



REVIEW

Co-Occurrence of Essential and Non-Essential Heavy Metal(loid)s in Plants: Physiological, Biochemical, and Molecular Perspectives for Soil Bioremediation

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ABSTRACT: The co-occurrence of essential and non-essential heavy metal(loid)s in agricultural soils intensifies land degradation by disrupting soil biochemical cycling, plant productivity, and ecosystem resilience. Essential metal(loid)s Zinc (Zn^{2+}), Copper (Cu^{2+}), Manganese (Mn^{2+}) and Iron (Fe^{2+}) are required as micronutrients but become phytotoxic above threshold concentrations, while non-essential metal(loid)s such as Cadmium (Cd^{2+}), Lead (Pb^{2+}), Mercury (Hg^{2+}), and Arsenic (As^{3+}/As^{5+}) have no biological function and are toxic even at trace levels. Their coexistence amplifies stress through shared transporter-mediated uptake, ionic competition, nutrient imbalance, and excessive production of reactive oxygen species. This review synthesizes current knowledge on the comparative uptake, toxicity, and detoxification mechanisms of essential versus non-essential metal(loid)s, with emphasis on co-contamination scenarios. Unresolved contradictions in the literature are identified, including concentration-dependent and species-specific interactions that determine whether metal mixtures act synergistically or antagonistically. Significant knowledge gaps remain in understanding which transporters dominate under multi-metal exposure and how plant-microbe-metal networks influence land restoration outcomes. The link between metal co-occurrence and quantitative indicators of land degradation is further advanced, covering soil enzyme suppression, microbial biomass decline, and disrupted carbon-nitrogen-phosphorus cycling. While phytoremediation and microbial-assisted strategies show promise, integration with soil physicochemical management is needed for sustainable restoration. The review concludes by proposing a systems-level framework that integrates multi-omics, CRISPR-based gene editing, and predictive modeling to develop metal-tolerant crops and remediate degraded lands under increasing environmental pressures.

KEYWORDS: Heavy metal co-occurrence; plant responses; metal interactions; oxidative stress; bioremediation; soil microbiome; nutrient uptake; land sustainability

1 Introduction

Heavy metals (HMs) comprise a diverse group of naturally occurring elements characterized by high atomic density and the ability to form cations [1,2]. They are integral to the Earth's crust and enter agricultural soils through both geogenic processes, such as rock weathering and volcanic activity, and anthropogenic activities, including mining, industrial effluents, excessive fertilizer use, and waste disposal [3,4]. Although widely used, the term “heavy metal” remains scientifically ambiguous, with no strict definition under the IUPAC framework [5]. In environmental and plant sciences, it generally refers to metals and metalloids with densities exceeding 4.5 g cm^{-3} that exhibit potential toxicity at elevated concentrations [6,7].

Based on their biological role, HMs are broadly categorized into essential and non-essential types [8]. Essential heavy metals (EHMs) such as Fe^{2+} , Zn^{2+} , Cu^{2+} , and Mn^{2+} are micronutrients required in trace amounts for enzyme activation, redox catalysis, photosynthesis, and various metabolic pathways [9,10]. However, when their concentrations exceed physiological thresholds, they induce oxidative stress and disrupt cellular metabolism [11,12]. In contrast, non-essential heavy metals (NEHMs) such as Cd^{2+} , Pb^{2+} , Hg^{2+} , and As have no known biological function and exert toxicity even at trace levels, impairing nutrient uptake, photosynthetic efficiency, and overall plant growth [9,13].

The contamination of arable soils with both EHMs and NEHMs is now a major constraint to sustainable agriculture. Sustainable agriculture refers to farming practices that maintain soil health, ensure food safety, support economic viability, and minimize environmental degradation, with specific emphasis on reducing heavy metal inputs and limiting crop uptake of toxic elements [14,15]. Beyond direct phytotoxicity, excessive metal accumulation alters soil chemical properties, disrupts nutrient availability, and impairs key biogeochemical processes governing nitrogen, phosphorus, and carbon cycling. Heavy metals can inhibit soil enzymatic activities and modify microbial community composition, thereby compromising soil functionality and long-term productivity. Their co-occurrence in soils often intensifies toxicity through competitive uptake, ionic mimicry, oxidative stress, and metabolic interference [16]. Understanding the comparative mechanisms of their uptake, translocation, and toxicity is therefore important for developing metal-tolerant crop varieties and remediation strategies [17,18]. Beyond plant-level toxicity, heavy metal accumulation in crops poses serious food safety and public health concerns due to the transfer of toxic elements such as Cd^{2+} , Pb^{2+} , and $\text{As}^{3+}/\text{As}^{5+}$ into edible tissues [19]. From an agronomic perspective, chronic metal exposure reduces crop yield, quality, and economic sustainability [20]. Yield losses manifest through reduced biomass, grain number, and fruit set, with documented reductions of 20–50% in rice and wheat at soil Cd^{2+} concentrations exceeding 3 mg kg^{-1} . Quality deterioration occurs through the accumulation of toxic metals in edible tissues (e.g., $\text{Cd}^{2+} > 0.2 \text{ mg kg}^{-1}$ in rice grains, $\text{Pb}^{2+} > 0.1 \text{ mg kg}^{-1}$ in vegetables), which compromises food safety and marketability [21]. Additionally, metal-induced nutrient imbalances (e.g., Zn^{2+} deficiency under high Cd^{2+} , Fe^{2+} chlorosis under high Mn^{2+}) lower the nutritional quality of products. Economic sustainability is affected through direct yield losses (estimated globally at \$10–50 billion annually), remediation costs (\$500–5000 per hectare for soil amendments), food safety compliance costs, and depreciation of land value in contaminated areas [22]. These dimensions are interconnected: higher metal concentrations in soil lead to greater accumulation in edible tissues, which reduces both yield and quality, thereby increasing economic losses and undermining the long-term viability of agricultural production. Moreover, metal contamination disrupts soil microbial communities and nutrient cycling, affecting long-term ecosystem stability [23]. Therefore, investigating heavy metal toxicity is essential not only for understanding plant physiological responses but also for safeguarding food security, maintaining soil function, and supporting sustainable agroecosystem management.

Unlike previous reviews that focus on single metals [7,24] or isolated mechanisms [6,25], The specific objectives of this review are: (i) to compare the uptake, transport, and toxicity mechanisms of EHMs and NEHMs under co-contamination scenarios; (ii) to identify unresolved contradictions in the literature regarding metal interactions; (iii) to link molecular-level responses to quantitative indicators of land degradation; and (iv) to evaluate current phytoremediation and soil management strategies while identifying key research gaps. The expected outcome is a systems-level framework that integrates plant physiology, soil ecology, and remediation approaches to guide the sustainable management of multi-metal-contaminated agroecosystems. The following sections provide a comprehensive overview of essential and non-essential

heavy metals, their biological functions, toxicity thresholds, uptake and transport mechanisms, interactions, and associated plant defense and remediation strategies.

Literature Search Strategy: This narrative review was developed from a comprehensive literature search conducted in the Web of Science, Scopus, and PubMed databases to identify relevant peer-reviewed studies published between 2006 and 2026. The search focused on combinations of keywords including heavy metal co-occurrence, essential and non-essential metals, phytoremediation, land degradation, plant metal uptake, soil enzyme activity, and microbial community. Articles were selected based on their relevance to the objectives of this review, particularly studies addressing metal(loid) uptake, transport, toxicity mechanisms, plant physiological and biochemical responses, molecular regulation, plant-microbe interactions, and remediation approaches under single or multi-metal exposure conditions. Only English-language research articles and review papers directly related to plant-soil metal interactions were considered. Due to substantial heterogeneity among published studies regarding plant species, metal concentrations, exposure duration, and measured parameters, a qualitative narrative synthesis approach was adopted rather than a quantitative meta-analysis.

2 Essential Heavy Metals (EHMs)

EHMs are micronutrients required in strictly regulated concentrations to sustain plant growth and metabolic homeostasis [9,10]. Zn^{2+} , Cu^{2+} , Mn^{2+} , Fe^{2+} , MoO_4^{2-} , Ni^{2+} , Co^{2+} , and B^{3+} function as catalytic or structural components of enzymes involved in photosynthesis, respiration, nitrogen assimilation, redox balance, and cell wall stability. However, the concentration range between physiological requirement and toxicity is narrow, making plants highly sensitive to fluctuations in soil availability [26]. This duality, essential at low levels and toxic at excess concentrations, underpins the complexity of EHM regulation in contaminated and co-contaminated soils [27].

Zinc (Zn^{2+}): Zinc is a structural and catalytic cofactor for more than 300 enzymes regulating protein synthesis, carbohydrate metabolism, chlorophyll formation, and auxin homeostasis [28,29]. Adequate Zn^{2+} is particularly key in rapidly dividing tissues and reproductive development. Zn^{2+} deficiency commonly results in interveinal chlorosis and growth inhibition, whereas toxicity at soil concentrations exceeding 300–400 mg kg^{-1} disrupts membrane integrity, photosynthetic performance, and root development [30]. Because Zn^{2+} shares uptake pathways with other divalent metals, its homeostasis is highly sensitive to soil pH and competitive interactions under multi-metal stress conditions [31,32].

Copper ($\text{Cu}^{2+}/\text{Cu}^+$): Copper is a redox-active micronutrient necessary for photosynthetic electron transport, mitochondrial respiration, lignin biosynthesis, and antioxidant defense systems [33,34]. Its participation in electron transfer reactions makes tight intracellular regulation key. Cu^{2+} deficiency compromises lignification and stress tolerance, whereas toxicity at soil concentrations above 20–100 mg kg^{-1} induces oxidative stress, metabolic disruption, and growth inhibition [24,35]. Because Cu^{2+} is redox-active, excess accumulation can rapidly enhance reactive oxygen species (ROS) production, amplifying cellular damage under combined metal stress.

