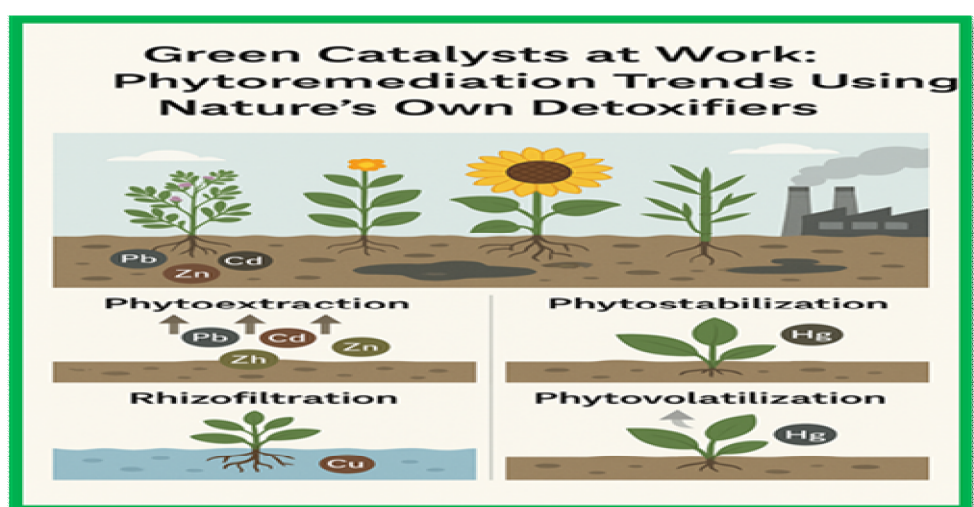


Fig1: Illustrating different sources of Heavy Metal in Plants, their translocation, penetration and deposition through cuticular cracks.

Over exposure to heavy metals can harm organisms and plants by interfering with metabolic processes of essential glands and organs. Additionally, they disrupt the biological function of the essential dietary minerals by displacing them from their natural location (Timothy and Williams, 2019)

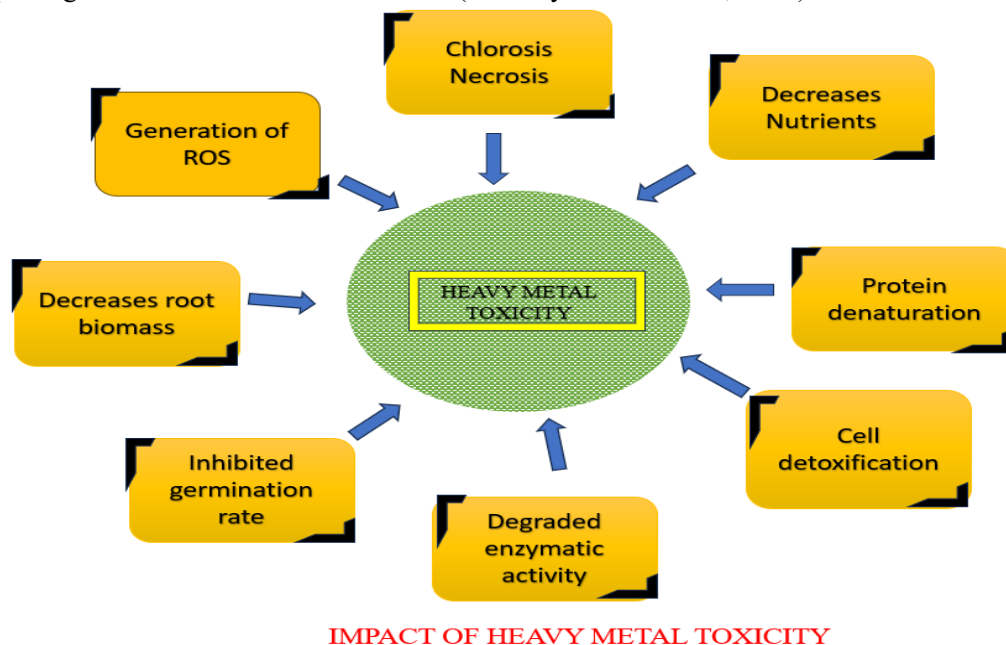


Fig2: Impact of Heavy Metals toxicity on different part of plants externally as well as internally.

