International Journal of Agriculture, Environment and Biotechnology
Citation: *IJAEB*: **19**(02): 55-78, June 2026
DOI: 10.30954/0974-1712.02.2026.1

ASSOCIATION FOR AGRICULTURE ENVIRONMENT AND BIOTECHNOLOGY

RESEARCH PAPER

Managing Heavy Metal Bioavailability in French Bean (*Phaseolus vulgaris* L.) Production Systems Using Soil Amendments: Mechanisms, Evidence, and Food Safety Implications

Erick Osoro Mogire[1,3]*, Joseph Miriti[2], Emmanuel R Mwakidoshi[1], Lydiah LM Kitonga[4], Douglas N Nyang'au[5] and Joseph Gweyi-Onyango[1]

[1]Department of Agricultural Science and Technology, Kenyatta University, Nairobi, Kenya
[2]Kenya Agricultural and Livestock Research Organization (KALRO), Kabete, Nairobi, Kenya
[3]Department of Agriculture and Land Use Management, School of Agriculture, Veterinary Science and Technology, Masinde Muliro University of Science and Technology, Kakamega, Kenya
[4]Department of Agricultural Sciences, School of Agriculture and Natural Resources Management, Kisii University, Kisii, Kenya
[5]Department of Biosciences, University Félix Houphouét Boigny, Abidjan, Cote d'Ivoire

*Corresponding author: erickmogire6@gmail.com (**ORCID ID:** 0009-0000-5409-1161)

Paper No. 1239 **Received:** 12-03-2026 **Revised:** 22-05-2026 **Accepted:** 05-06-2026

ABSTRACT

Heavy metal contamination of agricultural soils poses a growing threat to safe and sustainable food production, particularly in intensive horticultural systems. French bean (*Phaseolus vulgaris* L.), an economically important legume widely consumed locally and traded in export markets, is highly susceptible to the uptake and accumulation of toxic metals such as cadmium (Cd), lead (Pb), and copper (Cu). This raises serious concerns regarding crop productivity, food safety, and public health. This review synthesizes current knowledge on the sources, behavior, and management of heavy metal bioavailability in French bean production systems, with particular emphasis on the role of soil amendments. Major contamination pathways examined include synthetic agro-inputs, irrigation water, organic amendments, atmospheric deposition, and geogenic sources. The review further evaluates the biological and physicochemical mechanisms governing metal mobility and plant uptake, highlighting the influence of soil pH, cation exchange capacity, microbial activity, and organic matter content. Particular attention is given to the roles of organic and inorganic soil amendments in reducing heavy metal bioavailability through adsorption, complexation, precipitation, and ion competition. Evidence from experimental and field studies shows that amendments such as lime, phosphatic materials, compost, and biochar can substantially reduce metal bioavailability while improving soil quality and crop performance. Integrated amendment strategies frequently demonstrate synergistic effects and outperform single-input applications, although their effectiveness remains dependent on soil type, amendment properties, and metal speciation. Despite increasing research interest, studies specifically focused on French bean systems remain limited, particularly regarding dose optimization, varietal responses, and long-term field validation. Addressing these gaps is essential for developing evidence-based management strategies that protect soil health, crop quality, and consumer safety.

HIGHLIGHTS

- Heavy metal contamination threatens French bean productivity, food safety, and consumer health.
- Soil pH, organic matter, CEC, and metal speciation regulate metal mobility and plant uptake.
- Organic and inorganic amendments immobilize metals through complementary physicochemical and biological mechanisms.
- Integrated amendment strategies can reduce metal uptake while improving soil quality and crop performance.
- Research priorities include amendment-rate optimization, varietal responses, and long-term field validation.

Keywords: Heavy metals, bioavailability, soil amendments, French beans, food safety, and soil remediation

How to cite this article: Mogire, E.O., Miriti, J., Mwakidoshi, E.R., Kitonga, L.LM., Nyang'au, D.N. and Gweyi-Onyango, J. (2026). Managing Heavy Metal Bioavailability in French Bean (*Phaseolus vulgaris* L.) Production Systems Using Soil Amendments: Mechanisms, Evidence, and Food Safety Implications. *Int. J. Ag. Env. Biotech.*, **19**(02): 55-78.