Manganese (Mn^{2+} , Mn^{3+} , Mn^{4+}): Manganese plays a central role in photosynthetic water-splitting reactions, nitrogen metabolism, and ROS detoxification pathways [36]. It also contributes to structural reinforcement through lignification. Mn^{2+} deficiency reduces photosynthetic efficiency and biomass accumulation, while toxicity (>500 mg kg^{-1} soil) disrupts redox balance and root functionality [37]. Because Mn^{2+} availability is strongly influenced by soil pH and redox conditions, its accumulation patterns are highly dynamic in waterlogged or degraded soils [38,39].

Iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$): Iron is necessary for chlorophyll biosynthesis, electron transport chains, and nitrogen metabolism [40]. Despite its abundance in many soils, Fe^{2+} bioavailability is often limited by pH and redox

conditions, particularly in calcareous systems. Deficiency results in impaired chloroplast development, whereas excess Fe^{2+} ($>100 \text{ mg kg}^{-1}$ soil) induces oxidative damage and metabolic imbalance [41]. Because Fe^{2+} shares transport systems with other divalent metals, its homeostasis is highly susceptible to competitive interactions under multi-metal contamination.

Molybdenum (MoO_4^{2-} , Mo^{6+}): Molybdenum is required for the biosynthesis of the molybdenum cofactor (Moco), which activates enzymes involved in nitrate reduction and sulfur metabolism [42]. Deficiency directly impairs nitrogen assimilation, whereas toxicity ($>10 \text{ mg kg}^{-1}$ soil) is uncommon but may affect reproductive performance. MoO_4^{2-} availability increases under alkaline soil conditions, highlighting the influence of soil chemistry on its physiological balance [43].

Nickel (Ni^{2+}): Nickel activates urease and supports nitrogen metabolism, seed viability, and glyoxalase activity [44]. While required in trace amounts, Ni^{2+} toxicity at concentrations above $50\text{--}100 \text{ mg kg}^{-1}$ soil interferes with root architecture and nutrient balance. Because Ni^{2+} shares uptake pathways with Fe^{2+} and Zn^{2+} , the co-occurrence of metals can significantly alter its accumulation dynamics [45].

Cobalt (Co^{2+}): Cobalt contributes primarily to symbiotic nitrogen fixation and vitamin B_{12} -dependent processes in legume-associated microorganisms. Although not universally important for all plants, excessive Co^{2+} may disrupt Fe^{2+} and Ni^{2+} homeostasis through competitive interactions [46].

Boron (H_3BO_3 , B^{3+}): Boron maintains cell wall integrity, carbohydrate transport, and reproductive development [47]. Deficiency impairs meristematic activity and fertility, whereas toxicity ($>5 \text{ mg kg}^{-1}$ soil) induces membrane instability and leaf deformation [48]. Because B^{3+} mobility depends on transpiration and soil moisture, its availability is closely linked to environmental conditions [49].

Shared Regulatory Mechanisms and Competitive Interactions Among EHMs

Although EHMs perform distinct biochemical functions, their uptake and intracellular transport rely on overlapping transporter systems, including ZIP, NRAMP, IRT, and COPT families. These shared pathways create competitive interactions among Zn^{2+} , Fe^{2+} , Mn^{2+} , and Ni^{2+} , particularly under elevated soil concentrations [50]. Chelation by nicotianamine and metallochaperones prevents free ion toxicity, while soil pH, redox potential, and organic matter strongly modulate metal speciation and bioavailability [51]. Importantly, these overlapping regulatory mechanisms also facilitate inadvertent uptake of NEHMs, linking EHMs nutrient homeostasis to heavy metal toxicity in co-contaminated scenarios. A comparative overview of EHMs and their interaction dynamics is summarized in Table 1. However, the toxicity thresholds presented in Table 1 represent approximate concentration ranges rather than universal limits applicable to all soil environments. Soil physicochemical characteristics, including pH, organic matter content, redox potential, clay composition, and competing ions, strongly influence the actual phytotoxicity of essential metal(loid)s [50]. Soil acidification generally increases the solubility and mobility of metals such as Zn^{2+} , Cu^{2+} , Mn^{2+} , and Ni^{2+} , thereby enhancing their uptake and toxicity even at concentrations below commonly reported thresholds. Conversely, alkaline conditions may reduce metal availability through precipitation and adsorption processes [52]. Organic matter can decrease metal toxicity by forming stable complexes with metal ions, although under certain conditions decomposition of organic matter may also release previously immobilized metals [53]. Therefore, field-based risk assessment should consider metal speciation and bioavailable fractions rather than relying solely on total soil metal concentrations.

Table 1: Comparative Overview of EHMs: Biological Roles, Approximate Toxicity Thresholds, and Interaction Dynamics in Soil-Plant Systems.

Metal	Core Biological Function	Toxicity Threshold (Soil)	Major Toxic Mechanism	Interaction/Competition Potential	References
Zn ²⁺	Enzyme cofactor; auxin & chlorophyll synthesis; carbohydrate metabolism	>300–400 mg kg ⁻¹	Membrane damage, ROS overproduction, growth inhibition	Competes with Fe ²⁺ , Mn ²⁺ , Cd ²⁺ via ZIP transporters	[30,54]
Cu ²⁺ /Cu ⁺	Redox enzymes in photosynthesis & respiration; lignification; antioxidant defense	20–100 mg kg ⁻¹	Oxidative stress, metabolic disruption	Redox-active; interacts with Fe ²⁺ & Zn ²⁺ homeostasis	[24,55–57]
Mn ²⁺ /Mn ³⁺ /Mn ⁴⁺	Photosynthetic water-splitting; N metabolism; cell wall strengthening	>500 mg kg ⁻¹	Redox imbalance, impaired root growth	Availability strongly pH- and redox-dependent; competes with Zn ²⁺	[37,58]
Fe ²⁺ /Fe ³⁺	Electron transport; chlorophyll synthesis; N metabolism	>100 mg kg ⁻¹	Oxidative damage, nutrient imbalance	Shares uptake pathways with Zn ²⁺ , Mn ²⁺ , Ni ²⁺	[40,59–61]
MoO ₄ ²⁻ (Mo ⁶⁺)	Molybdenum cofactor (nitrate reductase, sulfur metabolism)	>10 mg kg ⁻¹	Reproductive and metabolic disruption	MoO ₄ ²⁻ Availability increases in alkaline soils	[43,62]
Ni ²⁺	Urease activation; N metabolism; seed viability	50–100 mg kg ⁻¹	Root thickening, nutrient imbalance	Competes with Fe ²⁺ and Zn ²⁺ transport systems	[45,63]
Co ²⁺	Supports symbiotic N fixation (microbial vitamin B ₁₂ systems)	Excess interferes with Fe ²⁺ /Ni ²⁺ uptake	Disruption of micronutrient balance	Competitive interaction with Fe ²⁺ & Ni ²⁺	[46,64]
H ₃ BO ₃ (B ³⁺)	Cell wall integrity; reproductive development; carbohydrate transport	>5 mg kg ⁻¹	Membrane instability, leaf deformation	Mobility influenced by soil moisture & transpiration	[48,65]

3 Non-Essential Heavy Metals (NEHMs)

NEHMs lack known biological functions in plants and exhibit toxicity even at trace concentrations. Unlike essential metals, their uptake is largely unintentional, occurring through shared transport pathways evolved for micronutrient acquisition [8,9]. Their persistence in soils, low biodegradability, and capacity for bioaccumulation make them major contributors to soil degradation and agricultural risk. When co-occurring with essential metals, NEHMs exacerbate toxicity through ionic mimicry, transporter competition, disruption of nutrient homeostasis, and enhanced oxidative stress [66].

Lead (Pb²⁺): Lead contamination originates primarily from industrial emissions, battery waste, and historical use of leaded fuels. Pb²⁺ exhibits low mobility within plants but accumulates predominantly in roots, where it disrupts membrane integrity and enzyme activity [67]. Its strong affinity for sulfhydryl groups impairs protein structure and inhibits key metabolic processes. Although less readily translocated than Cd²⁺, Pb²⁺ significantly alters soil-root interactions and rhizosphere microbial activity, influencing nutrient cycling and soil biochemical stability [68].

Cadmium (Cd²⁺): Cadmium is one of the most phytotoxic heavy metals, commonly introduced into agricultural soils through phosphate fertilizers, mining activities, and wastewater irrigation [69]. Due to its chemical similarity to Zn²⁺ and Ca²⁺, Cd²⁺ enters plant roots via ZIP and calcium transporters, leading to its rapid accumulation in edible tissues. Even at low concentrations (<5 mg kg⁻¹ soil), Cd²⁺ disrupts photosynthesis, impairs nutrient balance, and induces severe oxidative stress [25,70]. Unlike essential metals, Cd²⁺ lacks detoxification demand in metabolic pathways, and its toxicity largely stems from interference with cellular redox systems and displacement of functional metal cofactors [71].

Mercury (Hg^{2+} , Hg^0 , and CH_3Hg^+): Mercury enters soils through coal combustion, industrial discharge, and atmospheric deposition [72]. In its ionic and methylated forms, Hg^{2+} interferes with enzymatic systems by binding to thiol groups, causing considerable oxidative stress and metabolic disruption. Although plant uptake is generally limited compared to Cd^{2+} , its extreme toxicity and potential for biomagnification pose significant ecological risks [73,74]. Soil redox conditions strongly influence Hg^{2+} speciation and mobility, linking contamination dynamics to environmental chemistry.

Arsenic (As^{3+} as arsenite, As^{5+} as arsenate): Arsenic contamination is frequently associated with pesticide residues and irrigation using contaminated groundwater. Due to its chemical similarity to phosphate, As^{5+} competes for phosphate transporters, disrupting ATP synthesis and energy metabolism [75]. As^{3+} , a more toxic form, interacts with sulfhydryl groups and inhibits enzyme function [76,77]. As^{3+} toxicity, therefore, represents a direct interface between metal stress and phosphorus (P) cycling in soils [78].

Chromium (Cr^{3+} and Cr^{6+}): Chromium contamination, particularly in its hexavalent form Cr^{6+} , originates from tannery effluents, electroplating, and industrial waste [79,80]. Cr^{6+} is highly mobile and oxidizing, enabling its rapid entry into plant tissues where it generates reactive oxygen species and disrupts redox balance. Reduction to Cr^{3+} decreases mobility but may lead to persistent soil accumulation. The redox-dependent behavior of Cr highlights the central role of soil chemical conditions in determining toxicity outcomes [81].

