



Review Article

Volume-06|Issue-04|2026

Structural Effect and Mechanism of Heavy Metal on Plant Growth

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Article History

Received: 20.06.2026

Accepted: 08.07.2026

Published: 10.07.2026

Citation

Mishra, R. S. & Sharma, A. (2026). Structural Effect and Mechanism of Heavy Metal on Plant Growth. *Indiana Journal of Multidisciplinary Research*, 6(4), 6-11.

Abstract: Heavy metal contamination has become one of the most serious environmental challenges affecting agricultural productivity and ecosystem sustainability worldwide. While essential heavy metals such as iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo), and nickel (Ni) are required in trace amounts for normal plant growth and metabolic processes, their excessive accumulation causes severe physiological, biochemical, and molecular disturbances in plants. Toxic heavy metals including cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), and chromium (Cr) adversely affect seed germination, photosynthesis, nutrient uptake, respiration, enzyme activity, and overall plant development, resulting in reduced crop productivity and potential risks to human health through the food chain.

The present review aims to summarize the structural effects, toxicity mechanisms, uptake pathways, and tolerance strategies of heavy metals in plants. Information presented in this review has been compiled from published scientific literature, books, and peer-reviewed research articles available through recognized scientific databases. The review discusses the major sources of heavy metal contamination, their physiological and biochemical impacts on plants, metal uptake and translocation mechanisms, chelation by phytochelatins and metallothioneins, hyperaccumulation, and plant adaptive responses under heavy metal stress. Furthermore, recent advances in phytoremediation and eco-friendly approaches for mitigating heavy metal toxicity are highlighted.

The review concludes that improving our understanding of heavy metal uptake, detoxification mechanisms, and stress tolerance strategies is essential for developing sustainable agricultural practices and enhancing crop resilience in contaminated environments. Future research should focus on integrating molecular biology, biotechnology, and precision agriculture to improve heavy metal tolerance and ensure environmental and food safety.

Keywords: Heavy metals, Plant growth, Heavy metal toxicity, Phytochelatins, Metallothioneins, Phytoremediation, Stress tolerance, Hyperaccumulation.

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INTRODUCTION

Environmental contamination by heavy metals has become a global concern due to rapid urbanization, industrialization, mining activities, and other anthropogenic sources, resulting in both short-term and long-term adverse effects on ecosystems (Kumar *et al.*, 2015; Khanna *et al.*, 2018). Heavy metals such as aluminum (Al), arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) are among the major environmental pollutants affecting soil and water quality (Kumar *et al.*, 2016, 2017). Heavy metals are generally defined as metallic elements with a specific gravity greater than 5 g/cm³ (Khanna *et al.*, 2018).

Plants growing in heavy metal-contaminated soils exhibit significant physiological, biochemical, and molecular alterations, including impaired nutrient uptake, reduced photosynthesis, disrupted respiration, altered gaseous exchange, oxidative stress, and inhibited growth. The extent of heavy metal toxicity depends on

several factors, including the plant species, the type and concentration of the metal, its chemical form, duration of exposure, and the physicochemical properties of the soil. Excessive accumulation of heavy metals ultimately affects plant growth, development, productivity, and overall ecosystem health.

REVIEW METHODOLOGY

This review was conducted using a systematic literature search and qualitative analysis of published scientific studies on the structural effects and mechanisms of heavy metals on plant growth. Relevant literature was collected from internationally recognized scientific databases, including Google Scholar, Scopus, Web of Science, PubMed, and ScienceDirect. Peer-reviewed research articles, review papers, book chapters, and reports published primarily between 2000 and 2024 were considered to ensure comprehensive and up-to-date coverage of the subject.

The literature search was performed using combinations of keywords such as "heavy metal toxicity

in plants," "plant heavy metal uptake," "heavy metal stress," "phytochelatins," "metallothioneins," "phytoremediation," "heavy metal accumulation," "plant tolerance mechanisms," and "metal transport in plants." Only English-language publications with relevant scientific content were included in the review.

Articles focusing on the physiological, biochemical, molecular, and ecological effects of heavy metals on plants were selected for detailed analysis. Studies with insufficient scientific evidence, duplicate publications, conference abstracts without full-text availability, and non-peer-reviewed sources were excluded. The selected literature was critically evaluated to identify the major sources of heavy metal contamination, mechanisms of metal uptake and translocation, toxicity symptoms, detoxification pathways, chelation mechanisms involving phytochelatins and metallothioneins, hyperaccumulation, and recent advances in phytoremediation technologies.