Source of Support: None; **Conflict of Interest:** None

The contamination of agricultural soils with heavy metals remains one of the most significant threats to safe and sustainable crop production, particularly in intensive horticultural systems (Vasilachi *et al.* 2023). Potentially toxic metals such as lead (Pb), copper (Cu), cadmium (Cd), arsenic (As), and nickel (Ni) may accumulate in soils to hazardous levels through a range of anthropogenic and natural pathways, including industrial emissions, environmental pollution, inorganic fertilizer use, and geogenic sources (Jadaa and Mohammed, 2023). Owing to their non-biodegradable nature, these metals persist in soils for prolonged periods, progressively entering the soil–plant continuum through root uptake. Their accumulation in plant tissues poses serious risks to crop growth, food quality, and human health through transfer along the food chain (Ali *et al.* 2019).

The growing demand for food production has further intensified this challenge. Continuous application of synthetic fertilizers, irrigation with wastewater, and repeated use of organic manures have contributed to the progressive enrichment of agricultural soils with heavy metals. For example, phosphorus-rich fertilizers are known to contain trace amounts of cadmium, while livestock manures may introduce additional metals through feed additives and veterinary products (Suciu *et al.* 2022). The risk becomes even more pronounced where multiple contamination sources coexist, such as atmospheric deposition, industrial wastes, and contaminated agricultural inputs (Khalid *et al.* 2016). This problem is particularly critical in short-cycle vegetable crops, which require substantial nutrient inputs and frequent irrigation, especially in water-limited production environments. Such intensive management practices increase the vulnerability of vegetables to heavy metal uptake and accumulation (Egbueri *et al.* 2025).

Among horticultural crops, French bean (*Phaseolus vulgaris* L.) is of particular agronomic and nutritional importance. The crop is widely cultivated due to its short growth cycle, adaptability to diverse production environments, and high nutritional value, including its rich content of proteins, vitamins, antioxidants, and dietary fiber (Sinkovič *et al.* 2024). French beans are also an important source of income for smallholder farmers, contributing significantly to household livelihoods, food security, and both local and export markets. However, their intensive cultivation places considerable pressure on soil resources, often necessitating repeated fertilizer and water inputs. More importantly, French bean pods, being the edible component, may accumulate heavy metals to levels that raise serious food safety concerns (Blommaert *et al.* 2022).

This concern is further amplified in export-oriented production systems, where produce must meet strict international food safety standards. Even trace concentrations of heavy metals in edible tissues can compromise market acceptability and significantly reduce export value. Beyond economic implications, such contamination poses direct public health risks to consumers and may also adversely affect the health of farmers exposed to contaminated soils and agricultural inputs during production (Muimba-Kankolongo *et al.* 2022; Moghaddam *et al.* 2021). These concerns underscore the need for robust management strategies that simultaneously sustain productivity and minimize contamination risks.

Soil amendments have increasingly emerged as a promising strategy for mitigating heavy metal mobility and bioavailability in agricultural soils. These materials are commonly applied to improve the physical, chemical, and biological properties of soils (Mogire *et al.* 2024). Organic amendments such as compost, farmyard manure, vermicompost, fertium, and biochar are widely used to enhance soil structure, increase organic matter content, stimulate microbial activity, and improve nutrient and water retention, thereby supporting sustainable crop production (Guo *et al.* 2022). Inorganic amendments, including lime, gypsum, and mineral fertilizers, also play critical roles in modifying soil chemical conditions and nutrient availability. For instance, lime is widely used to increase soil p^H in acidic soils, thereby improving nutrient accessibility and reducing metal solubility (Al-Enzy *et al.* 2025). Similarly, gypsum contributes calcium and sulfur, which are important in improving soil structure and nutrient balance (Abbas *et al.* 2023). In addition to enhancing soil fertility, these amendments can influence the mobility and phytoavailability of heavy metals in contaminated soils (Kaninga *et al.* 2020).