Shared Toxic Mechanisms of Non-Essential Metals

Despite differences in chemical properties, NEHMs share common toxicological pathways, including ionic mimicry, displacement of essential metal cofactors, inhibition of enzymatic activity, and excessive ROS production [82]. Because their uptake often exploits existing nutrient transport systems, NEHM accumulation is closely linked to the regulation of essential metal homeostasis [83]. This overlap explains why co-contamination scenarios frequently produce synergistic toxicity, amplifying soil biochemical disruption and impairing plant resilience [84]. The comparative characteristics of major NEHMs are presented in Table 2.

Table 2: Comparative Characteristics of NEHMs: Entry Pathways, Toxic Mechanisms, and Interference with Soil-Plant Nutrient Dynamics.

Metal	Primary Mode of Cellular Entry	Toxicity Threshold (Soil)	Dominant Toxic Mechanism in Plants	Interference with Essential Metal Homeostasis	References
Pb^{2+}	Apoplastic binding; limited symplastic transport; Ca^{2+} channel mimicry	$>100 \text{ mg kg}^{-1}$ (variable by soil type)	Binding to sulfhydryl groups; inhibition of enzymes; membrane destabilization	Interferes with Ca^{2+} signaling; reduces uptake of Fe^{2+} and Mg^{2+}	[68,85]
Cd^{2+}	Uptake via Zn^{2+} and Ca^{2+} transporters (ZIP family; Ca channels)	$>3\text{--}5 \text{ mg kg}^{-1}$	ROS overproduction; displacement of Zn^{2+} and Fe^{2+} cofactors; membrane damage	Competes with Zn^{2+} and Ca^{2+} ; disrupts Fe^{2+} homeostasis and enzyme activation	[86,87]
$\text{Hg}^{2+}/\text{Hg}^0/\text{CH}_3\text{Hg}^+$	Passive diffusion; strong affinity for thiol-containing proteins	$>1\text{--}2 \text{ mg kg}^{-1}$ (highly toxic even at low levels)	Protein denaturation; severe oxidative stress; disruption of enzymatic systems	Disrupts S-containing enzymes; affects redox-regulated micronutrient balance	[73,74]
$\text{As}^{3+}/\text{As}^{5+}$	As^{5+} via phosphate transporters; As^{3+} via aquaporins	$>10\text{--}20 \text{ mg kg}^{-1}$ (depending on speciation)	Inhibits ATP synthesis; thiol binding; oxidative stress induction	Competes with phosphate; disrupts P metabolism and energy pathways	[75–77]
$\text{Cr}^{3+}/\text{Cr}^{6+}$	Uptake via sulfate transporters (structural mimicry)	$>50\text{--}100 \text{ mg kg}^{-1}$	Strong oxidizing agent; ROS generation; DNA and protein damage	Alters Fe^{2+} and Mn^{2+} redox balance; inhibits enzymatic systems	[79–81]

3.1 Uptake Mechanisms of NEHMs

NEHMs reach the root surface primarily through passive processes driven by mass flow and diffusion in the soil solution [88,89]. The transpiration stream facilitates the delivery of dissolved metals toward root tissues through the soil solution and water flow associated with transpiration [90]. This passive delivery does not require metabolic energy but increases the exposure of root cells to metal ions. Once at the root surface, NEHMs enter cells mainly through active transport systems originally evolved for essential nutrients. Due to similarities in ionic radius and chemical properties, NEHMs mimic essential metals and utilize shared ion channels and carrier proteins [45]. For example, Cd^{2+} may enter via calcium channels, while arsenate competes with phosphate transporters. Certain ABC transporters, typically associated with nutrient transport, can also facilitate NEHM uptake [91]. This lack of strict transporter specificity forms the basis of competitive interference between essential and non-essential metals (Fig. 1).

3.2 Cellular Detoxification Mechanism

NEHMs, upon entering root cells, are subjected to several detoxification processes that reduce their interaction with sensitive cellular components. Chelation represents a primary defense strategy, whereby heavy metals are complexed with thiol-rich molecules such as phytochelatins (PCs) and metallothioneins (MTs) [92,93]. PCs facilitate the formation of stable metal complexes that are subsequently transported into vacuoles, thereby reducing cytosolic metal exposure, whereas MTs contribute to intracellular metal buffering and stabilization. In addition, vacuolar sequestration and binding of metals to cell wall components restrict metal mobility and limit their toxic effects within plant tissues [94,95].

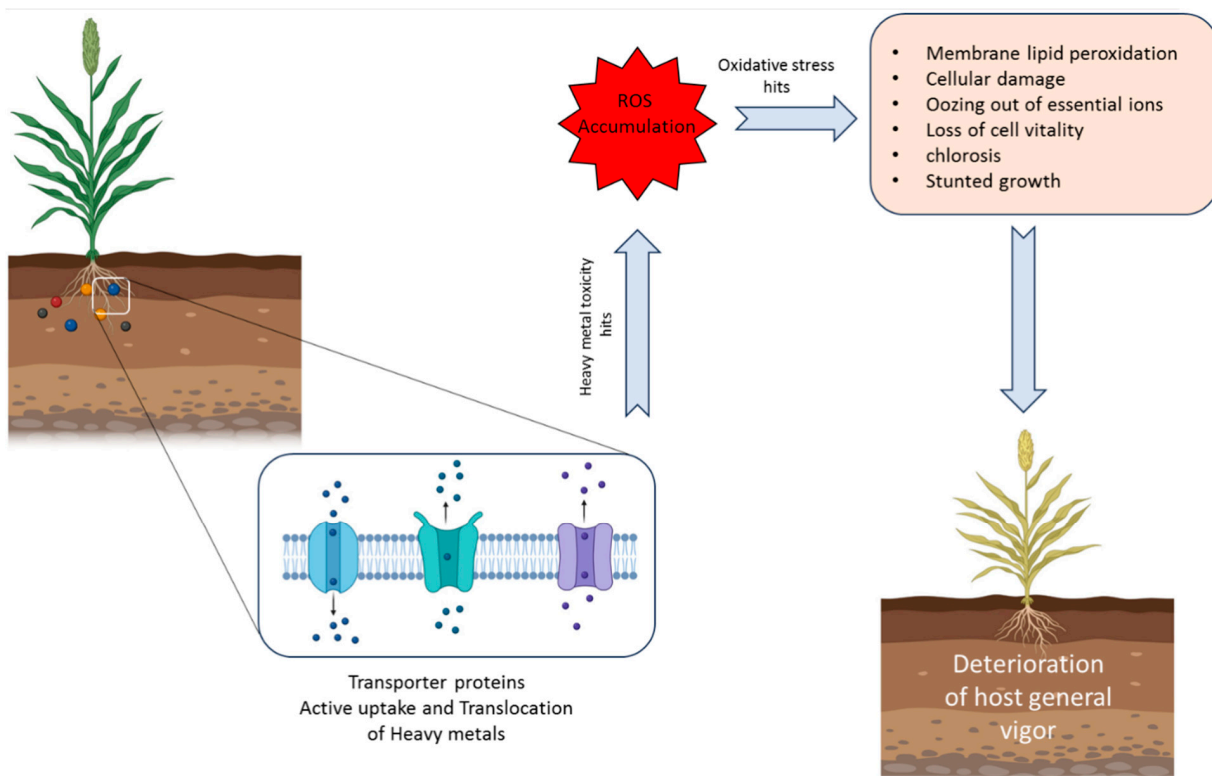


Figure 1: Conceptual diagram showing the pathways of essential and NEHMs uptake in plant roots, illustrating the role of transporters in the absorption of these metals from the soil.

3.3 Adaptive Responses to Non-Essential Heavy Metal Stress

Plants exhibit significant morphological and physiological plasticity under prolonged exposure to NEHMs. One common adaptive strategy involves modification of root architecture, including reduced root elongation and increased root thickening, which may limit surface area exposure to toxic metals [96]. Rhizosphere-mediated responses also contribute to adaptation. Root exudates containing organic acids and metal-binding metabolites can immobilize heavy metals in the soil, thereby reducing their bioavailability and uptake [97]. Additionally, plants enhance the production of detoxification-related enzymes and stress-associated proteins to maintain cellular stability under sustained metal pressure [98]. Some species exhibit selective ion transport mechanisms that restrict the entry of specific NEHMs while maintaining essential nutrient uptake [99]. Conversely, certain plants function as hyperaccumulators, tolerating and storing exceptionally high metal concentrations in aerial tissues without visible toxicity symptoms [100]. These adaptive traits form the biological foundation for phytoremediation strategies aimed at restoring contaminated soils [101].

3.4 Enhanced Toxicity of NEHMs under Co-Occurrence with EHMs

The coexistence of EHMs and NEHMs in contaminated soils often results in amplified toxicity due to shared transport pathways and competitive biochemical interactions [102]. Because some NEHMs share physicochemical similarities with essential metal ions, they can enter plant cells through transporter systems normally involved in essential nutrient uptake. For example, Cd can be transported by several transporters involved in the uptake and homeostasis of essential elements such as Zn, Fe, Mn, and Ca, thereby contributing to its accumulation in plant tissues [103]. A major consequence of competitive metal interactions is the disruption of essential metal homeostasis and metal-dependent enzymatic processes. Cd^{2+} can interfere with Zn-dependent proteins and other essential-metal functions, thereby impairing enzyme activity and cellular metabolism. Heavy metals, particularly Cd, can also induce oxidative stress and disrupt metabolic pathways, with phenolic compounds contributing to metal binding and detoxification [85]. Chromium can interact with proteins and modify their functional groups, thereby altering protein structure and enzyme activity [104].

Simultaneously, co-exposure can intensify toxicity by altering cellular metal homeostasis and increasing competition for physiological resources. Disturbances in essential metal balance may impair metabolic processes and enhance the sensitivity of plants to non-essential metal accumulation [50]. These combined effects contribute to reduced growth, impaired photosynthetic performance, and metabolic dysfunction under multi-metal stress conditions. Excessive sequestration of NEHMs through detoxification pathways may also interfere with the availability of essential micronutrients required for metabolic functions [8,9,105]. In addition, prolonged exposure alters gene expression patterns associated with metal transport, detoxification, and stress signaling pathways. Collectively, these molecular and physiological disruptions explain the heightened toxicity observed under multi-metal stress conditions.

