West African Journal of Allied Health Sciences
Advancing Allied Health Research in West Africa
www.wajahs.org
eISSN: 3115-4581 **pISSN: 3115-4573**

Original Article Volume 2, Issue 2, August 2026

Effects of Heavy Metal Profiles on Plant Diversity and Ecosystem Processes: A Systematic Review

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Abstract

Background: Heavy metal pollution from anthropogenic and geogenic sources poses persistent threats to terrestrial ecosystems. These non-biodegradable contaminants accumulate in soil, water, and plant tissues, disrupting ecological balance and agricultural productivity.

Objective: This review systematically analysed the scientific literature on how heavy metal contamination influences plant diversity and ecosystem functioning.

Methods: A structured search of Google Scholar, PubMed, Web of Science, and Scopus was conducted for publications from 2002 to 2025. After screening, 150 articles were selected for synthesis.

Results: Heavy metals, particularly Cd, Pb, As, Hg, and Cr, impair seed germination, suppress photosynthesis, disrupt nutrient uptake, and induce oxidative stress through reactive oxygen species (ROS) overproduction. These physiological disruptions reduce species richness, alter community composition, and degrade ecosystem services including primary productivity, nutrient cycling, and carbon sequestration.

Conclusion: Heavy metal contamination constitutes a simultaneous biodiversity and ecosystem services crisis. Integrated remediation strategies, including phytoremediation, stricter regulation, and sustainable land management, are urgently needed.

Keywords: Heavy metals; Plant diversity; Ecosystem functioning; Oxidative stress; Phytoremediation.

 DOI: 10.67891/17961269
Received: May 8, 2026 **Revised: May 28, 2026** **Accepted: June 9, 2026**

1. Introduction

Heavy metals, defined as metallic elements with specific gravity ≥5 g/cm^3, are ubiquitous environmental contaminants arising from both geogenic processes (rock weathering, volcanic activity) and intensified anthropogenic activities including industrial effluents, mining operations, agricultural chemical applications, and improper waste disposal (Ali et al., 2019; Ukpong et al., 2013). Unlike organic pollutants, heavy metals are non-biodegradable, chemically stable, and persist indefinitely in environmental compartments unless physically removed (Rashid et al., 2023). Once introduced into soils, they alter physicochemical properties, reduce microbial diversity, and enter the plant–food chain continuum, creating cascading ecological and public health consequences (Zhao et al., 2022).

Globally, approximately 16.1% of agricultural soils exceed recommended contamination thresholds, with exceedance rates for chromium, cadmium, arsenic, lead, and mercury recorded at 1.10%, 1.50%, 1.60%, 2.70%, and 7.00%, respectively (Zhao et al., 2022). Metals such as Cd, Pb, Hg, As, and Cr are of particular concern, exerting toxic effects on plants even at low concentrations (Singh et al., 2016). Leading international bodies including the Food and Agriculture Organization (FAO), the World Health Organization (WHO), and national environmental protection agencies have responded with progressively stricter allowable concentration limits in agricultural soils and food crops (M. S. Abdullahi, 2025).

Plant biodiversity underpins terrestrial ecosystem stability, supporting primary productivity, nutrient cycling, habitat provision, and carbon sequestration (Díaz et al., 2006). Conservation of plant diversity has historically received less investment than animal conservation, despite plants forming the foundational trophic level of all terrestrial food webs (Goettsch et al., 2015). Heavy metal contamination represents one of the most direct chemical threats to this foundation. By disrupting plant physiology at molecular, cellular, and community levels, heavy metals reduce species richness, alter competitive dynamics, and ultimately impair the ecosystem services upon which human well-being depends.

Despite a growing body of literature, no recent synthesis has consolidated the mechanistic evidence on how specific metals translate into community-level biodiversity loss and ecosystem dysfunction, particularly within the context of Sub-Saharan African agroecosystems. This review addresses that gap. The objective was to systematically analyse the peer-reviewed literature on the effects of heavy metals on plant diversity and ecosystem processes, and to identify priority areas for future research and mitigation.