The collected information was synthesized and organized thematically to provide a comprehensive understanding of heavy metal toxicity, plant defense mechanisms, and sustainable approaches for mitigating heavy metal stress in agricultural ecosystems.

Role and sources of heavy metals in plants

Different heavy metals play a vital role in nature as they are essential for the plant's normal growth. Important heavy metals such as Cu, Zn, Fe, Mn, Mo, and Ni play important roles in plant biochemistry and physiology (Zhuang *et al.*, 2009). As essential micronutrients, Cu and Zn are very important for normal plant growth as they either serve as an enzyme reaction cofactor and activator or exert a catalytic property in metal lo proteins such as a prosthetic group. These crucial heavy metals also involve redox reactions, transferring electrons, basic functions in nucleic acid metabolisms, and being an integral part of several enzymes as a direct participant. The availability at a certain concentration of these essential metals in growing medium is very important, but their excess concentration results in several toxic effects (Nagajyoti *et al.*, 2010).

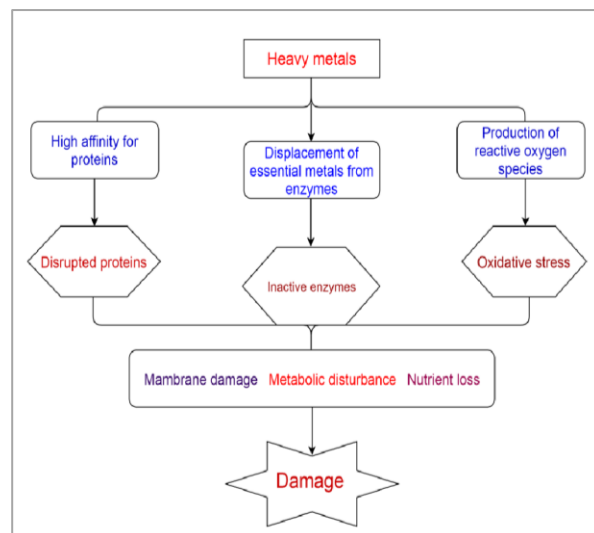


Figure 1: Summary of heavy metals induced toxicity mechanism in plants (Adopted from: Kumar *et al.*, 2016).

These heavy metals are also known as trace elements (10mg/Kg or mg/L in soil/aquatic medium) or ultra-trace elements (1µg/Kg or µg/L in soil / aquatic medium) because of their presence in the soil environment. In addition to these essential trace elements, another category of heavy metals, Class B metals, considered to be non-essential trace elements such as Hg, Ag, Pb, and Ni, etc., are in nature very toxic. The mechanism of heavy metal-induced toxicity in plants is summarized in Figure 1. In a terrestrial system, plants are stationary and their roots are the main contact sites for trace metal ions, while the entire plant body is exposed in the aquatic system and metal ions are absorbed directly from the surface soft he leaves due to particle deposition (Kibria, 2014). Plants are stationary, and plant roots for heavy metal ions are the main contact site. Because of this contact, due to the deposition of particles containing these metals, plants absorb heavy metals primarily through roots and also through the leaf surfaces. Those plants that are grown in aquatic systems face greater toxicity as the whole plant body is exposed to toxicions in this type of plant. Some heavy metals are considered essential elements for plants (Fe, Cu, Mo, and Zn). Two key functions of essential heavy metals in cells are involvement in redox reactions and being an integral part of enzymes.