The Basic Mechanism of Phytoremediation:

Phytoextraction: This involves the uptake of heavy metals from the soil by plant roots and their subsequent translocation and accumulation in the harvestable parts of the plant, primarily the shoots. Plants known as "hyper-accumulators" are particularly adept at this process, accumulating exceptionally high concentrations of metals without showing toxicity symptoms. After harvest, the contaminated plant biomass can be safely disposed of or even used for "phyto-mining" to recover valuable metals.

Phytostabilization:

In this method, plants immobilize heavy metals in the soil, typically within the rhizosphere (the soil immediately surrounding the roots), reducing their mobility and bioavailability. This can occur through adsorption to root surfaces, precipitation within the soil, or conversion of the metals into less toxic forms. Phytostabilization is crucial for

preventing the spread of contaminants through leaching into groundwater or airborne dust. (Mahar *et al.*, 2016).

Rhizofiltration:

Specifically applied to aquatic environments, rhizofiltration uses plant roots (especially those of aquatic or wetland plants) to absorb and adsorb heavy metals from contaminated water bodies. The extensive root systems act as natural filters, trapping pollutants and preventing their further dispersal.

Phytovolatilization:

This less common mechanism involves the uptake of certain heavy metals (like mercury or selenium) by plants and their subsequent conversion into a gaseous form, which is then released into the atmosphere through transpiration. While effective, concerns exist regarding the potential for airborne

redeposition of these volatile compounds (Singh and Prasad, 2015)

Green Catalyst as emerging Agents in Phytoremediation

Green Catalysts are environmentally benign materials derived from natural sources or designs to mimic biological processes, offering an eco-friendly approach to enhance phytoremediation. These catalysts, including plant-based bio-nanomaterials, enzymes, and plant exudates, play a pivotal role in accelerating the detoxification and breakdown of heavy metals and organic pollutants in contaminated soils. Green catalysts promote redox reactions, chelation, or transformation of toxic substances without generation harmful by-products. In phytoremediation, they either directly enhance the plant's uptake ability or improve soil properties to facilitate remediation (Ali *et al.*, 2013). For instance, biochar a carbon rich material derived from the pyrolysis of biomass- acts both as a green catalyst and a soil amendment. It improves soil structure, enhances microbial activity, and immobilizes heavy metals, thereby supporting plant growth and phytoremediation (Beesley *et al.*, 2011).

Several plant species such as *Medicago sativa* (alfalfa), *Tagetes erecta* (marigold), *Brassica juncea* (Indian mustard), *Helianthus annuus* (Sunflower), and *Bambusa vulgaris* produce organic acids, flavonoids, and enzymes that function as natural green catalysts. These substances improve metal solubilization, transport, and sequestration in plant tissues. *Brassica juncea* is known to secrete glutathione and phytochelatin that chelate heavy metals like Cd and Pb (Majdoub, 2020). Biogenic nanoparticles synthesized using plant extracts (green synthesized nanomaterials) are emerging a hybrid green catalysts. These Nano catalysts enhance contaminant degradation and promote rhizosphere interactions without introducing synthetic chemicals. For example, iron oxide nanoparticles derived from *Azadirachta indica* leaf extracts improve the phytoremediation of Cr (VI) and As

(V) (Sharma *et al.*, 2021). Green catalyst also modulate microbial communities in the rhizosphere, Bio-organic amendments like vermicompost, humic substances and compost tea act synergistically with plant roots and soil microbes to accelerate biotransformation process (Glick, 2010).

The impact of green catalysts extends beyond environmental benefits to encompass economic advantages as well. By reducing energy consumption, minimizing waste, and often enabling higher yields and purities, green catalytic processes can lead to significant cost savings. Moreover, the production of safer and more sustainable products can open up new markets and enhance a company's reputation, contributing to long-term economic viability. (Chen *et al.*, 2004).