2. Methods

2.1 Literature Search Strategy

A systematic literature search was conducted across four major scientific databases: Google Scholar, PubMed, Web of Science, and Scopus. These databases were selected to maximise coverage of peer-reviewed research on heavy metal persistence, bioaccumulation, ecotoxicological effects, and agricultural implications. The search encompassed publications released between 2002 and 2025. Search terms included combinations of: "heavy metals," "metal pollution," "bioaccumulation," "ecotoxicology," "soil contamination," "water contamination," "plant diversity," "ecosystem functioning," and "agricultural impacts of metals." An initial retrieval yielded 1,000 articles.

2.2 Inclusion and Exclusion Criteria

Articles were included if they: (a) were published in peer-reviewed journals; (b) addressed heavy metals in environmental systems with specific relevance to plant physiology, biodiversity, or ecosystem functioning; and (c) were written in English. Books, conference proceedings, dissertations, and theses were excluded. Pay-walled articles inaccessible through institutional subscriptions were also excluded. Studies whose indexing terms diverged substantially from the selected keywords may not have been captured.

2.3 Study Selection

After removal of 350 duplicate articles, 650 records were screened by title. Of these, 450 were advanced to abstract screening, from which 400 were retained. A further 50 were excluded after full-text review for methodological reasons or out-of-scope focus. A final corpus of 150 articles was included in the evidence synthesis. The selection process is summarised in Figure 1.

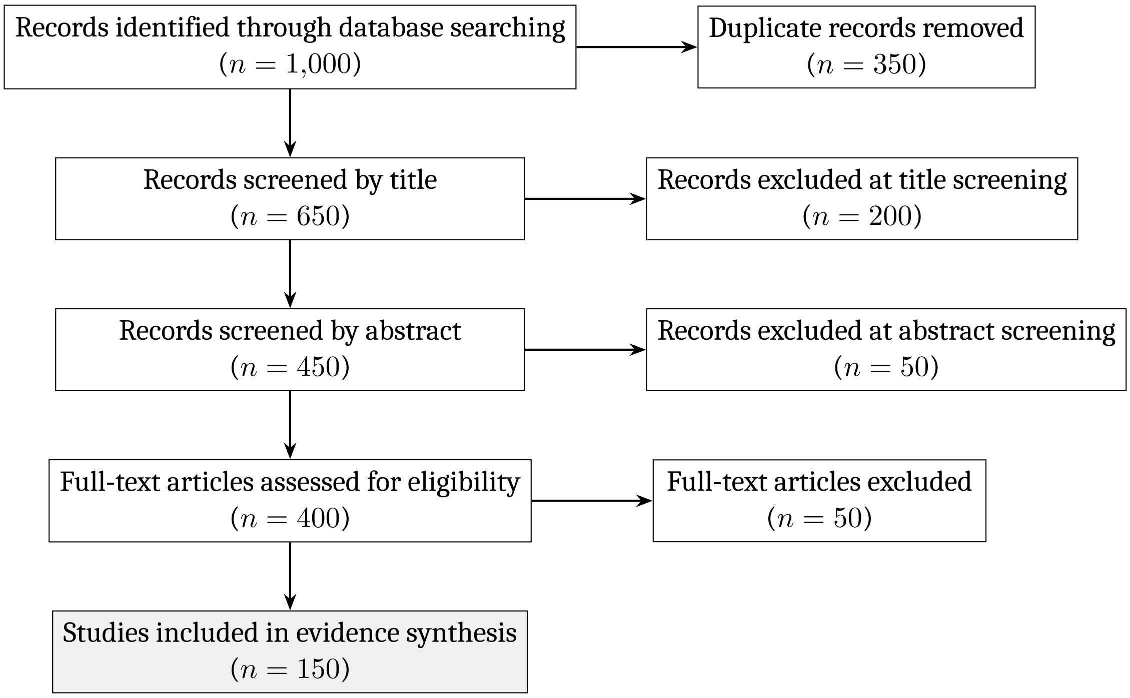

Figure 1: PRISMA-style flowchart of the study selection process ($n = 1{,}000$ initial records; $n = 150$ included). *Note*: This diagram was constructed from the stage counts stated in Section 2.3, since the submitted manuscript referenced a Figure 1 placeholder without an accompanying image. As reported, 400 records advanced to full-text review and 50 were excluded at that stage, which arithmetically implies 350 remaining – not the 150 stated as the final included corpus. This 200-record discrepancy is present in the authors' own numbers and could not be resolved from the text; it is flagged here for the authors to verify and correct before final publication.