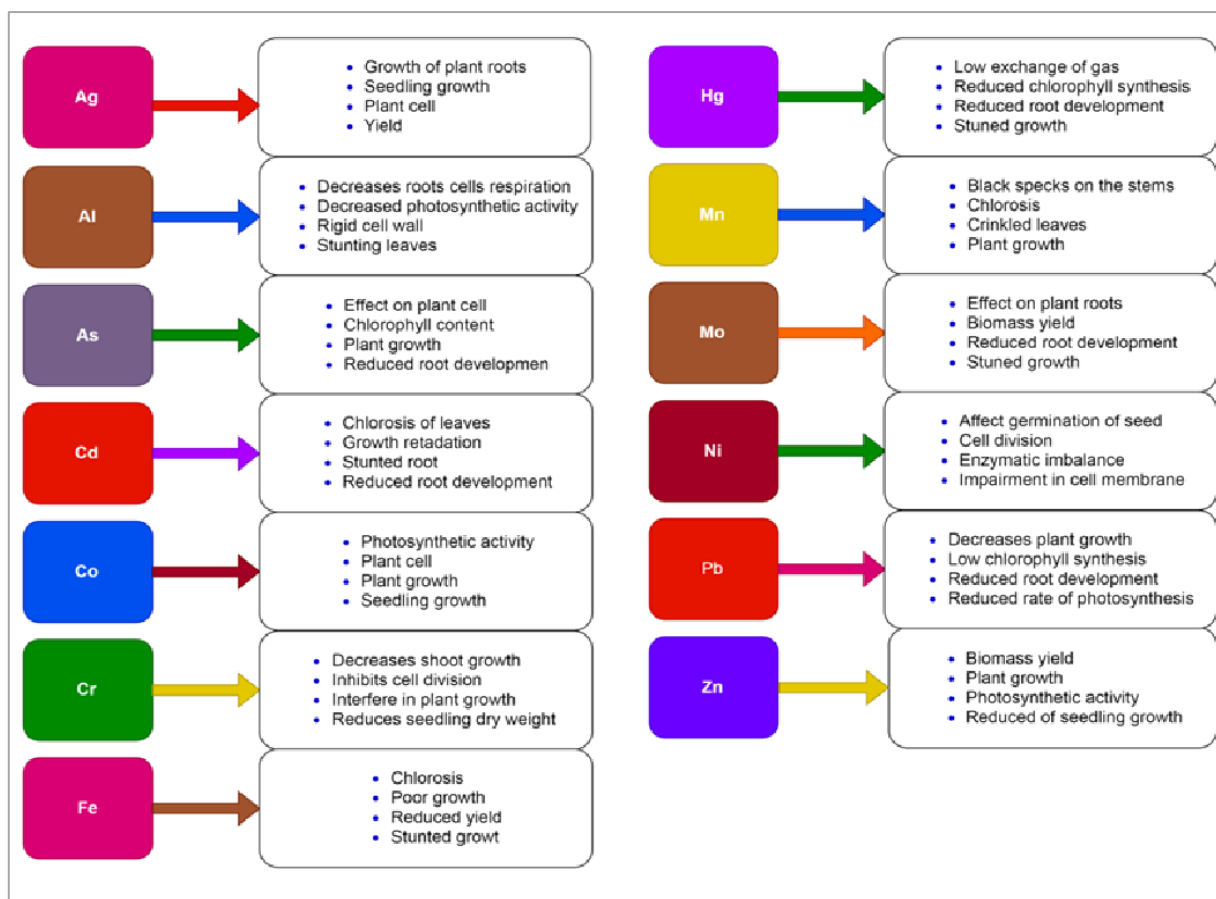


Figure 2: Heavy metal toxicity symptoms in plants (Adopted from: Kumar and Aery, 2016).

Serve as cofactors and activators of various enzyme reactions and play a vital role in the formation of enzyme–substrate metal complexes or as catalytic prosthetic groups in metalloenzymes. They participate in electron transport and structural functions in nucleic acid metabolism (Nagajyoti et al., 2010). Figure 2 shows the toxic effects of some heavy metals. Metal pollution is a worldwide issue for soil and water environments. The adverse effects of heavy metals on the growth and activities of soil microbes may also indirectly affect plant growth (Kumar et al., 2016).

Heavy metal interference with ionic homeostasis and enzyme activity affects single-organ physiological processes (such as root nutrient uptake), followed by multiple processes such as germination, photosynthesis, respiration, plant water balance, metabolism, and reproduction. Indeed, visible symptoms of heavy metal toxicity include chlorosis, necrosis, senescence, wilting, stunted growth, low biomass production, limited seed numbers, and eventually death. Plants growing under heavy metal stress must spend more energy on survival, which would otherwise be available for other physiological processes. This deficiency in the amount of energy required may result in an overall decrease in plant growth under such hostile metal-stressed environments (Kumar and Aery, 2016).

