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# Bioremediation: A Sustainable Solution for Heavy Metal-Contaminated Soils in Indian Agriculture

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Heavy metal contamination of agricultural soils is becoming an increasing concern in India, mainly due to mining activities, industrial discharge, excessive use of agrochemicals and rapid urbanisation. Cadmium, lead, chromium, nickel and zinc have all been found to build up in agricultural soils in several agro-ecological areas, causing concern regarding soil health, crop production and food safety. Although conventional physical and chemical remediation methods can effectively remove or immobilise these metals, their high cost, energy requirements and potential damage to soil structure make them difficult to apply on working farms. Bioremediation uses plants, microorganisms, fungi, biochar and earthworms. These organisms and materials help reduce heavy metal contamination. They can remove, transform or immobilise metals in soil. Such methods support the recovery of contaminated agricultural soils. They are also relatively affordable for farmers. Their application can fit existing farming practices. This makes them suitable for Indian agricultural conditions.

**Keywords:** Heavy metals, Bioremediation, Soil health, Sustainable agriculture, Phytoremediation

## Heavy metal poisoning: Hidden crisis beneath India's soil

Indian agriculture has come a long way over the decades, and that journey has done a lot to keep the country's food security on solid ground. The variety of soils in India includes the fertile alluvial areas of the Indo-Gangetic Plains, the black cotton soils of the central part of the country, the lateritic soils of the peninsula, and the arid soils typical of the western region. Pollutants from human activity keep piling into the soil and over time this is wearing away at its health. Heavy metals such as lead, cadmium, chromium, nickel and zinc are present at increasing levels in the agricultural soils of Punjab, Haryana, Uttar Pradesh, Delhi, the industrial belts of Maharashtra and Gujarat and the Odisha and Jharkhand mining regions. Heavy metals originate from the sources of mining, industries, untreated sewage, pesticides and fertilizer, automobile emissions and the combustion of fossil fuels (Naidu *et al.*, 2025). Many organic pollutants eventually break down by themselves, but heavy metals do not decompose and therefore remain in the soil once they have got there, often for decades. Over time, they build up in the soil and work their way into plants through the roots, stems and leaves. The gradual and quiet build-up of metals and metalloids has now become one of the most neglected dangers affecting Indian agriculture at present.

### Reckoning of heavy metals on life above the ground

The threat does not only affect the agricultural landscapes but also interferes with the plants metabolism. It damages cellular structures, inhibits enzyme activity and causes oxidative stress by disrupting essential physiological and biochemical processes (Rashid *et al.*, 2023).Plants shows the characteristic features of chlorosis, black darkened roots, stunted growth, poor flowering and seed setting ultimately leading to decreased yield and quality. The danger increases even further when the heavy metal builds up in edible parts of plants that are eaten by both humans and animals. Not only does its presence in food put agricultural sustainability at risk but also public health, so that the issue is all the more serious for Indian agriculture at present (Zhou *et al*., 2019; Weerasundara *et al*., 2017). To better understand the multifaceted impact of heavy metal damage, Figure1 illustrates the key mechanisms and visible symptoms associated with heavy metal-induced stress in plants.