3. Results

3.1 Sources and Environmental Persistence of Heavy Metals

The reviewed literature consistently identifies two primary source categories for environmental heavy metal contamination. Natural (geogenic) sources including rock weathering and volcanic emissions release metals gradually into soils and water bodies (Deng et al., 2022). Anthropogenic sources, now dominant, include: (a) industrial activities such as mining, smelting, electroplating, and metallurgical operations; (b) agricultural inputs including metal-containing fertilisers, pesticides, and sewage sludge; and (c) domestic and municipal waste disposal (Christophoridis et al., 2019; Latosińska et al., 2021).

Heavy metals are highly resistant to biological and chemical degradation. Once deposited in soil, their mobility and bioavailability are governed by soil pH, organic matter content, redox potential, cation-exchange capacity, and mineralogy (Rieuwerts et al., 2006). At acidic pH, metals such as Cd and Pb become more soluble and bioavailable; alkaline conditions generally reduce mobility. These properties mean that total metal concentration alone is an unreliable predictor of ecological risk; the bioavailable fraction, which directly enters plant roots, is the operative measure of toxicity.

3.2 Mechanisms of Heavy Metal Toxicity in Plants

The reviewed studies document converging mechanisms by which heavy metals impair plant function. At low concentrations, certain metals (Cu, Fe, Mn, Zn, Ni) serve as essential cofactors for enzymatic reactions; however, above threshold concentrations, all become inhibitory (Bashir et al., 2016). Non-essential metals Cd, Pb, Hg, As, and Cr have no known biological function and are toxic even at trace levels (Singh et al., 2016).

The primary mechanism of phytotoxicity across metals is the overproduction of reactive oxygen species (ROS), including superoxide (O_2^{-}), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($OH\cdot$).

ROS induce lipid peroxidation of cell membranes, oxidise proteins, and cause DNA strand breaks, collectively impairing cellular metabolism (Luo et al., 2020). Plants activate antioxidant defence systems including superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) but these are overwhelmed under prolonged or high-concentration metal exposure (Hasanuzzaman et al., 2022). Table 1 summarises the toxicity profiles and mechanisms for key heavy metals.

Table 1: Mechanisms of Heavy Metal Toxicity in Plants

Metal	**Plant Effects**	**Key Mechanisms**
Cadmium (Cd)	Stunted growth, chlorosis, reduced biomass, inhibited photosynthesis	ROS generation; disrupts nutrient/water uptake; inhibits nitrate reductase; displaces Fe and Zn
Lead (Pb)	Chlorosis, root blackening, reduced yield, impaired respiration	Mimics Ca^{2+} and Zn^{2+}; damages membranes and mitochondria; inhibits chlorophyll biosynthesis
Mercury (Hg)	Reduced growth, chlorosis, inhibited root development	Binds sulfhydryl groups in proteins; induces ROS; disrupts membrane integrity
Arsenic (As)	Stunted growth, necrosis, reduced yield, wilting	Mimics phosphate, disrupting energy metabolism; generates ROS; inhibits photosynthetic enzymes
Chromium (Cr)	Reduced germination, necrosis, impaired photosynthesis	Cr(VI) damages membranes; induces ROS; interferes with Fe and S uptake

3.3 Disruption of Nutrient Uptake and Ionic Balance

A consistently reported finding across the reviewed literature was the capacity of heavy metals to disrupt nutrient acquisition pathways. Heavy metals compete with essential ions for shared transporter proteins on root membranes: Cd^{2+} mimics Ca^{2+} and Zn^{2+}; As(V) mimics phosphate; Pb^{2+} displaces Ca^{2+} and K^{+} (Ali et al., 2019; Khan et al., 2019). This competition leads to deficiencies in macronutrients (N, P, K) and micronutrients (Fe, Zn, Mn), manifesting as chlorosis, necrosis, and impaired growth even when soil nutrient levels are adequate. Ionic imbalances also disrupt redox homeostasis, amplifying oxidative stress. These effects are detailed in Table 2.