Advance Strategies in Heavy Metal remediation

Emerging trends in heavy metal phytoremediation extend beyond the selection of individual plant species, researchers are increasingly exploring:

1. **Assisted Phytoremediation** which involves the use of amendments such as chelating agents (e.g., EDTA, EDDS), organic acids, or plant growth-promoting rhizo-bacteria (PGPR) to enhance metal bioavailability and uptake by plants. While chelating agents can improve efficiency, their potential environmental impact needs careful consideration (Guo *et al.*, 2020).
2. **Genetic Engineering and Plant Breeding:** Advances in biotechnology allow for the genetic modification of plants to enhance their metal tolerance, uptake capacity, and translocation efficiency. This opens avenues for creating "designer" hyperaccumulators tailored to specific contaminants and environmental conditions (Guan *et al.*, 2008).
3. **Rhizosphere Engineering:** Understanding and manipulating the complex interactions between plant roots, soil microorganisms, and heavy metals in the rhizosphere is crucial. Promoting beneficial microbial communities can significantly enhance phytoremediation

efficacy through processes like biosorption, biotransformation, and improved nutrient cycling (Ma *et al.*, 2016).

4. **Integrated Remediation Strategies:** Combining phytoremediation with other green technologies, such as bioremediation or myco-remediation, can offer more comprehensive and effective solutions for highly contaminated sites (Lux *et al.*, 2011).

Plant Species having Phytoremediation Potential

Some Plants offering great option for Heavy Metal Remediation in Soil:

Tagetes erecta, or the Mexican/Aztec marigold, has gained attention for its considerable potential in detoxifying cadmium (Cd) and copper (Cu) from contaminated soils. This ornamental plant exhibits strong metal tolerance and can accumulate substantial amounts of these metals in its above-ground tissues. Its ability to activate various stress-mitigation strategies, including antioxidative enzyme systems allows it to thrive in phytotoxic

S.No.	Plant Species	Metal accumulation plant part	Mode of Phytoremediation	Reference
1.	<i>Acanthus ilicifolius</i>	Roots, leaves	Phytostabilization, Rhizofiltration	Qiu <i>et al.</i> , 2011
2.	<i>Alternanthera philoxeroides</i>	Roots, stem	Rhizofiltration, Phytoextraction	Liu <i>et al.</i> , 2010
3.	<i>Arabis paniculata</i>	Roots leaves	Phytoextraction	Sun <i>et al.</i> , 2009
4.	<i>Bidens pilosa</i>	Roots, shoots	Phytoextraction	Wu <i>et al.</i> , 2010
5.	<i>Brassica juncea</i>	Roots, Shoots. leaves	Phytoextraction, Phytostabilization	Bartoli & Baron, 2022
6.	<i>Cynodon dactylon</i>	Roots, leaves	Phytostabilization, Phytoextraction	Tangahu <i>et al.</i> , 2011
7.	<i>Digitaria sanguinalis</i>	Shoots, Roots	Phytoextraction	Nowack <i>et al.</i> , 2006
8.	<i>Lupinus albus</i>	Roots	Rhizofiltration, Phytostabilisation	Evangelou <i>et al.</i> , 2007
9.	<i>Lupinus uncinatus</i>	Roots	Phytostabilization, Rhizofiltration	Manousaki & Kalogerakis, 2011
10.	<i>Picea abies</i>	Root	Phytostabilization	Gall <i>et al.</i> , 2015
11.	<i>Populus cathayana</i>	Root	Phytostabilization Rhizofiltration	He <i>et al.</i> , 2011
12.	<i>Quercus ilex</i>	Roots	Phytostabilization	Madejón <i>et al.</i> , 2006
13.	<i>Setaria plicata</i>	Roots, shoots	Phytostabilization, Phytoextraction	Bai <i>et al.</i> , 2015
14.	<i>Silphium perfoliatum</i>	Roots, shoots	Phytostabilization	Soleimani <i>et al.</i> , 2010
15.	<i>Solanum nigrum</i>	Roots, leaves	Phytoextraction	Wei <i>et al.</i> , 2004
16.	<i>Solanum xanthocarpum</i>	Root, stem, leaves	Phytoextraction	Chen <i>et al.</i> , 2010
17.	<i>Sorghum bicolor</i>	Roots, leaves	Phytoextraction	Chen <i>et al.</i> , 2014
18.	<i>Spinacia oleracea</i>	Leaves	Phytoextraction	Pandey & Singh 2015
19.	<i>Thlaspi caerulescens</i>	Leaves, Roots	Phytoextraction (Zn, Cd hyper-accumulator)	Zhao <i>et al.</i> , 2002
20.	<i>Typha latifolia</i>	Roots, Rhizomes	Rhizofiltration, Phytostabilization	Vymazal, 2011