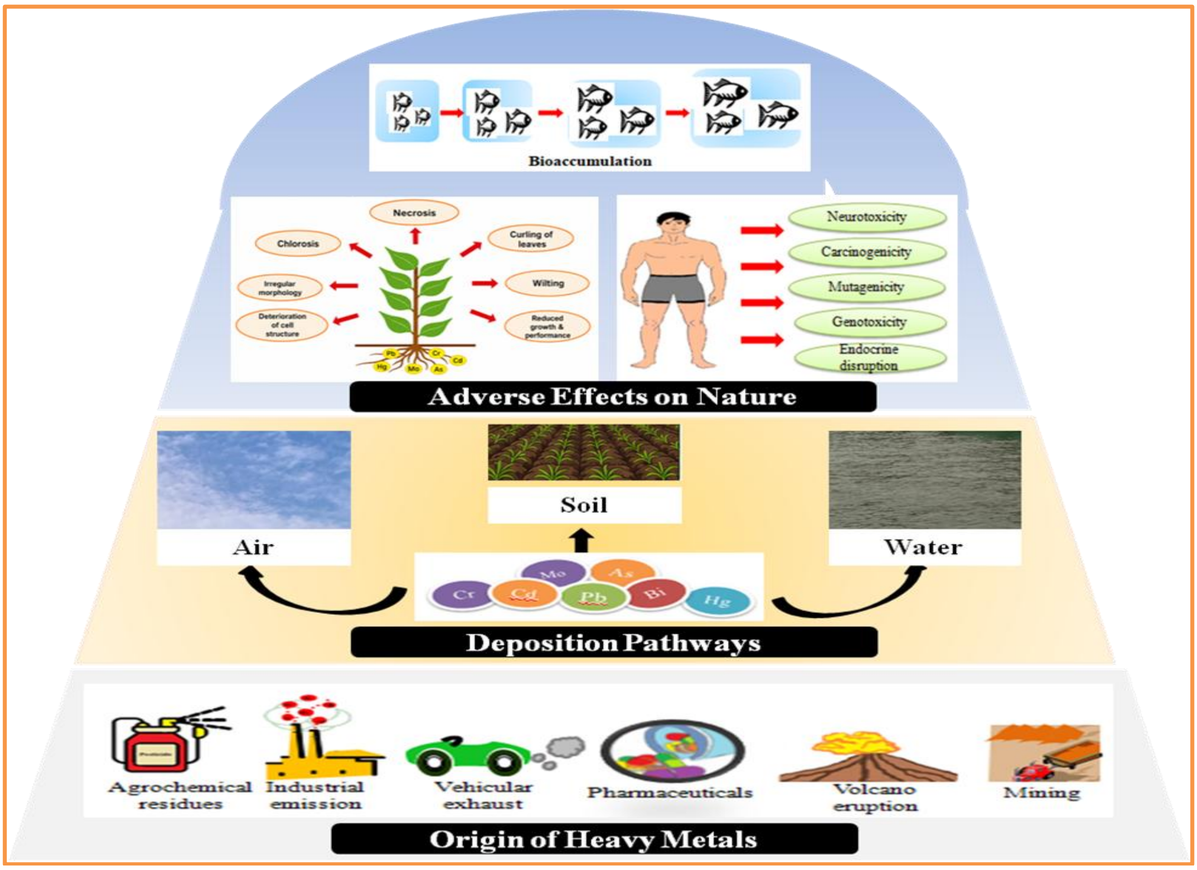


**Figure 1. Sources, pathways and impacts of heavy metal contamination**

## Limit of conventional cleanup

Conventional remediation methods such as excavation, soil washing, chemical stabilization and thermal or electrokinetic treatments, can remove or immobilize heavy metals from contaminated soils. However, these approaches are often expensive, energy-intensive and dependent on specialized equipment and technical expertise. There are several methods which consist of removing and moving the contaminated soil, a process that can disrupt farmland and result in more waste; other techniques simply immobilize the metals rather than getting rid of them altogether, while some of the treatments might also have a detrimental effect on the structure of the soil and on its biological activity, thus lowering the soil's long-term productivity (Sánchez-Castro *et al*., 2023; Dhaliwal *et al*., 2020). In India, over 85% of farmers work on small and marginal landholdings incapable to utilize these conventional remedies due to their expensive or impractical nature, showing the need for affordable, sustainable and soil-friendly alternatives.

## Bioremediation: The living cure to toxic legacy

These limitations have encouraged greater interest in sustainable, cost-effective and environmentally friendly alternatives. Bioremediation is one of the processes that have been considered as an ideal option for cleaning up heavy metal contamination in farmland soils (Koshlaf and Ball, 2017). In contrast, microbial bioremediation involves the use of naturally occurring bacteria present in the soil belonging to the genus *Bacillus* and *Pseudomonas* that are capable of converting hazardous metals such as chromium, mercury and arsenic to less mobile or hazardous forms (Ayilara & Babalola, 2023). Although bioremediation generally takes longer than chemical treatments, it is relatively inexpensive and can be more compatible with soil health. Bioremediation is often possible without the need to take farmland out of production. It is thus a realistic solution for Indian agriculture through the enhancement of soil health as well as crop production.

Bioremediation has different approaches, each of which is based on a specific biological process to reduce heavy metal pollution (Table 1). Phytoremediation uses plants capable of taking up and accumulating high concentrations of metals in their tissues. Indian mustard (*Brassica juncea*), sunflower (*Helianthus annuus*) and the arsenic-hyperaccumulating fern *Pteris vittata* can absorb metals through their roots and accumulate them in shoots and leaves. The contaminants can then be removed from the field by harvesting the metal-rich biomass (Ali *et al*., 2013). Microbial bioremediation, in contrast, takes advantage of naturally occurring bacteria that are found in the soil and belong to the genus of *Bacillus* and *Pseudomonas*, and that have the ability to transform hazardous metals like chromium, mercury and arsenic to a state that is less mobile or hazardous.Mycoremediation uses fungi such as *Aspergillus niger* and *Pleurotus* species. Their extensive fungal networks can bind, accumulate or immobilize heavy metals and may remain effective even under acidic or otherwise degraded soil conditions (Javaid *et al*., 2011).