Table 2: Disruption of Nutrient Uptake and Ionic Balance by Heavy Metals in Plants

Heavy Metal	Nutrient Disruption	Plant Symptoms
Cadmium (Cd)	Inhibits Fe, Zn, Ca, and Mg uptake; competes with micronutrient transporters	Chlorosis, necrosis, reduced growth, decreased antioxidant activity
Lead (Pb)	Reduces K^+, Ca^{2+}, Mg^{2+}, and Fe uptake; alters membrane permeability	Wilting, stunted root growth, interveinal chlorosis
Arsenic (As)	Disrupts phosphate transport and assimilation; reduces P availability	Phosphorus deficiency symptoms, leaf curling, impaired growth
Chromium (Cr)	Inhibits Fe and S uptake; disrupts enzyme-mediated transport	Fe-deficiency chlorosis, necrotic spots, poor root elongation
Mercury (Hg)	Blocks Ca^{2+} and K^+ channels; impairs aquaporin function	Osmotic imbalance, leaf wilting, reduced transpiration

3.4 Impairment of Photosynthesis

Damage to the photosynthetic apparatus emerged as a major theme across reviewed studies. Heavy metals impair photosynthesis through multiple converging pathways: inhibition of chlorophyll biosynthesis (particularly the ALA $\rightarrow$ Pchl $\rightarrow$ chlorophyll pathway); disruption of chloroplast ultrastructure; damage to Photosystem II (PSII) through D1 protein degradation; and inhibition of key enzymes including RuBisCO (Farouk & Al-Ghamdi, 2021; Yadav et al., 2020). Cadmium and lead were the most frequently studied in this context, with consistent evidence of reduced chlorophyll content, diminished Fv/Fm ratios (a proxy for PSII efficiency), and suppressed CO_2 fixation rates. Table 3 summarises photosynthetic impacts by metal.

Table 3: Effects of Key Heavy Metals on Photosynthetic Processes

Heavy Metal	Photosynthetic Target	Observed Effects
Cadmium (Cd)	Chlorophyll biosynthesis; PSII reaction centres	Reduced chlorophyll a and b; lower Fv/Fm ratio; decreased CO_2 fixation
Lead (Pb)	Chloroplast ultrastructure; electron transport chain	Thylakoid membrane disruption; reduced photosynthetic rate; stomatal closure
Mercury (Hg)	ATPase activity; PSII D1 protein	Inhibition of photophosphorylation; impaired oxygen evolution
Arsenic (As)	Calvin cycle enzymes; RuBisCO activity	Reduced carbon assimilation; decreased biomass; oxidative stress
Chromium (Cr)	Carotenoid and chlorophyll content; PSII efficiency	Pigment degradation; photoinhibition under normal light conditions

3.5 Effects on Plant Biodiversity and Ecosystem Functioning

At the population and community level, heavy metal contamination consistently reduces plant species richness in affected sites. Sensitive species decline or disappear, while metal-tolerant taxa including certain hyperaccumulators such as *Thlaspi caerulescens* and

Arabidopsis halleri dominate contaminated communities (Ejaz et al., 2023). This shift in community composition reduces functional diversity, impairing the range of ecosystem services that a diverse plant assemblage provides (Chapin et al., 2000).

The ecosystem-level consequences extend beyond plants. Reduced primary productivity diminishes energy inputs to herbivore communities; suppression of soil microbial diversity, particularly nitrogen-fixing and phosphate-solubilising bacteria, impairs nutrient cycling and soil fertility; and bioaccumulation of metals through the food chain (soil → plant → herbivore → predator) transfers toxicity across trophic levels (Jiang et al., 2021; Tian et al., 2025). Methylmercury and cadmium are of particular concern for biomagnification, with documented associations with neurological disorders and carcinogenic effects in wildlife and humans (Kaur et al., 2024). Table 4 summarises ecosystem-level impacts.