Mechanisms of Heavy Metal Chelation in Crop Plants

Chelation is a type of molecular chemical bonding involving metal ions. Heavy metal chelation is one of the primary mechanisms by which plants detoxify and tolerate high concentrations of heavy metals. Chelation occurs when a ligand binds to a heavy metal ion through donor atoms. Ligands are molecules that interact with the electronic orbitals of a central metal ion and form secondary valence bonds, resulting in the formation of stable metal complexes. High production of various metal-chelating molecules, such as organic acids, phytochelatins, metallothioneins (MTs), phytosiderophores, and ferritin, or the overexpression of metal transporter protein-coding genes, increases the tolerance and accumulation of heavy metals in plant tissues (Verkleij et al., 2003; Kumar et al., 2016).

During the chelation process, heavy metals first reach the rhizosphere, where chelation occurs both outside the plant body (extracellularly) and within plant cells (intracellularly). Several organic acids present in root exudates are responsible for the extracellular chelation of heavy metals, whereas various organic acids, amino acids, and peptides mediate intracellular heavy metal chelation within plant cells. Metal-binding proteins and peptides preferentially bind toxic metals such as Cd, Hg, Pb, and Cr while minimizing interference with essential metals such as Zn and Cu (Ryu et al., 2003; Yang et al., 2005).

Chelators can be classified into natural and synthetic chelating agents. Plants produce a variety of ligands, including citric acid, malic acid, amino acids, and sulfur-containing compounds, which form stable metal complexes. These ligands play a major role in detoxification by reducing the persistence and toxicity of heavy metals within plant tissues. Citrate is the principal ligand for Ni in *Thlaspi vingense* leaves (Krämer et al., 2000), whereas citrate and acetate bind Cd in *Solanum nigrum* leaves (Sun et al., 2006). In addition, a large proportion of Zn is complexed with malate in *Arabidopsis halleri*, while Cd is complexed in *Thlaspi caerulescens* (Sarret et al., 2002). In Se-hyperaccumulator plants, the principal detoxification strategy involves the formation of selenoamino acids, primarily selenocysteine (Se-Cys), resulting from the assimilation of selenite in leaf chloroplasts. Aluminum (Al)-induced release of organic anions such as malate, oxalate, and citrate, which chelate Al³⁺ in the rhizosphere and prevent its entry into plant roots, has been demonstrated in several plant species, including wheat, maize, buckwheat, rye, taro, and snap bean (Sors et al., 2009).

Metallothioneins and Phytochelatins

Metallothioneins (MTs) are a family of small, highly conserved, cysteine-rich metal-binding proteins that play important roles in zinc and copper homeostasis, protection against oxidative stress, and buffering of toxic heavy metals. Metallothioneins are generally classified into three types: (I) mammalian metallothioneins, consisting of 61 amino acids and lacking aromatic amino acids or histidines; (II) metallothioneins from *Candida albicans*, yeast, and cyanobacteria (Winge et al., 1985), with similar chelators found in *Saccharomyces cerevisiae*, which contribute to enhanced copper tolerance (Kägi, 1991); and (III) distinct polypeptides composed of units of γ -glutamylcysteinyl peptides.

Metallothioneins are cysteine-rich (containing more than 30% cysteine residues), low-molecular-weight (2–16 kDa), metal-binding proteins that play crucial roles in metal detoxification and homeostasis. They possess a unique ability to bind d-block metal ions through abundant cysteinyl residues present in their structure. Heavy metals such as Cd, Zn, Hg, Ag, and Pb induce metallothionein synthesis in both plants and animals. Cadmium is considered the most effective inducer of metallothionein production, followed by Ag, Bi, Pb, Zn, Cu, Hg, and Au (Kägi, 1991).

In transgenic tobacco plants expressing yeast metallothionein together with a polyhistidine cluster, Cd uptake increased significantly. Similarly, the introduction of a tobacco metallothionein gene enhanced tolerance to heavy metals such as Cd, Zn, and Ni (Macek et al., 2002; Pavlíková et al., 2004).