Table 1: Plants having Potential for Phytoremediation

environments, making it a valuable candidate for phytoextraction. It has been identified as an

effective phytoextractor for Zn and Cd, while acting as an excluder for Pb in certain soil types. The plant's ability to accumulate these metals in its aerial parts means that once the plant matures, the contaminated biomass can be harvested and disposed of safely, effectively removing the metals from the soil system (Deepika *et al.*, 2023). The aesthetic appeal of *Tagetes erecta* also offers an added benefit, promoting the "greening" of remediation sites. (Tangahu *et al.*, 2011)

Helianthus annuus, the common sunflower, is another robust plant known for its rapid growth and high biomass, making it an excellent candidate for phytoextraction. Sunflowers have shown significant efficacy in remediating a range of heavy metals, including cadmium (Cd), lead (Pb), and zinc (Zn), from both aquatic and soil environments. Its deep and widespread root system to absorb heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), arsenic (As), and nickel (Ni) from the soil and transport them to its above-ground parts, including stems and leaves. Recent advancements have explored enhancing its remediation potential through the application of chelating agents like EDTA and plant hormones such as IAA, which can significantly boost metal uptake and translocation to harvestable parts. The ability of *Helianthus annuus* to accumulate high levels of metals while maintaining substantial biomass makes it particularly appealing for large-scale applications (Alaboudi *et al.*, 2018).

Brassica juncea, or Indian mustard, is a well-established and widely investigated hyper-accumulator, particularly effective in the phytoextraction of heavy metals such as arsenic (As), copper (Cu), nickel (Ni), cadmium (Cd), mercury (Hg), and lead (Pb) (Pathak *et al.*, 2013). Its robust growth, high biomass, and efficient translocation of metals to shoots make it a cornerstone of phyto-remediation research. Mechanistic studies have elucidated its various strategies, including the production of metal-binding proteins like phytochelatins and metallothioneins, which play crucial roles in metal detoxification and sequestration. The adaptability of *Brassica juncea*

to diverse environmental conditions further solidifies its position as a leading green catalyst in soil detoxification. (Singh *et al.*, 2022)

Medicago sativa, commonly known as alfalfa, stands out as a "green alchemist" with significant potential in metal phytoremediation and soil detoxification. Due to high production of *Medicago sativa* which is perennial plant, is largely used for phytoremediation. It does not require any particular culture treatments during its growth cycle and can be harvested several times (Gou *et al.*, 2020). Its high biomass production facilitates the removal of substantial amounts of accumulated metals when harvested. Alfalfa has capacity to accumulate various heavy metals, including lead (Pb), cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn), often with higher concentrations observed in the roots than in the shoots, indicating a degree of phytostabilization as well (Wang *et al.*, 2015). Ongoing research, particularly in genetic engineering, continues to unlock its full potential, paving the way for a greener and healthier future for our soils (Li *et al.*, 2020).