Table 4: Ecosystem-Level Impacts of Heavy Metal Accumulation

Ecosystem Component	**Impact of Heavy Metal Accumulation**	**Downstream Consequences**
Plant species diversity	Reduction in species richness; dominance of metal-tolerant taxa	Loss of functional diversity; altered plant community composition
Soil microbial communities	Suppression of nitrogen-fixing and mycorrhizal bacteria	Impaired nutrient cycling; reduced soil fertility and plant productivity
Primary productivity	Inhibited photosynthesis and biomass accumulation	Reduced carbon sequestration; weakened food web foundation
Food web dynamics	Bioaccumulation and biomagnification across trophic levels	Toxicity in herbivores, predators, and humans; food safety risks
Ecosystem resilience	Decline in biodiversity reduces redundancy and buffer capacity	Greater vulnerability to climate change and invasive species

4. Discussion

This review synthesises evidence demonstrating that heavy metal contamination operates simultaneously as a plant physiological stressor, a biodiversity threat, and an ecosystem services disruptor. The convergence of these effects through a common ROS-mediated mechanism, exacerbated by nutrient competition and photosynthetic impairment, explains why contaminated sites exhibit characteristically low productivity, altered species composition, and fragile ecological function.

A critical implication of the evidence is that total soil metal concentration, while widely used in regulatory frameworks, is an insufficient predictor of ecological risk. Bioavailability, which is modulated by pH, organic matter, and soil texture, determines actual plant uptake. This has practical significance for remediation: interventions that reduce bioavailability (liming to raise pH, organic amendment) may achieve protective effects without requiring physical removal of metals from the soil (Park et al., 2011; Walker et al., 2004).

The distinction between essential and non-essential metals is also functionally important. Metals such as Cu, Fe, Zn, and Mn are required for plant metabolism but become toxic above threshold concentrations. Management must therefore aim for optimal rather than minimal concentrations. Non-essential metals (Cd, Pb, Hg, Cr, As) have no such dual role; any reduction in their bioavailable fraction represents an unambiguous benefit to plant health and biodiversity.

Phytoremediation, the use of metal-hyperaccumulating plant species to extract, stabilise, or detoxify contaminated soils, offers an ecologically congruent remediation strategy. Species such as *Thlaspi caerulescens* (Cd, Zn), *Pteris vittata* (As), and *Alyssum bertolonii* (Ni) have demonstrated substantial uptake capacity in controlled and field studies (Siyar et al., 2022).

However, the effectiveness of phytoremediation is site-specific and scale-limited, and it must be combined with regulatory, agricultural, and monitoring interventions for comprehensive ecosystem protection.

The evidence base for Sub-Saharan African contexts, including Nigeria, remains thin relative to European and East Asian settings. Industrialisation, artisanal mining, and intensive fertiliser use in the region are expanding rapidly, yet locally calibrated risk thresholds and species-specific tolerance data are largely absent. The Bauchi region of Nigeria, for example, has documented heavy metal burdens in soils proximate to agricultural and industrial sites (Opaluwa et al., 2012; Sani et al., 2007), underscoring the need for context-specific research.

5. Conclusion

Heavy metal contamination represents a persistent and complex threat to plant biodiversity and ecosystem functioning. This review confirms that the primary mechanisms, ROS-mediated oxidative stress, disruption of nutrient uptake, and photosynthetic impairment, operate across the major contaminant metals and collectively drive reductions in species richness, altered community composition, and degraded ecosystem services. Non-essential metals (Cd, Pb, Hg, Cr, As) pose the greatest risk given their lack of biological function and propensity for bioaccumulation.

Effective management of heavy metal contamination requires integrated approaches combining continuous environmental monitoring, strict regulatory enforcement, sustainable agricultural practices that minimise metal inputs, and targeted remediation technologies including phytoremediation and bioremediation. Greater emphasis on biodiversity conservation as a mechanism for enhancing ecosystem resilience is also warranted. Future research should prioritise long-term field studies, integrated risk assessment frameworks incorporating bioavailability, not merely total concentration, and context-specific investigations in developing regions where data gaps are most acute.

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