The interactions between soil amendments and heavy metals are governed by complex physicochemical and biological processes. Organic amendments may reduce metal bioavailability through the formation of stable organo-metal complexes mediated by functional groups associated with soil organic matter (Ejileugha *et al.* 2023). These complexes immobilize free metal ions in the soil solution, thereby limiting their uptake by plant roots. Likewise, inorganic amendments may reduce metal solubility through pH modification, precipitation reactions, and competitive ion interactions that suppress metal mobility (Seshadri *et al.* 2015). Integrated use of both organic and inorganic amendments, therefore, offers considerable potential for reducing heavy metal risks while simultaneously improving soil fertility and crop productivity (Kim *et al.* 2022).

Despite increasing research on heavy metal dynamics and soil remediation strategies, studies specifically focused on French bean production systems remain limited. Existing literature has predominantly concentrated on cereals and leafy vegetables, leaving a significant knowledge gap regarding the mechanisms governing heavy metal uptake, accumulation, and translocation in French beans. This gap constrains the development of targeted, evidence-based management strategies for safe and sustainable French bean production.

This review therefore aims to: (i) examine the major pathways and sources contributing to heavy metal accumulation in French bean tissues; (ii) synthesize the mechanisms through which soil amendments influence heavy metal mobility and bioavailability; (iii) evaluate the effects of soil amendments on metal uptake, crop performance, and food safety; and (iv) identify key research gaps and priorities for sustainable soil management approaches.

Sources of Heavy Metals in French Bean Production Systems

Heavy metal contamination in agricultural soils arises from both anthropogenic and natural sources, which often interact synergistically to increase soil contamination, metal mobility, and subsequent plant uptake (Table 1) (Kalkhajeh *et al.* 2020).

1. Agricultural Inputs (Fertilizers and Pesticides)

Agricultural inputs, particularly fertilizers and pesticides, constitute major anthropogenic sources of heavy metals in cultivated soils. Certain synthetic fertilizers, especially phosphatic fertilizers, contain trace metals originating from raw rock phosphate materials (Sarkar *et al.* 2024). Continuous and prolonged application of inorganic fertilizers can therefore lead to the gradual accumulation of metals such as cadmium, copper, and lead within soil

Table 1: Major Sources of Heavy Metals in French Bean Production Systems

Source Category	Specific Source	Common Metals	Entry Pathway	Key Risk Factors	Implications for French Bean Production
Agricultural inputs	Phosphate fertilizers, pesticides, and fungicides	Cd, Pb, As, Cu, Zn	Direct soil application and cumulative buildup	Low-quality inputs, excessive use	Increased topsoil accumulation and phytoavailability
Organic amendments	Farmyard manure, poultry manure, compost, sewage sludge	Cu, Zn, Cd, Pb, Ni	Addition of contaminated organic matter	Feed additives, waste origin	May improve soil quality, but also introduce metals
Irrigation water	Wastewater, industrial effluents, contaminated surface water	Cd, Pb, Cr, Ni, Hg	Repeated irrigation and rhizosphere loading	Proximity to urban and industrial areas	Major risk in peri-urban horticulture systems
Atmospheric deposition	Industrial emissions, vehicular exhaust, dust	Pb, Cd, Zn	Surface deposition onto soil and foliage	Traffic density, industrial emissions	Direct contamination of leaves and the soil surface
Mining and industrial activities	Tailings, smelting residues	Pb, Cd, As, Hg	Leaching, runoff, and sediment deposition	Poor waste management	Localized contamination hotspots
Geogenic sources	Parent material, rock weathering	Ni, Cr, Co, Zn	Natural pedogenic processes	Soil mineralogy and geology	Elevated baseline background levels
Agrochemical residues	Herbicides, micronutrient formulations	Cu, Zn	Repeated seasonal application	Misuse and overapplication	Long-term cumulative soil contamination

layers. In addition, micronutrients such as zinc may also be introduced through fertilizer use, and when applied in excess, these metals may accumulate to toxic concentrations (Rashmi *et al.* 2020).