Phytochelatins are glutathione-derived oligopeptides synthesized by the enzyme phytochelatin

synthase. They are present in plants, fungi, nematodes, algae, and cyanobacteria. Phytochelatins function as metal chelators and are essential for heavy metal detoxification. Their general structure is $(\gamma\text{-Glu-Cys})_n\text{X}$, where X represents Gly, β -Ala, Ser, or Glu, and n generally ranges from 2 to 11, with the most common forms containing two to four peptide units. Phytochelatins are synthesized in the cytosol from glutathione-derived peptides and have been reported in monocots, dicots, gymnosperms, and algae (Cobbett and Goldsbrough, 2002).

Plants exposed to Cd stress produce approximately 2.7–3 times higher concentrations of phytochelatins than plants grown under normal conditions. Phytochelatins form PC–metal(loid) complexes that are transported into vacuoles, thereby reducing the concentration of toxic metals in the cytosol (Guo et al., 2012).

In addition to natural chelators, several synthetic chelating agents have been developed. Ethylenediaminetetraacetic acid (EDTA) is one of the most widely used synthetic chelators (Grčman et al., 2001). EDTA binds heavy metal ions, increasing their mobility and facilitating their transport across plant membranes. Application of EDTA has been reported to enhance Pb accumulation in *Brassica juncea* (L.) Czern. by 1,000–10,000 times compared with untreated plants. More recently, ethylenediaminedisuccinate (EDDS), a structural isomer of EDTA, has also been used in phytoremediation studies to improve heavy metal accumulation in plants (Grčman et al., 2003; Luo et al., 2005).

Response of Plants Towards Different Heavy Metals

Toxic heavy metals pose a serious threat to living organisms and plants because they are highly persistent and remain in the soil ecosystem for long periods. In terrestrial plants, roots are the primary sites of contact and exposure to toxic heavy metals. In aquatic plants, the entire plant body is directly exposed to metals present in the growing medium. The growing medium contains both essential and non-essential metals, which become toxic when present in excessive concentrations, resulting in the inhibition of plant growth and development and, in severe cases, plant death (Figure 3).

Plants have evolved several effective and efficient mechanisms to cope with heavy metal stress and ensure their survival. These adaptive mechanisms include immobilization, exclusion at the plasma membrane, restriction of metal absorption and transport, synthesis of specific heavy metal transporters, induction of stress proteins, chelation, and sequestration by specific ligands (Clemens, 2001; DalCorso et al., 2008; Adrees et al., 2015).

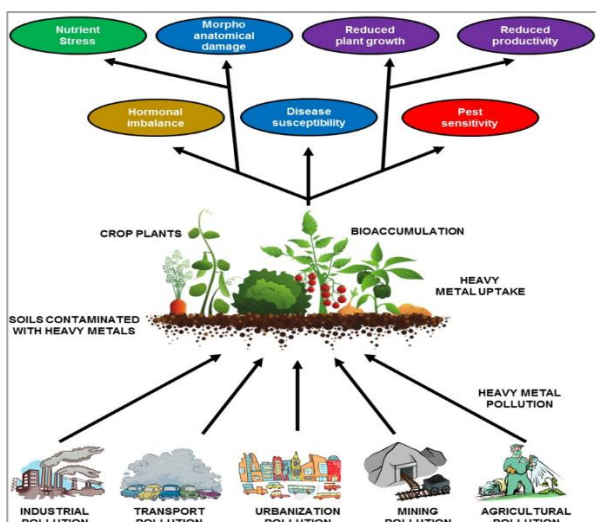


Figure 3: Response of crop plants toward different kinds of environmental pollution.

There are two major mechanisms by which plants maintain a low concentration of metal ions in the cytoplasm, thereby enhancing heavy metal tolerance. The first mechanism prevents toxic metals from being transported across the plasma membrane. This can be achieved either by increasing metal ion binding to the cell wall or by actively pumping metal ions out of the cell through membrane-bound efflux pumps. The second mechanism involves detoxification of toxic metal ions through chelation or by converting them into less toxic forms (Tong *et al.*, 2004).

Plants possess a remarkable ability to solubilize and absorb various soil nutrients by producing chelating agents and modifying rhizosphere pH and redox reactions (oxidation and reduction processes). They also have highly specific mechanisms for the uptake, translocation, and accumulation of different nutrients and metals. These mechanisms facilitate heavy metal uptake and translocation because many heavy metals possess physical and chemical properties similar to those of essential mineral nutrients (Tangahu *et al.*, 2011; Kumar *et al.*, 2017).