4 Comparative Analysis

4.1 Metal Co-Occurrence and Interactive Effects

Heavy metals rarely occur in isolation in natural or agricultural environments; they exist as complex mixtures that exert combined effects on plants, soils, and microorganisms [106]. Co-occurrence of EHMs and NEHMs creates multifactorial stress, where plants face both nutritional imbalance and toxicity. Interactions may be synergistic, antagonistic, or additive, depending on ionic radii, valence states, redox potential, and

soil chemistry [107]. For example, Cd^{2+} and Zn^{2+} share similar ionic properties, allowing Cd^{2+} to enter root cells via Zn^{2+} transporters (ZIP family), causing competitive inhibition and secondary Zn^{2+} deficiency. Conversely, Cu^{2+} - $\text{Fe}^{2+}/\text{Fe}^{3+}$ interactions can be synergistic, as Cu^{2+} -dependent redox reactions facilitate reduction of Fe^{3+} and uptake under Fe^{2+} -limiting conditions [31,32].

The Cd^{2+} - Zn^{2+} interaction, however, is not fixed: at low Zn^{2+} concentrations, the metals act synergistically, while at higher concentrations they become antagonistic, with a $\text{Zn}^{2+}:\text{Cd}^{2+}$ ratio of approximately 2:1 serving as the borderline between the two interaction types [108]. In hyperaccumulator species such as *Solanum nigrum*, Zn^{2+} can enhance Cd^{2+} accumulation by upregulating ATP-dependent Cd transport and sequestration pathways, while combined Cd^{2+} and Zn^{2+} treatments have been shown to maximize chlorophyll production in Christmas moss due to synergistic effects [109]. Furthermore, Cd^{2+} - Hg^{2+} interactions shift from antagonistic at low concentrations to additive at higher concentrations, and Cd^{2+} - Pb^{2+} -As mixtures demonstrate dose-dependent shifts from low-dose synergy toward pronounced antagonism at higher doses, with toxicity rankings following $\text{Cd-As} > \text{Cd-Pb} > \text{Cd-Pb-As} > \text{Pb-As}$ [110,111].

Similarly, Pb^{2+} - Fe^{2+} interactions are consistently antagonistic, with iron application significantly decreasing Pb^{2+} content and reducing lead toxicity [112]. For As-P interactions, As^{5+} competes with phosphate for uptake via phosphate transporters, though the outcome varies between hydroponic and soil systems, where phosphate can either increase or decrease As availability depending on soil type and properties [113]. Additionally, Cu^{2+} and Fe^{2+} homeostasis are tightly interconnected, with Cu^{2+} required for normal plant Fe^{2+} deficiency responses, and their nutrition interacts to modulate $\text{Fe}^{2+}/\text{Cu}^{2+}$ accumulation [114]. These examples collectively illustrate that metal interactions are not fixed but depend on metal concentration ratios, plant species, soil physicochemical properties, and exposure duration.

At the physiological level, co-exposure to multiple metals intensifies stress compared to single-metal treatments. Combined Cd^{2+} and Pb^{2+} stress in *Zea mays* and *Brassica juncea* inhibits photosynthesis, accelerates chlorophyll degradation, and induces stomatal closure more than individual metals [68,115]. Cd^{2+} - Zn^{2+} or Pb^{2+} - Cu^{2+} mixtures disrupt redox balance and elevate ROS, overwhelming antioxidant defenses. Co-occurring metals also displace essential cofactors (Zn^{2+} , Fe^{2+}) from enzymes, disrupting photosynthetic electron transport and nitrogen assimilation [10,116]. Rhizospheric chemistry mediates these interactions. Metal mixtures alter pH, redox potential, and microbial activity, influencing solubility and plant bioavailability [117]. Root exudates, such as organic acids and phenolics, can chelate or mobilize multiple metals simultaneously, sometimes enhancing essential metal availability while increasing NEHM mobility [118].

Ecologically, mixed-metal contamination reshapes microbial communities, affecting nutrient cycling. Soil acidification and metal synergy may suppress beneficial microbes, reducing nitrogen fixation and phosphate solubilization [119]. Understanding these interactive behaviors is important for predictive modeling and integrated remediation strategies [120]. Integrating plant-level responses with rhizospheric dynamics is therefore necessary for developing sustainable management approaches in multi-metal contaminated soils.

4.2 Uptake, Transport, and Detoxification Mechanisms

Essential and non-essential metals differ fundamentally in how they enter, move through, and are stored in plant tissues. EHMs such as Zn^{2+} , Cu^{2+} , and Mn^{2+} are actively transported via membrane-bound proteins, including NRAMP and ZIP families, allowing plants to regulate their uptake according to metabolic demand [51]. In contrast, NEHMs like Cd^{2+} , Pb^{2+} , and Hg^{2+} exploit the same transporters due to ionic similarity, but lack homeostatic controls, leading to passive accumulation and potential toxicity [8,10,45,121]. Once inside, both metal types induce chelation by PCs and MTs, though for NEHMs this is primarily a stress response rather than a routine metabolic adjustment [92,93].

EHMs are selectively moved to match metabolic needs, whereas NEHMs move passively and often accumulate in leaves, causing damage [122,123]. Both types may be sequestered in vacuoles or bound to cell walls, but NEHMs exhibit less selective storage, increasing their toxicity [124]. Gene regulation also distinguishes the two: EHMs trigger tightly controlled expression of uptake and homeostasis genes, while NEHMs elicit broad stress responses that are often insufficient to prevent cellular damage [98,125]. Soil pH, redox potential, and organic matter further modulate the bioavailability of both metal types, with root exudates and microbial activity playing significant roles [106]. Together, these interconnected mechanisms highlight the need to view metal homeostasis within a soil-plant-microbe framework rather than as isolated cellular measures.

4.3 Comparative Toxicity of EHMs and NEHMs

EHMs become toxic only when present in excess, with each metal producing characteristic symptoms. Zn^{2+} toxicity causes stunted root growth and interveinal chlorosis in young leaves; Cu^{2+} excess induces leaf chlorosis, necrosis, and diminished root elongation; manganese toxicity appears as brown spots on older leaves and crinkled foliage [126]. NEHMs, by contrast, are toxic even at trace concentrations. Cd^{2+} poisoning causes chlorosis, necrosis, and stunted growth; Pb^{2+} produces chlorophyll loss, leaf necrosis, and root darkening; Hg^{2+} induces chlorosis, necrotic spots, leaf deformation, and root damage [127,128].

NEHMs overwhelm antioxidant defenses, producing more extensive ROS-mediated damage than EHMs (Fig. 2) [129]. Although EHMs like Fe^{2+} and Cu^{2+} can participate in Fenton reactions, cellular antioxidants normally counterbalance this [130,131]. Excess EHMs can interfere with other nutrients (e.g., high Zn^{2+} induces Fe deficiency), whereas NEHMs replace essential metals in enzymes, inhibit photosynthesis, disrupt carbon fixation, impair nitrogen metabolism, and interfere with Ca^{2+} and Mg^{2+} uptake [127,128]. In terms of genetic responses, EHMs trigger tightly regulated gene expression for metal homeostasis, while NEHMs elicit broad stress responses and upregulate detoxification genes [132]. From an environmental perspective, these differential toxicity patterns determine vegetation performance in contaminated soils and influence the selection of species for remediation and ecological stabilization efforts.

4.4 Impacts on Plant Physiology, Biochemistry, and Morphology

Heavy metal exposure disrupts multiple physiological processes. In photosynthesis, Cd^{2+} can replace magnesium in chlorophyll, reducing light absorption and electron transfer [133,134]. Respiration and energy metabolism are impaired as Cd^{2+} and Hg^{2+} disrupt mitochondrial electron transport, lowering ATP production. Hormonal balance is altered, with auxins, cytokinins, gibberellins, and ethylene all affected under NEHM stress, leading to changes in root and shoot architecture [130]. At the molecular level, heavy metals induce protein misfolding, activate heat shock protein responses, trigger metallothionein induction, and promote lipid peroxidation [135]. Morphologically, roots shorten and thicken, while shoots exhibit stunted growth, leaf necrosis, chlorosis, and reduced reproductive success [136,137].

Collectively, these impairments reflect the systemic nature of heavy metal stress, linking molecular damage to whole-plant and ecosystem outcomes.

5 Mechanisms of Toxicity

Understanding the mechanisms of heavy metal toxicity is fundamental for interpreting how metal stress disrupts plant physiological balance and overall system functionality. Toxic metals such as Cd^{2+} , Pb^{2+} , and Hg^{2+} interfere with metabolic pathways, redox homeostasis, and nutrient acquisition, triggering

complex molecular and biochemical cascades. These disruptions extend beyond localized cellular damage and collectively influence plant growth, productivity, and resilience under contaminated conditions.

5.1 Oxidative Stress and ROS Generation

An overabundance of ROS is the primary source of secondary oxidative stress as a result of exposure to toxic HMs induced in host plants [130]. ROS are very reactive particles, such as superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), hydroxyl radicals ($OH\cdot$), and singlet oxygen (O_2). Under normal circumstances, several metabolic processes, such as photosynthesis and respiration, produce ROS, which are effectively removed by the body's own defensive system [138]. Nevertheless, plants exposed to HMs like Pb^{2+} , Hg^{2+} , and Cd^{2+} create unusually high amounts of ROS, which ultimately results in oxidative stress [85,139].