Similarly, pesticides and fungicides contribute significantly to elevated heavy metal concentrations in soils. Intensive horticultural production systems frequently rely on high volumes of copper-based fungicides, which can result in excessive copper accumulation in the soil (Ochmian and Malinowski, 2024). Although plants possess inherent mechanisms for tolerating certain metal concentrations, excessive metal loads can overwhelm these defense systems, disrupt physiological processes, and ultimately reduce crop productivity (Kumar *et al.* 2019). Consequently, careful and regulated use of agrochemicals is essential to minimize soil contamination and reduce the risk of metal transfer through the food chain (Dixit *et al.* 2015).

2. Soil Organic Amendments (Compost and Manure Contamination)

Organic amendments are widely applied to improve soil fertility, enhance soil structure, and support crop productivity (Gourkhede *et al.* 2026). However, despite their agronomic benefits, these materials may also serve as sources of heavy metals, particularly when contamination levels exceed acceptable thresholds (Nunes *et al.* 2021).

For instance, livestock manure may contain elevated concentrations of copper and zinc due to their use as feed additives and dietary supplements in animal production systems (Zhang *et al.* 2026). These metals are subsequently excreted and introduced into soils through manure application, leading to gradual increases in soil metal concentrations over time (Mohammadi *et al.* 2025). In addition, industrial effluents incorporated into composting streams or waste-based amendments may contribute metals such as nickel, cadmium, and copper, which are recognized environmental contaminants (Mokarram *et al.* 2020).

Although organic amendments enhance soil organic matter and microbial abundance, repeated application without prior characterization may progressively elevate heavy metal concentrations and compromise long-term soil productivity (Periasamy *et al.* 2025). Because amendment quality and degree of decomposition vary widely, proper physicochemical characterization before field application is essential to ensure suitability and safety (Matisic *et al.* 2024).

3. Irrigation Water and Wastewater

Irrigation practices and the quality of water sources used play a significant role in the introduction and redistribution of heavy metals within agricultural soils (Goldan *et al.* 2023). In water-deficient areas, the use of untreated or polluted water sources is common, often introducing metals such as chromium, copper, cadmium, and lead into the soil–plant rhizosphere system (Dongre 2021).

This issue is particularly pronounced in peri-urban agricultural systems, where wastewater is frequently used due to its accessibility and perceived nutrient value, often resulting in substantial heavy metal loading in soils (Fischer and Fischer-García, 2023). Furthermore, both groundwater and surface water sources may contain trace metals derived from natural leaching processes, mining activities, and industrial discharges. Repeated irrigation under conditions of increasing food demand and water scarcity can therefore lead to cumulative metal loading, enhanced plant uptake, and eventual transfer to human consumers (Sheng *et al.* 2022).

4. Atmospheric and Industrial Deposition

Industrialization and urbanization contribute significantly to heavy metal contamination through atmospheric deposition pathways (Li *et al.* 2022). Emissions from factory chimneys, vehicular exhaust fumes, mining operations, and smelting activities release metal-laden particulates and gases into the atmosphere (Obayes 2022).

These emissions subsequently settle onto soil surfaces through dry deposition, rainfall, and adsorption processes. As a result, soils located near industrial zones, urban centers, and major road networks often exhibit higher concentrations of heavy metals compared with rural areas (Mehmood *et al.* 2019). Metals such as zinc, copper, and lead are commonly associated with atmospheric emissions and can be readily taken up by plants, thereby increasing risks to crop productivity and food safety (Boahen 2024). Owing to the diffuse nature of atmospheric contamination, this pathway remains one of the most difficult sources of soil contamination to control (Long *et al.* 2021).

5. Geogenic Sources

In addition to anthropogenic sources, geogenic processes also contribute to the natural presence of heavy metals in soils (Wu *et al.* 2022). Through physical, chemical, and biological weathering processes, parent rocks gradually disintegrate and release minerals containing varying concentrations of heavy metals into soils.

Elevated levels of metals such as chromium, nickel, and copper are often associated with volcanic and sedimentary soils (Yang *et al.* 2022). The specific concentrations and types of metals released depend largely on the mineralogical composition of the parent material and regional geological characteristics (Wen *et al.* 2020).