Metal accumulation in plants is influenced by several factors, including plant species, plant structure, growth stage, plant vigor, soil pH, root system depth, temperature, partial oxygen pressure, carbohydrate content, respiration rate, nutrient availability, and the presence of soil microorganisms (Chen *et al.*, 2006). Plants can also precipitate heavy metals by altering the pH of the rhizosphere or by releasing anions such as PO_4^{3-} . During the adsorption process, the root surface effectively binds numerous heavy metals. Metals such as Cd, Ni, Pb, and Sr are rapidly accumulated in root tissues (Hossain *et al.*, 2012).

Based on their mechanisms of adaptation to heavy metal stress, plants are generally classified into

three categories: **excluders, accumulators, and indicators**, as proposed by Baker (1981).

Hyperaccumulation of heavy metals is the process by which plants accumulate metals at concentrations exceeding 0.1–1% of their dry weight. Baker and Brooks (1989) introduced the term **hyperaccumulator** to describe plants containing more than $1,000 \text{ mg kg}^{-1}$ of nickel (Ni) in their leaves. Baker *et al.* (2000) further reported that plants accumulating more than 100 mg kg^{-1} Cd (0.01%) or more than 500 mg kg^{-1} Cr (0.05%) in dry leaf tissue can also be regarded as hyperaccumulator species.

Hyperaccumulator plants have the remarkable ability to tolerate and accumulate exceptionally high concentrations of heavy metals. Certain plant species naturally grow in heavy metal-contaminated soils and accumulate substantial quantities of metals as an ecological adaptation (Lombi *et al.*, 2002). The principal mechanisms involved in heavy metal hyperaccumulation include bioactivation of metals in the rhizosphere through root–microbe interactions, enhanced activity of metal transporter proteins in cell membranes, detoxification through apoplastic sequestration, chelation of heavy metals in the cytoplasm by various ligands, and sequestration of metal–ligand complexes into vacuoles.

Silver (Ag)

Silver (Ag) occurs in the Earth's crust and soils at average concentrations of approximately 0.06 mg kg^{-1} and 0.13 mg kg^{-1} , respectively. It is used primarily in the photographic industry and also finds applications in batteries, coins, jewelry, silverware, catalysts, brazing, and the soldering of electronic components. Silver toxicity primarily depends on the concentration of free silver ions (Ag^+), which are predominantly present in the aqueous phase. Several physicochemical characteristics of soil and water reduce silver toxicity by limiting the formation of free Ag^+ ions or by preventing their binding to reactive surfaces of living organisms.

For a long time, the toxic effects of Ag on plants grown in soil were not well documented (Khanna *et al.*, 2018). Ratte (1999) reported that approximately 5 mg kg^{-1} Ag in shoots and about $1,500 \text{ mg kg}^{-1}$ Ag in bush bean roots significantly reduced crop yield without producing visible symptoms of toxicity. Wallace *et al.* (1977) reported that Ag in the nutrient medium at a very low concentration ($10 \text{ } \mu\text{g L}^{-1}$) stimulated grass root growth. They suggested that certain cations, such as Ag, Co, and Cu, may indirectly alter cellular metabolism, thereby promoting a higher rate of cell growth. Silver can also replace K^+ binding sites in plant cells, thereby influencing various physiological and biochemical processes.

CONCLUSION

Anthropogenic activities have continuously increased the levels of various contaminants, particularly heavy metals, in agricultural soils. This review highlights the numerous toxic effects of heavy metals on plants and demonstrates that excessive metal accumulation adversely affects plant growth, development, and overall productivity. Plants respond to heavy metal stress through a range of integrated defense mechanisms, among which antioxidant defense systems play a central role in enhancing tolerance against metal-induced oxidative damage.

Heavy metals may also be absorbed by plant roots because of their ionic affinity with root enzymes and transport systems, leading to their translocation into the edible vegetative parts of crops. This accumulation poses potential health risks to humans and animals through the food chain. Therefore, effective mitigation of heavy metal contamination is essential to minimize environmental and health risks. The adoption of eco-friendly approaches, including phytoremediation, sustainable soil management practices, and continuous environmental monitoring, can significantly reduce heavy metal contamination and contribute to sustainable agricultural production and environmental protection.

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