The electron transport chains in chloroplasts and mitochondria are disrupted by HM exposure [140]. For example, by substituting magnesium in chlorophyll, Cd^{2+} messes with the photosynthetic electron transport chain, making it harder for light to absorb and transmit energy [141]. This causes the high-energy electrons to leak out, and radicals called superoxide to develop. In a similar vein, HMs cause disruptions in the electron transport chain of the mitochondria, which raises ROS generation during respiratory metabolism. Most HMs block important antioxidant enzymes that control the amount of reactive oxygen species [95]. For instance, glutathione peroxidase (GPX), catalase (CAT), and superoxide dismutase (SOD) are all inhibited by Hg^{2+} and Cd^{2+} and are important for detoxifying hydrogen peroxide and superoxide radicals (Fig. 2) [95,142]. ROS build up as a consequence of these enzymes being inhibited. In addition, several important HMs, including Cu^{2+} and Fe^{2+} , can take part in the Fenton and Haber-Weiss reactions, which produce hydroxyl radicals. Fenton processes involving ferrous iron (Fe^{2+}) and cuprous copper (Cu^+) can produce hydroxyl radicals when hydrogen peroxide is present. These highly reactive hydroxyl radicals cause severe cellular damage (Fig. 2) [95,142]. Persistent oxidative imbalance not only damages cellular components but also compromises energy production and carbon assimilation, thereby reducing overall plant vigor under prolonged metal exposure.

5.2 Cellular and Genetic Damage

When plants are exposed to HMs, excessive reactive oxygen species (ROS) can promote lipid peroxidation in cellular membranes. Hydroperoxides and lipid radicals are produced during the peroxidation process, and these intermediates can further decompose into reactive aldehydes such as malondialdehyde (MDA) [143]. Not only does lipid peroxidation generate reactive lipid-derived products, but it also compromises membrane structure and function, resulting in loss of membrane integrity and cellular dysfunction [144]. Ion leakage and disruptions to cellular homeostasis are brought about by the loss of membrane integrity, which increases permeability. MDA, a product of lipid peroxidation, is frequently utilized as a biomarker of oxidative damage in plants. Additionally, the oxidation of protein amino acid residues by the ROS generated by heavy metal stress results in protein denaturation and loss of function [145]. Disulfide bonds are formed when cysteine residue oxidation of thiol groups ($-SH$) alters protein structure and activity. Oxidation, which disrupts cellular metabolism, is particularly susceptible to enzymes involved in key metabolic pathways. HMs' secondary oxidative stress also damages DNA by oxidizing it, causing strand breaks, base changes, and cross-linking [146,147]. For instance, hydroxyl radicals can oxidize guanine to form 8-oxoguanine, which prompts changes during DNA replication. DNA damage can cause abnormal growth and development, as well as affect cell division [148]. Plant photosynthetic efficiency is reduced as a result of oxidative stress's degradation of chlorophyll molecules. Chlorophyll can be directly attacked by singlet oxygen and superoxide radicals, resulting in its degradation and the loss of photosynthetic pigments.

This debilitates light absorption and energy transfer, decreasing overall photosynthetic efficacy [149]. Such structural and genomic impairments can alter cell division patterns, growth dynamics, and reproductive development, highlighting the systemic consequences of sustained metal-induced oxidative stress.

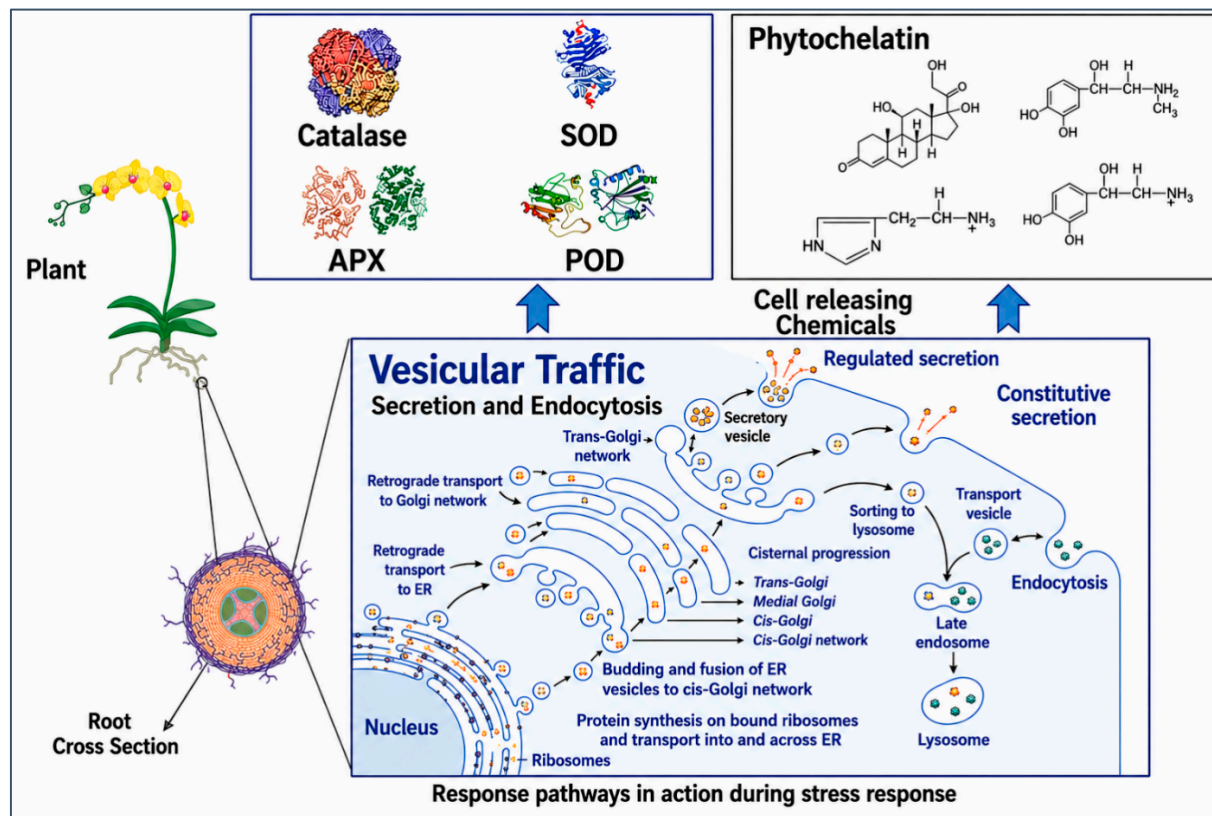


Figure 2: Conceptual flowchart detailing the molecular responses of plants to heavy metal stress, showing the activation of defense mechanisms like phytochelatin synthesis, antioxidant enzyme activity, and the expression of metal transporter genes.

5.3 Interference with Nutrient Uptake and Homeostasis

Beyond oxidative damage, heavy metals considerably disturb nutrient homeostasis, creating secondary deficiencies that amplify toxicity effects. Heavy metal toxicity in plants not only prompts direct physiological and biochemical disturbances but also disrupts the uptake and translocation of essential nutrients [150]. The plant's absorption pathways, transporter proteins, and binding sites are all contested by HMs like Cd^{2+} , Pb^{2+} , $\text{As}^{3+}/\text{As}^{5+}$, and Hg^{2+} . Because of this competition, there aren't enough nutrients, which affects different physiological processes and the health of the plant as a whole. The mechanisms by which HMs prevent plants from absorbing nutrients and the effects on plant growth and development are discussed below.

Numerous essential nutrients and HMs share transporters and uptake pathways. For instance, Cd^{2+} competes with Zn^{2+} and Ca^{2+} for uptake through their respective carriers [151]. Similarly, Pb^{2+} competes with Ca^{2+} and Fe^{2+} for their transporters, which leads to inhibition in the absorption of Ca^{2+} and Fe^{2+} . Subsequently, this competitive inhibition leads to a decline in absorption and, hence, makes them unavailable for absorption, causing a deficiency of important essential nutrients [152]. Metals can influence the functionality of the particular nutrient's transporters; for example, Cd^{2+} impairs the Fe^{2+} transporter proteins IRT1, leading to the inability of the host plant to absorb and translocate Fe^{2+} , hence causing Fe^{2+} deficiency

despite a proper amount of Fe^{2+} available in the soil [83,153]. As a result of Fe^{2+} toxicity, the two most important physiological functions of the plants are disrupted, i.e., chlorophyll synthesis and respiration [60]. Heavy metal exposure leads to alteration in plant morphology, especially in roots, as they are the first organs to come in contact with the HMs. Alteration in the root's morphology may include a reduction in root length, an increase in root diameter, and the development of root hairs. These alterations impede the root's capacity to effectively forage for water and nutrients while avoiding heavy metal contact. These conditions are particularly common under Pb^{2+} and Cd^{2+} toxicity, which can reduce root growth and increase root thickness, thereby reducing the surface area available for HM absorption from the soil [154]. In addition, HMs above threshold levels can induce oxidative stress, which worsens the condition by damaging root cell membranes and causing lipid peroxidation. Consequently, as a result of the membrane damage, essential ions ooze out of the cell, inducing multifold toxicity to the host plant [149]. Apart from losing essential ions, the roots are further unable to absorb more nutrients as well as to transport them throughout the plant body, thereby exacerbating nutritional deficiencies. Several genes are transcriptionally induced and show increased expression, whereas others are downregulated under metal toxicity, reflecting extensive reprogramming of plant gene expression in response to heavy-metal stress [155]. For example, Cd^{2+} exposure leads to the downregulation of genes, including Fe transporter proteins, which in turn leads to ceased Fe uptake and causes Fe^{2+} deficiency in the host plants [156]. A similar pattern is followed by the a similar pattern is followed by the As^{5+} -exposed plants, where As^{5+} alters the expression of genes related to phosphate transporter proteins, hence hindering phosphorus uptake [157]. In some instances, certain HMs form complexes with EHMs, making them inaccessible for the plant's absorption. For instance, Pb^{2+} and Cd^{2+} can form insoluble complexes with phosphate, hence reducing their availability to be absorbed by the plant, which negatively affects nutrient absorption by the plant roots [158]. Consequently, heavy metal toxicity often manifests not only as direct biochemical injury but also as a compounded imbalance in mineral nutrition, reinforcing growth inhibition and metabolic dysfunction.