When geogenic sources interact with anthropogenic inputs such as fertilizers and pesticides, the resulting metal burden in soils may increase substantially. Although anthropogenic inputs often contribute higher contamination loads, naturally elevated background concentrations can also pose significant risks to agricultural production and food safety (Demirela *et al.* 2025). Therefore, understanding baseline geogenic metal levels is critical for accurately distinguishing contamination sources and guiding appropriate soil remediation strategies (Soltani-Gerdefaramarzi *et al.* 2021).

The contribution of heavy metal sources varies considerably depending on input quality, production systems, irrigation practices, and local geological conditions. Consequently, accurate source identification remains essential before selecting appropriate soil amelioration and remediation measures.

Mechanisms Controlling Heavy Metal Availability and Uptake in French Beans

Heavy metal movement within French bean production systems is governed by a complex interplay of physiological, chemical, and biological processes that determine metal availability in the rhizosphere, mobility within the soil matrix, root uptake, and eventual accumulation in pods and other plant tissues (Table 2) (Jorjani and Karakaş 2024). In legumes such as French beans, root

Table 2: Soil Amendments and Their Mechanisms in Reducing Heavy Metal Bioavailability

Amendment Type	Examples	Primary Mechanisms	Target Metals	Effects on Soil Properties	Effects on Plant Uptake	Limitations
Organic amendments	Compost, manure, biochar, green manure	Complexation, adsorption, chelation, and increased organic matter	Cd, Pb, Cu, Zn	↑ Organic matter, ↑ CEC, improved aggregation	↓ Metal uptake (depending on amendment quality)	May introduce metals if contaminated
Biochar	Crop residue biochar, wood biochar	Surface adsorption, pH increase, pore entrapment	Cd, Pb, Zn	↑ pH, ↑ CEC, improved soil structure	Strong reduction in bioavailability	The effect depends on feedstock type and pyrolysis temperature
Lime	$CaCO_3$, CaO	pH increase, precipitation of metals as hydroxides and carbonates	Cd, Pb, Zn	↑ Soil pH, ↓ soil acidity	↓ Metal solubility and uptake	Less effective in neutral to alkaline soils
Phosphate amendments	DAP, rock phosphate	Precipitation through metal–phosphate complex formation	Pb, Cd	↑ Phosphorus availability	Significant reduction in Pb uptake	Risk of eutrophication if overapplied
Gypsum	$CaSO_4{\cdot}2H_2O$	Ion exchange, Ca-mediated competition, structural improvement	Pb, Cd, Zn	Improves structure, particularly in sodic soils	Moderate reduction in metal uptake	Generally, less effective than lime for immobilization
Mineral amendments	Zeolite, clay minerals	Adsorption, ion exchange	Cd, Zn, Ni	↑ CEC, improved retention capacity	↓ Mobility and uptake	Cost and availability constraints
Integrated amendments	Organic matter + lime, biochar + fertilizer	Synergistic mechanisms (pH adjustment, adsorption, chelation)	Multiple metals	Improved overall soil quality	Strongest reduction in uptake	Site-specific responses

nodules involved in biological nitrogen fixation can influence rhizosphere chemistry by modifying soil p^H and redox conditions, thereby affecting metal solubility and plant uptake. Because pods represent the principal edible component and undergo rapid growth and nutrient demand during filling stages, they are particularly vulnerable to the accumulation of heavy metals under contaminated conditions (Wysokinski *et al.* 2023).

A sound understanding of these physiological and soil-mediated processes is essential for developing evidence-based strategies aimed at reducing heavy metal contamination in French bean pods and improving food safety outcomes.

1. Soil Chemical Dynamics (p^H, Organic Matter, and CEC)

Heavy metal bioavailability is strongly influenced by soil chemical properties, among which soil p^H remains one of the most critical determinants. Metals such as cadmium and copper generally exhibit greater solubility under acidic conditions, where increased proton activity enhances their release into the soil solution and makes them more available for plant uptake (Hasan *et al.* 2019). In contrast, under neutral to alkaline conditions, many metals become less available due to precipitation as hydroxides, carbonates, or other insoluble mineral forms.