**Table 1. Bioremediation methods for heavy metal–contaminated soils and their suitability**

| Method | Key organisms/agents | Target heavy metals | Farmer's advantage |
|---|---|---|---|
| Phytoremediation | Indian mustard, sunflower, *Pteris vittata* (fern) | Cd, Pb, As, Zn, Ni | Cheap; crop can double as green cover; improves soil |
| Microbial remediation | *Bacillus*, *Pseudomonas* spp. | Cr, Hg, As, Pb | Works in situ; low cost; suited to large fields |
| Mycoremediation | *Aspergillus niger*, Pleurotus spp. | Cd, Pb, Cu, Hg, Zn | Tolerates acidic, poor-quality soils |
| Rhizoremediation | Plant-microbe consortia (*Pseudomonas*, *Rhizobium*) | Pb, Cd, Ni, Zn | Boosts fertility while cleaning soil |
| Biochar-assisted remediation | Pyrolysed crop residue + native microbes | Pb, Cd, As, Cu, Zn | Converts farm waste into a useful input; improves pH |
| Vermiremediation | *Eisenia fetida* (earthworm) | Cd, Pb, Cu, Zn | Simplest, lowest-cost option; adds organic matter |

Biological remediation works better when organisms interact with each other. Rhizoremediation is a synergistic technique of heavy metal management involving plant roots and beneficial rhizosphere microbes. Root exudates can increase metal availability, while microbes help immobilise, transform or take up these metals and, at the same time, contribute to better soil fertility (Ilyas *et al*., 2024). Biochar-assisted remediation adds to these biological processes by adding biochar produced from crop residues or other agricultural waste to contaminated soils. Biochar adsorbs heavy metals and decreases their bioavailability. It can at the same time raise the pH of the soil and its capacity to hold water, as well as offer a suitable habitat for beneficial microorganisms. This makes biochar a useful way of turning agricultural waste into a valuable soil amendment (Chen *et al*., 2024). Vermiremediation with earthworms such as *Eisenia fetida* adds another biological component in that it improves soil structure, stimulates microbial activity and reduces the amount of heavy metals available for take-up by plants (Panda & Bhatta, 2014). All of these methods demonstrate that bioremediation is not merely a single technology but an integrated, nature-based one; it is able to help in the restoration of contaminated soils while at the same time supporting long-term crop production and environmental health.

Bioremediation allows for the restoration of polluted soils, especially heavy metal polluted soils, while ensuring the balance that is essential for sustainable agriculture. Traditional methods of restoration disrupt soils and create a lot of infrastructure. They often also take long periods of time to restore soils. Bioremediation harnesses natural processes to remove pollutants. Most key steps happen where the pollution is and require little site preparation and disturbance. Many crop growing and soil restoration techniques are mostly incompatible with each other, but bioremediation allows both to happen in concert with little disturbance to the farming activities. Additionally, bioremediation decreases heavy metal contamination by supporting the growth of microorganisms and beneficial fungi, which can improve soil structure and the soil's ability to hold water and nutrients. There are many benefits to supporting the growth of microorganisms and beneficial fungi by adding biochar and compost to soil. All of these improvements also make for better growing conditions for crops. Bioremediation uses much less energy than other remediation techniques, so the environmental impact is much smaller. Bioremediation most likely can be integrated into traditional farming techniques, which also makes it much easier to implement. This makes bioremediation even more valuable for supporting the health of farm soils, improving crop safety, and improving sustainability of Indian agriculture.

## Summary

Indian agriculture is facing serious issues concerning heavy metal contamination which are affecting soil health, crop productivity and food safety. Heavy metal contamination remediation is costly with potential constraints, and resources that limit their adoption on agricultural lands. Bioremediation is a more economical and sustainable solution for heavy metal contamination. Bioremediation uses the capability of plants, microbes, fungi, biochar and earthworms to add beneficial services to remove heavy metal contamination and enhance soil fertility and crop productivity. These services are sustainable, low cost and may be adopted for use with existing farming practices. Bioremediation offers a lot of potential for returning abandoned and impacted farmlands from heavy metal contamination, and protecting India's agriculture. Sustainable remediation technologies hold the potential for ongoing safe food production and maintaining productive farms of the future.

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