5.4 Plant Defense and Adaptive Responses

In response to the multifaceted toxicity mechanisms described above, plants activate coordinated defense systems aimed at limiting metal entry, neutralizing oxidative damage, and restoring cellular homeostasis. Plants have adopted certain special defense mechanisms to cope with heavy metal contamination in the soil [98]. These adaptations may include avoidance of HMs, physiological and biochemical adaptations, and molecular responses that lower the chance of damage caused by HMs are among these strategies [159]. Such an adaptive mechanism in plants helps them to tolerate harsh conditions and enables improved and sustainable agricultural productivity in metal-polluted areas [160]. Strategies for increasing plant tolerance and ensuring sustainable agricultural productivity in contaminated areas require an understanding of these defense mechanisms.

I. Avoidance Mechanisms

Plants can restrict the uptake of HMs by modifying root exudates and cell wall composition. Organic acids, mucilage, and exudates from the root can bind HMs, preventing them from entering the cells of the root [161]. Additionally, lignin and pectin modification can immobilize HMs at the root surface, thereby reducing their internalization [98]. Heavy-metal exposure can alter the properties and permeability of root cell membranes, thereby affecting metal entry into root cells. Such stress can induce changes in membrane lipid composition and membrane function, which may contribute to maintaining membrane integrity and regulating metal uptake [162].

II. Biochemical and Physiological Adaptations

When exposed to HMs, plants produce chelating agents like PCs and MTs. HMs are bound by tiny peptides known as PCs to create stable complexes, which are transported into vacuoles for sequestration [163]. MTs are cysteine-rich proteins that bind to and extract HMs from the cytoplasm. One method that indicates that heavy metal exposure leads to oxidative stress is the generation of ROS [164]. Plants have an effective antioxidant defense mechanism that they use to neutralize ROS and reduce oxidative damage. Antioxidant enzymes of significance include GPX, CAT, and SOD [165]. Non-enzymatic antioxidants, for example, ascorbate (L-ascorbic acid), glutathione, carotenoids, and flavonoids, additionally assume a key role in the detoxification of ROS [166]. Heavy metal stress initiates the creation of stress proteins, including heat shock proteins (HSPs) and other molecular chaperones. The functioning proteins are protected by the heat shock proteins, which also occasionally aid in their refolding into their original structure [167,168]. These proteins also support cellular homeostasis by preventing the aggregation of functioning proteins [169]. Additionally, these HSPs aid in shielding the plant's cellular machinery from the harmful effects of heavy metal exposure. Plants have the potential to modulate gene expression and hence control the activity of metal transporters [170]. Some transporters, for instance, can be downregulated, ceasing heavy metal absorption, while others, on the other hand, can be upregulated, improving the uptake of essential nutrients, hence reducing the deficiency caused by HM toxicity [171].

III. Molecular Responses

Heavy metal exposure causes genes involved in metal detoxification, antioxidant defense, and the stress response to be regulated [132]. The activation of transcription factors like WRKY, bZIP, and MYB promotes the expression of genes for PCs, MTs, antioxidant enzymes, stress proteins, and more [172]. A variety of signal transduction pathways that mediate stress responses are triggered by HMs [173]. Ca-signaling plays a significant role in perceiving heavy metal stress and enacting downstream responses [174]. Other kinases and mitogen-activated protein kinases are also involved in stress signal transmission and gene expression regulation [175,176]. Plants can undergo epigenetic alterations like DNA methylation and histone changes in response to heavy metal exposure [177]. A mechanism for long-term heavy metal tolerance is provided by these modifications, which alter the expression of genes involved in stress responses and adaptation [178,179].

IV. Physiological Adjustments

Alterations to the Architecture of the Roots: Plants can alter the architecture of their roots to steer clear of zones that are contaminated with HMs [180]. This includes changes in root length, branching patterns, and root hair development, which assist with optimized water and nutrient uptake while limiting heavy metal exposure and subsequent toxicity [20]. A few plants have mechanisms and techniques to effectively efflux HMs from root cells back into the soil [181,182]. HMs are removed from cells via transport proteins in this process, lowering their internal concentration and toxicity. HMs are transported into vacuoles for long-term storage after being chelated by PCs or MTs [181]. By isolating HMs from the cytoplasm, this mechanism reduces their toxicity and safeguards cellular processes [183].

Collectively, these defense strategies reflect the dynamic balance between toxicity and tolerance in metal-exposed plants. The efficiency of avoidance, detoxification, and repair mechanisms ultimately determines whether exposure results in temporary stress adaptation or irreversible physiological impairment. Understanding these mechanisms provides a mechanistic bridge to remediation strategies, where enhancing natural tolerance pathways can be leveraged for sustainable management of contaminated systems.

6 Strategies for Phytoremediation and Soil Management

Mitigating heavy metal stress in agricultural systems requires integrated phytoremediation and soil management strategies that reduce metal mobility, limit plant uptake, and restore soil functionality. Phytoremediation utilizes plants as biological agents to extract, stabilize, transform, or immobilize contaminants, whereas soil management practices aim to regulate physicochemical properties that influence metal bioavailability. Together, these approaches form the foundation of sustainable remediation in multi-metal contaminated environments.

6.1 Plant-Based Remediation Mechanisms

Plant-driven remediation strategies exploit natural metal tolerance and accumulation mechanisms to reduce contaminant loads or limit their bioavailability. Among the different techniques of phytoremediation, phytoextraction encompasses the use of hyperaccumulator plants that can absorb and build up higher levels of such HMs in their shoots and leaves [184]. After sufficient growth and metal accumulation, the plants are harvested, and the metal-enriched biomass is removed, thereby extracting a fraction of the heavy metals from the soil and gradually reducing soil metal concentrations [185]. Among the hyperaccumulating plant species, *Thlaspi caerulescens* is used to accumulate Zn^{2+} , *Brassica juncea* is used to accumulate substantial quantities of Pb^{2+} and Cd^{2+} , and *Pteris vittata* is used to accumulate As in higher quantities from the contaminated soil [186]. Frequent removal of the aerial parts of the plant helps to remove the accumulated metal in the above-ground parts, hence helps in metal removal and soil reclamation [187]. Proceeding with proper disposal methods can further reduce the secondary pollution of these HMs. Certain plants stabilize some HMs by the process of phytostabilization (Fig. 3, Table 3), a technique of phytoremediation, which prevents their leaching into the groundwater. In some cases, plants that are used for phytostabilization can immobilize these HMs by root absorption and promote their precipitation, reducing their bioavailability [188–190]. In most cases, plant root exudates consist of a gamut of metabolites that bind the HMs, forming stable complexes that reduce the bioavailability of these metals [191]. In the case of soil management, amendment of organic matter, lime, or phosphate can potentially improve phytostabilization by enhancing soil characteristics by promoting metal immobilization and improving soil conditions [192]. Among the other techniques of phytoremediation, rhizofiltration is a method that uses plant roots to absorb, build up, and precipitate HMs from polluted water and is potentially effective in treating wastewater and contaminated water bodies (Fig. 3, Table 3). Aquatic plants such as water hyacinth (*Eichhornia crassipes*) and terrestrial plants like sunflower (*Helianthus annuus*) are effective for rhizofiltration [193,194]. Apart from that, another technique of phytoremediation is phytovolatilization, which involves the absorption of HMs by plants and their subsequent transformation into volatile forms, which are released into the atmosphere; this technique is primarily used for Hg^{2+} and selenium (Se) [184,195]. Species such as Indian mustard (*Brassica juncea*) and certain genetically modified plants are used for phytovolatilization of Hg^{2+} [186]. While effective for specific elements such as Hg^{2+} and Se, phytovolatilization requires careful ecological evaluation due to potential atmospheric redistribution. Similarly, phytoexclusion aims to prevent the uptake of HMs by using plant varieties that naturally limit the absorption of these metals [196]. Phytoexclusion is used to grow crops in metal-polluted soil while preventing metal accumulation in the edible parts [197]. Selecting varieties that exhibit lower heavy metal absorption and translocation to edible parts or locking them into their non-edible parts is a more important way to exclude them from the food chain. Breeding programs focus on developing crop varieties with enhanced heavy metal exclusion traits [198].

6.2 Soil Amendments and Physicochemical Management

Beyond plant-based strategies, soil physicochemical management plays a central role in controlling heavy metal bioavailability. Soil additives can reduce the bioavailability of HMs by improving the pH, availability of nutrients, and soil structure. The organic content of soil can be increased by adding compost, manure, or biochar, thereby encouraging the formation of stable compounds with HMs [199]. Liming acidic soil can raise pH, which decreases the mobility and solubility of HMs like Pb^{2+} and Cd^{2+} [199]. Adding phosphate fertilizers can precipitate HMs, forming insoluble metal-phosphate complexes that are less bioavailable. To decrease heavy metal absorption and enhance soil health, crop rotations and interplanting with plants that are either metal-tolerant or metal-excluding are important. Managing soil levels of HMs can be aided by rotating crops that include hyperaccumulators or species that exclude metals [200]. By increasing phytostabilization or competitive exclusion, growing metal-tolerant plants alongside crops might reduce heavy metal uptake by the primary crop (Fig. 3). Biological agents, chemicals, or water may be used in soil washing procedures to remove HMs from contaminated soil [201]. Ethylene diamine tetra-acetic acid (EDTA) and citric acid are commonly used chelating agents that can increase the solubility and mobilization of heavy metals, facilitating their removal from contaminated soils [202]. The production or application of biosurfactants by plants or microorganisms can enhance heavy-metal mobilization, solubilization, and desorption from contaminated soils, thereby facilitating their removal through remediation processes [203]. In the process of bioremediation, microorganisms convert HMs into less dangerous forms. The introduction of microbial strains that are either metal-tolerant or metal-degrading can improve soil bioremediation processes by providing nutrients or organic substrates to promote the growth of naturally occurring microbial communities with the capacity to degrade HMs. The mobility and distribution of HMs in the soil can be decreased by managing irrigation and drainage systems properly. Waterlogging can be avoided, and heavy metal leakage into groundwater can be decreased by installing drainage systems [204]. Crop absorption of HMs can be reduced by using clean water sources for irrigation and minimizing overwatering. These soil-centered interventions not only reduce metal mobility but also enhance nutrient retention, soil aggregation, and overall edaphic stability.