Bambusa vulgaris, a fast-growing bamboo species, has emerged as a promising green catalyst for phytoremediation and soil detoxification, especially in areas contaminated with heavy metals. Its remarkable remediation potential stems from a unique combination of physiological and ecological traits, including a deep and extensive root system, rapid growth, high biomass yield, and tolerance to environmental stresses. Unlike many traditional plants, *Bambusa vulgaris* exhibits both phytoextraction and phytostabilization capabilities, making it a multifaceted tool for remediating degraded lands. Its fibrous root system efficiently uptakes metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), copper (Cu), and nickel (Ni) from the soil matrix. These elements are subsequently translocated to the culms and leaves (Yiping *et al.*, 2010; Singh *et al.*, 2022). In addition to phytoextraction, *Bambusa vulgaris* also plays a crucial role in phytostabilization, where heavy metals are immobilized within the

rhizosphere (Kumar & Maiti, 2015). These microbes, supported by bamboo root exudates, enhance the degradation of organic pollutants and indirectly improve the bioavailability of metals for uptake. EDTA and PGPR have also found to be increasing its efficiency of remediation (Choudhury *et al.*, 2018). Post-harvest, the contaminated bamboo biomass can be processed for biochar production or other safe bioenergy alternatives, thereby converting waste into a resource while ensuring that heavy metals do not re-enter the environment (Rai *et al.*, 2021). This circular approach makes bamboo a sustainable and eco-friendly tool in the broader framework of soil restoration and green remediation.

Conclusion:

The integration of green catalysts, particularly phytoremediators such as *Tagetes erecta*, *Medicago sativa*, *Helianthus annuus*, *Brassica juncea* and *Bambusa vulgaris*, into environmental remediation frameworks represents a transformative advance in sustainable soil detoxification strategies. Owing to their exceptional physiological attributes—rapid biomass accumulation, extensive rhizosphere development, and a demonstrated capacity for both phytoextraction and phytostabilization. They exemplify the potential of plant-based systems to remediate heavy metal-contaminated environments while concurrently contributing to soil regeneration and resource valorization. As interdisciplinary research continues to elucidate the complex plant-metal interactions and optimize biotechnological interventions, the scalability and efficiency of such phytotechnologies are expected to improve significantly. Nevertheless, challenges in field-level implementation, lifecycle sustainability, and regulatory integration underscore the need for continued innovation, comprehensive environmental assessments, and supportive policy frameworks. Ultimately, the adoption of green catalytic systems heralds a paradigm shift toward ecologically consonant remediation, aligning technological advancement

with environmental stewardship and forging a viable path toward planetary health and resilience.

Challenges & Future Perspective

There are several challenges which can interfere with large-scale implementation of plants for soil remedial processes. One of the primary limitations is that phytoremediation is a time-intensive process, often requiring multiple growing cycles to achieve effective decontamination. Additionally, many phytoremediator species possess shallow root systems, restricting their ability to remediate deeper soil layers where heavy metals often accumulate. The effectiveness of phytoremediation is also heavily influenced by environmental variables such as soil texture, pH, organic matter content, and climatic conditions, which can vary significantly across sites. Another critical issue is the safe disposal of biomass after metal uptake, as improperly managed plant residues can lead to secondary pollution. Moreover, most phytoremediation species exhibit metal-specific uptake capabilities, limiting their efficiency in sites contaminated with multiple heavy metals. But economically, phytoremediation is relatively low-cost remedial approach more suiting to the environment and also human inhabitation. Proper policy support, public awareness, and biotechnological interventions can prove it to be most beneficial alternative to remove heavy metal toxicity from soil and block the chain of bio-accumulation.

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Author Contribution

The corresponding author, Dr. Tulika Mishra is working in the area of Phytoremediation and Medicinal plants, with an experience of about 21 years and has published many research and review papers in this area. She has conceptualized the

study and edited the entire work. Mr. Raj K. Pandey, Ms. Rajkumari Maurya and Ms. Pragati Pandey are pursuing their Ph.D. Degree under the guidance of the corresponding author from the Department of Botany, D. D. U Gorakhpur University, Gorakhpur (U.P.), India and their areas of thrust are also related to Phytoremediation and Medicinal Plants.

Conflict of Interest:

There is no conflict of interest.

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