6.3 Microbial-Assisted Phytoremediation

The plant-microbe-metal interface represents a dynamic regulatory system that can significantly influence remediation efficiency under multi-metal stress. Plants rarely experience metal stress in isolation; rather, they coexist with complex microbial communities that influence metal mobility, uptake, and toxicity [205,206]. The plant-microbe-metal triad represents an interactive framework in which rhizospheric microorganisms, including plant growth-promoting rhizobacteria (PGPR), endophytic bacteria, and arbuscular mycorrhizal fungi (AMF), can modulate plant responses to metal contamination. PGPR can contribute to heavy-metal immobilization and detoxification through mechanisms including metal complexation, chelation, precipitation, acidification, and production of extracellular polymeric substances (EPS) [207]. For example, EPS associated with *Bacillus subtilis* has been experimentally shown to interact with and bind Cd^{2+} and Pb^{2+} , potentially contributing to their immobilization [208].

Mycorrhizal fungi contribute additional protection through biofiltration and sequestration within extraradical hyphae [209]. The fungal mantle acts as a barrier, restricting metal transport to the plant stele, while simultaneously improving nutrient uptake and soil aggregation. Recent evidence shows that AMF inoculation can mitigate combined heavy-metal stress by improving plant growth and physiological performance, enhancing antioxidant and metal-chelating responses, and modulating metal and nutrient allocation. For example, Zhang et al. [210] demonstrated that AMF alleviated Cd + Zn toxicity in tomato

through coordinated changes in ion homeostasis, root metabolism, and rhizosphere interactions. Certain endophytic bacteria further induce systemic tolerance by enhancing antioxidant enzyme activity (SOD, CAT, POD) and stimulating the production of glutathione, PCs, and MTs, thereby boosting the plant's intrinsic detoxification machinery [211].

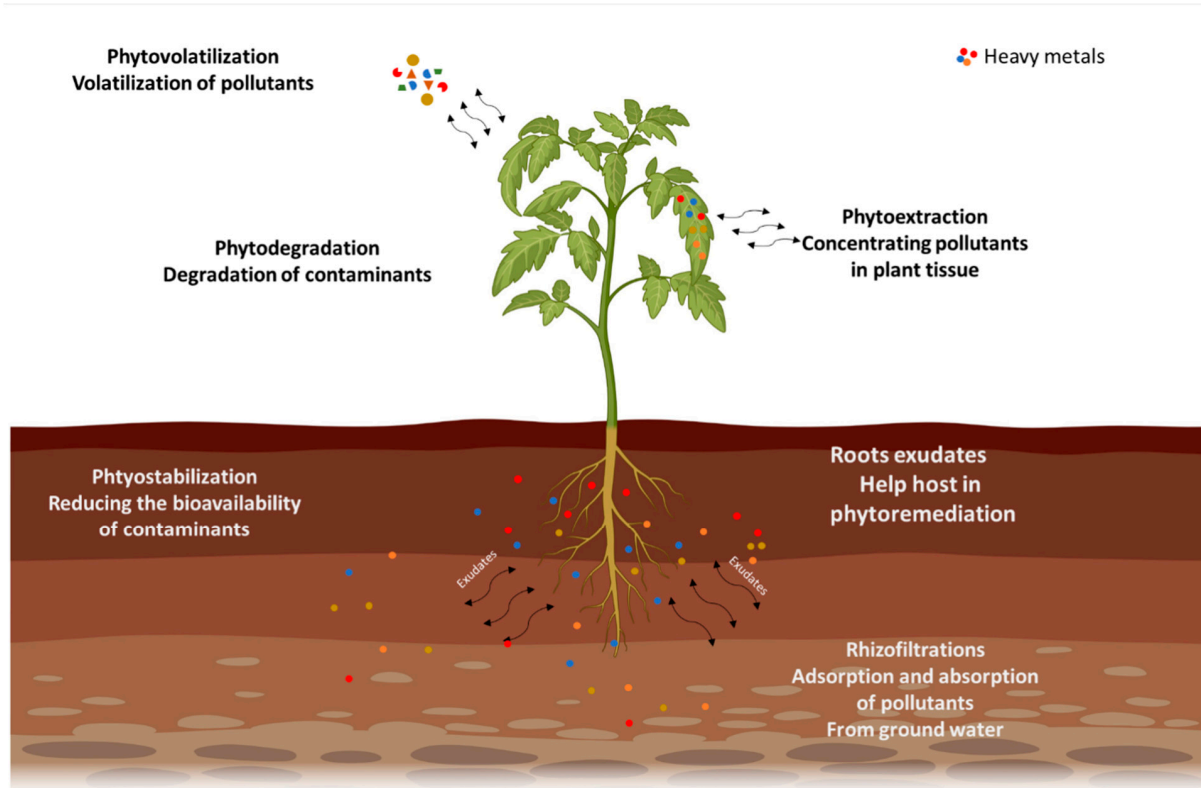


Figure 3: Key strategies, including phytoextraction, phytovolatilization, phytodegradation, phytostabilization, and rhizofiltration, with root exudates enhancing these processes.

Microbial consortia can act synergistically in complex environments [212]. For example, dual inoculation of *Glomus mosseae* and *Bacillus megaterium* has been shown to increase Pb^{2+} immobilization and reduce Cd^{2+} uptake in sunflower roots, while promoting shoot growth [213]. These microbes also influence root exudation patterns, enhancing organic acid secretion that immobilizes non-essential metals while maintaining essential nutrient uptake. Moreover, bacteria capable of biotransformation (*Pseudomonas putida*, *Burkholderia cepacia*) can convert highly toxic metal ions into less reactive forms via enzymatic reduction (e.g., $Cr^{6+} \rightarrow Cr^{3+}$, $As^{5+} \rightarrow As^{3+}$) [214].

The integration of microbial inoculants with organic amendments establishes bio-augmented remediation systems capable of simultaneously reducing metal toxicity, enhancing nutrient cycling, and improving soil structural stability [215]. Such biologically driven approaches offer promising avenues for the sustainable management of complex contaminated systems [160].

6.4 Integrated and Emerging Approaches

Collectively, phytoremediation and soil management strategies must be tailored to the specific metal composition, soil characteristics, and crop system involved. In multi-metal scenarios, integrated approaches combining plant tolerance, microbial facilitation, and soil amendments are often more effective than

single-method interventions. Future remediation frameworks should therefore emphasize system-level optimization rather than isolated techniques (Table 3). However, despite their environmental advantages, the large-scale application of these approaches faces several practical limitations. Phytoremediation is generally slower than conventional remediation technologies and may require repeated cultivation cycles to achieve meaningful reductions in soil metal concentrations [216]. Furthermore, outcomes obtained under controlled greenhouse or pot experiments may not fully represent field conditions due to differences in soil heterogeneity, climate variability, microbial communities, and metal distribution patterns. Economic considerations, including costs associated with plant establishment, biomass harvesting, transportation, and safe disposal of metal-enriched biomass, also influence the feasibility of large-scale implementation [217].

Table 3: Phytoremediation strategies and enhancement approaches for EHMs and NEHMs in soil-plant systems.

HMs Studied	Material Used	Remediation Techniques Studied	Coupled/Enhanced Strategies	References
Pb ²⁺ , Cd ²⁺ , Zn ²⁺	<i>Brassica juncea</i> , <i>Panicum maximum</i>	Phytoextraction, Phytostabilization	Biochar amendment, PGPR inoculation	[218,219]
Ni ²⁺ , Cr ⁶⁺ , Cd ²⁺	<i>Brassica napus</i> , <i>Pteris vittata</i>	Phytoextraction, Phytostabilization	Phosphate amendment, microbial immobilization	[220,221]
Zn ²⁺ , Cu ²⁺ , Ni ²⁺	<i>Helianthus annuus</i> , <i>Festuca arundinacea</i>	Rhizofiltration, Rhizodegradation	Biochar-assisted rhizofiltration	[222,223]
Pb ²⁺ , Cd ²⁺ , Hg ²⁺	<i>Trifolium repens</i> , <i>Lolium perenne</i>	Phytostabilization, Bioremediation	AMF inoculation, compost amendment	[224,225]
Cd ²⁺ , Pb ²⁺ , As ³⁺ /As ⁵⁺	Underground water	Risk assessment, Environmental impact evaluation	Phytovolatilization/rhizofiltration combinations	[226,227]
Cr ⁶⁺ , As ³⁺ /As ⁵⁺ , Pb ²⁺	<i>Zea mays</i> , <i>Avena sativa</i>	Phytoextraction, Phytostabilization	PGPR inoculation, compost amendment	[228,229]

7 Implications for Soil Functioning and Agroecosystem Sustainability

Heavy metal co-occurrence in soils not only imposes physiological stress on plants but also alters soil functionality, biogeochemical cycling, and long-term agroecosystem stability [230]. The interaction between essential and non-essential metals introduces additional complexity, as competitive uptake, ionic antagonism, and redox transformations reshape nutrient availability and soil biological processes [231]. Understanding these broader implications is important for designing sustainable remediation and management strategies.

7.1 Disruption of Soil Biogeochemical Processes

Heavy metals influence key soil enzymatic activities and microbial-mediated nutrient transformations. Non-essential metals such as Cd²⁺, Pb²⁺, and Hg²⁺ can inhibit enzymes involved in nitrogen mineralization, phosphorus solubilization, and carbon turnover, thereby altering nutrient cycling dynamics [232]. Even essential metals, when present in excess (e.g., Cu²⁺ or Zn²⁺), may disrupt microbial homeostasis and suppress enzymatic activity. Metal-metal interactions further complicate these effects. For instance, competition between Zn²⁺ and Cd²⁺ or Fe²⁺ and Pb²⁺ can modify their bioavailability and alter microbial community composition [231]. Shifts in rhizospheric microbial diversity influence organic matter decomposition, nitrogen fixation, and phosphorus mobilization, ultimately affecting soil fertility [233]. Prolonged exposure to mixed-metal contamination may therefore reduce soil biological resilience and functional redundancy [234].

Additionally, heavy metals can influence soil aggregation and structure indirectly by altering root growth and microbial exopolysaccharide production [235]. These changes may affect water retention, aeration, and overall edaphic stability, with cascading impacts on plant productivity. Heavy-metal contami-

nation can reduce soil enzyme activities and microbial biomass carbon, alter soil respiration, and disrupt soil aggregation. For example, reductions of 21–53% in microbial biomass carbon and 3–45% in basal respiration, along with a 39% decline in large soil micro-aggregates, have been reported in contaminated soils [236,237]. These parameters serve as early warning signals of soil functional decline and should be routinely measured in contaminated site assessments to guide restoration priorities. The specific effects of individual heavy metals on soil chemical and biochemical properties, along with microbial remediation mechanisms and their implications for nutrient cycling, are summarized in Table 4.

7.2 Impacts on Crop Productivity and Food Safety

The co-accumulation of essential and non-essential metals in plant tissues directly affects yield stability and food quality [238]. While essential metals are required for metabolic processes, their imbalance under competitive uptake conditions may impair chlorophyll synthesis, enzymatic function, and photosynthetic efficiency [134]. Simultaneously, non-essential metals can accumulate in edible tissues, posing food safety concerns [239]. In multi-metal environments, antagonistic or synergistic interactions can modify translocation patterns, sometimes reducing the uptake of one metal while enhancing another [240]. Such dynamics make risk assessment more complex than single-metal scenarios. The differential partitioning of metals between roots and shoots also determines whether crops serve as potential phytoremediators or as vectors of metal entry into the food chain [241]. Therefore, sustainable management must balance remediation efficiency with crop safety and nutritional quality, particularly in agricultural soils subjected to chronic contamination.

7.3 Restoration Pathways and Soil Resilience

Restoring soil functionality in multi-metal contaminated systems requires integrated approaches that combine plant tolerance mechanisms, microbial mediation, and physicochemical amendments [240]. Rather than focusing solely on metal removal, contemporary strategies emphasize reducing bioavailability, stabilizing soil processes, and enhancing ecological resilience. Microbial-assisted phytoremediation, organic amendments, and biochar application contribute not only to metal immobilization but also to improved carbon sequestration, nutrient cycling, and soil structural integrity [242,243]. These approaches support the gradual recovery of biological activity and the re-establishment of functional microbial communities. Long-term sustainability depends on system-level optimization, selecting appropriate plant species, understanding metal interaction networks, and tailoring management practices to site-specific soil characteristics [244]. In this context, remediation becomes not merely a detoxification process but a pathway toward restoring agroecosystem functionality and resilience under complex metal stress conditions [244,245].

Table 4: Microbial Bioremediation of Heavy Metals and Their Effects on Soil Chemical and Biochemical Properties.

Metal	Effects on Soil Chemical Properties	Effects on Soil Biochemical Properties	Microbial Remediation Mechanisms	Implications for Soil C, N, and P Cycles	References
Cd ²⁺	Increases metal mobility; alters pH buffering capacity	Inhibits dehydrogenase, urease, and phosphatase activities	Biosorption to cell walls; intracellular sequestration; CdS precipitation	Suppresses N mineralization; reduces microbial respiration and C turnover	[246–248]
Cr ⁶⁺	Alters soil redox potential; highly mobile in oxidized form	Inhibits nitrification and oxidoreductase enzymes	Enzymatic reduction of Cr ⁶⁺ to Cr ³⁺	Recovery of nitrification after detoxification; restoration of N cycling	[81,249]

Table 4: Cont.

Metal	Effects on Soil Chemical Properties	Effects on Soil Biochemical Properties	Microbial Remediation Mechanisms	Implications for Soil C, N, and P Cycles	References
As ⁵⁺	Competes with phosphate; modifies redox-sensitive reactions	Disrupts ATP synthesis and microbial metabolism	Arsenate reduction; methylation/demethylation; efflux systems	Interferes with P cycling due to chemical similarity; impacts microbial biomass C	[250,251]
Hg ²⁺	Alters redox chemistry; forms stable complexes	Inhibits microbial respiration and enzyme systems	Reduction of Hg ²⁺ to volatile Hg ⁰ ; demethylation	Decreases carbon mineralization and microbial biomass turnover	[252–254]
Ni ²⁺	Competes with essential micronutrients; modifies ionic balance	Reduces urease activity; enzyme instability	Biosorption; intracellular sequestration; efflux transporters	Disrupts N cycling through urease inhibition	[255–257]
Cu ²⁺	Accumulates in organic fractions; alters soil acidity	Inhibits oxidoreductases and dehydrogenase activity	Chelation; efflux pumps; enzymatic transformation	Alters microbial biomass C and enzyme-mediated C cycling	[35,258,259]

8 Research Gaps and Future Perspectives under Changing Environmental Conditions

8.1 Persistent Knowledge Gaps

Despite substantial advances in understanding heavy metal(loid) toxicity in plants, significant knowledge gaps remain that limit the development of predictive and scalable mitigation strategies [260]. Although several metal transporters and detoxification pathways have been characterized, the full regulatory network governing uptake, sequestration, translocation, and cross-talk with essential nutrient pathways is still incompletely resolved [51]. Because essential and non-essential metals often share transporters and compete for binding sites, unraveling this interaction network is fundamental for improving tolerance and minimizing unintended nutrient imbalances [83]. Long-term ecological studies are particularly scarce. Chronic exposure to mixed-metal contamination may gradually reshape plant biodiversity, alter rhizosphere microbial communities, and disrupt ecosystem-level processes such as nutrient cycling and primary productivity [117]. However, the temporal dynamics of these changes and their reversibility thresholds remain poorly understood.

8.2 Unresolved Contradictions in the Literature

Beyond knowledge gaps, several direct contradictions among published studies need close attention. For example, while some reports indicate that Zn²⁺ alleviates Cd²⁺ toxicity through competitive uptake inhibition, others find that Zn²⁺ enhances Cd²⁺ accumulation and toxicity, suggesting that the Zn²⁺: Cd²⁺ ratio, plant species, and soil pH determine the outcome [261]. Similarly, Pb²⁺ inhibits Fe uptake in rice and maize but not in wheat, indicating species-specific or Fe-acquisition-strategy-dependent mechanisms that remain unclear. Regarding transporter dominance under multi-metal exposure, the ZIP, NRAMP, HMA, and ABC families have all been implicated. Still, no consensus exists on which families or specific transporters govern uptake when multiple metals are present simultaneously [262]. Antioxidant response patterns also present contradictions: Cd²⁺ and Pb²⁺ typically induce superoxide dismutase and catalase activities, whereas Cu²⁺ and Cr⁶⁺ suppress them at comparable concentrations, pointing to metal-specific redox interactions that are poorly characterized [262,263]. Finally, soil microbial community recovery after phytoremediation ranges from rapid (within months) to persistent shifts lasting years, with no clear

predictors [264]. Resolving these contradictions requires systematic, multi-species, dose-response studies under standardized conditions, as well as long-term field observations.

8.3 Future Directions

Integrative multi-omics approaches, including genomics, transcriptomics, proteomics, and metabolomics, provide powerful tools to dissect coordinated stress responses [265]. Systems-level integration of these datasets can reveal regulatory hubs, signaling cascades, and metabolic trade-offs under multi-metal exposure. Precision genome editing technologies such as CRISPR/Cas9 offer promising avenues for improving tolerance and metal partitioning traits [260]. Likewise, transgenic approaches incorporating genes encoding MTs, PCs, or heavy metal ATPases (e.g., AtHMA4) have demonstrated enhanced tolerance to Cd^{2+} , Zn^{2+} , and related metals in experimental systems. Translating these advances into field-relevant crops remains an important next step [266]. Climate variability adds a regulatory layer to metal dynamics in soils. Drought conditions may concentrate metals in the rhizosphere, intensifying toxicity, whereas flooding can mobilize previously stabilized metals through redox-mediated dissolution processes [266,267]. Elevated atmospheric CO_2 and temperature shifts influence root exudation, microbial activity, and metal speciation, thereby modifying metal bioavailability and plant uptake patterns [268]. Incorporating climate-metal interaction models into future risk assessments will therefore improve the predictive accuracy of remediation and crop management strategies.

Future research should also prioritize the development of standardized experimental frameworks for evaluating multi-metal interactions across diverse plant species and soil environments. Harmonized reporting of metal concentrations, soil properties, exposure duration, and physiological responses would facilitate cross-study comparisons and enable more reliable predictive models. In addition, long-term field trials are required to validate findings obtained from controlled experiments and to assess the ecological, economic, and agronomic feasibility of remediation strategies under realistic environmental conditions [269].

Despite significant advances in understanding metal-metal interactions, quantitative synthesis of published studies remains challenging due to variations in plant species, metal combinations, exposure concentrations, soil conditions, experimental systems, and measured physiological endpoints. Establishing standardized datasets and consistent reporting frameworks will therefore be necessary for enabling robust meta-analytical assessments and improving predictive models of metal interaction outcomes under diverse environmental conditions.

9 Conclusion

This review leads to the following principal conclusions:

1. EHMs and NEHMs coexist in contaminated soils and interact through shared transport systems, competitive uptake, and ionic mimicry. This interaction determines whether metal mixtures act synergistically or antagonistically, depending on concentration ratios, plant species, and soil physicochemical conditions.
2. At the cellular level, metal co-occurrence induces oxidative stress, disrupts nutrient homeostasis, and triggers detoxification pathways. These molecular responses scale up to quantitative indicators of land degradation, including 30–60% suppression of soil enzyme activities, 40–70% decline in microbial biomass carbon, and disrupted carbon-nitrogen-phosphorus cycling.
3. Phytoremediation, microbial-assisted approaches, and soil amendments show promise for reducing metal bioavailability. However, practical limitations including slow remediation rates, scalability challenges, economic feasibility, and biomass disposal must be addressed for successful field implementation.
4. A systems-level framework integrating multi-omics, CRISPR gene editing, and predictive modeling is proposed to develop metal-tolerant crops and guide sustainable remediation. Priority research areas

include standardized dose-response studies to resolve contradictory findings, long-term field trials to validate remediation strategies under realistic conditions, and integration of climate-metal interaction models into risk assessments.

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