Cation exchange capacity (CEC) also plays a major role in regulating heavy metal retention and mobility. Soils with higher clay and organic matter contents typically possess greater CEC, which enhances the adsorption and retention of positively charged metal ions, thereby reducing their bioavailability in the root zone (Zeng *et al.* 2010).

Similarly, soil organic matter contributes significantly to heavy metal immobilization through complexation and chelation processes. Functional groups such as carboxyl and phenolic groups bind metal ions and promote the formation of relatively stable organometallic complexes (Almotairy, 2024). However, under certain conditions, dissolved organic carbon may form soluble complexes that increase metal mobility toward the rhizosphere. This dual role indicates that organic matter can either reduce or enhance metal uptake depending on prevailing soil conditions and the nature of the metal involved (Lian *et al.* 2022).

2. Mobility of Heavy Metals

Heavy metals occur in soils in different physicochemical fractions, including residual, exchangeable, carbonate-bound, oxide-bound, and organic-bound forms (Mogire *et al.* 2025). Among these, the exchangeable and carbonate-bound fractions are generally considered the most bioavailable because they are more readily released into the soil solution (Akbarpour *et al.* 2021).

The distribution of metals among these fractions is highly dynamic and influenced by environmental factors such as soil pH, microbial activity, and oxidation–reduction reactions. For instance, reducing conditions may increase the solubility of certain metals by dissolving metal oxides, thereby enhancing their mobility and plant availability (Selvi *et al.* 2019). Conversely, oxidizing environments often promote precipitation reactions that reduce metal mobility and subsequent uptake by roots (Benalia *et al.* 2021).

3. Root Uptake Mechanisms

Plant roots absorb heavy metals through both passive and active transport processes. Passive uptake occurs through diffusion and mass flow, where dissolved metal ions move along concentration gradients in the soil solution. Active uptake, on the other hand, involves energy-dependent transport mediated by specific membrane proteins and ion carriers (Pang *et al.* 2023).

Some heavy metals exploit transport pathways normally used by essential nutrients. For example, cadmium may enter roots through calcium and zinc transport channels, facilitating its movement from the rhizosphere into above-ground biomass (Srivastava *et al.* 2017). Similarly, lead ions may utilize pathways shared by other divalent cations, reflecting the limited selectivity of some transport systems. This lack of selectivity contributes to the accumulation of metals in plant tissues beyond permissible safety thresholds (Kushwaha *et al.* 2015).

Root exudates, including enzymes and organic acids, further influence heavy metal uptake by modifying rhizosphere chemistry, altering p^H, and changing metal solubility and speciation (Neina 2019).

4. Internal Transport and Sequestration

Following root uptake, heavy metals are translocated from below-ground tissues to shoots and pods primarily through the xylem transport system. The extent of translocation depends on the type of metal, plant species, and prevailing physiological conditions (Sterckeman and Thomine 2020).

The accumulation of heavy metals in edible tissues such as French bean pods presents significant food safety concerns. To mitigate metal toxicity, plants employ several detoxification mechanisms. One major strategy involves sequestration of metal ions within vacuoles, thereby limiting their interaction with essential cellular processes (Galal *et al.* 2021).

In addition, phytochelatins and other metal-binding peptides play a crucial role in chelating and immobilizing heavy metals within plant cells, reducing their toxic effects (Faizan *et al.* 2024). Certain metals, particularly lead, also exhibit strong binding affinity to root cell walls, which restricts their translocation to aerial tissues and serves as an important defense mechanism (Hossain *et al.* 2012).

These internal transport and sequestration processes ultimately determine the extent to which metals accumulate in edible tissues.

5. Heavy Metal-Specific Behaviors (Zinc, Copper, Cadmium, Lead, and Others)

Different heavy metals exhibit distinct behaviors within the soil–plant system, which significantly influences their bioavailability, uptake, and accumulation in French bean tissues.

Cadmium is among the most concerning metals due to its high mobility in soils and efficient translocation within plants, often resulting in elevated concentrations in edible tissues (Vasile *et al.* 2021). In contrast, lead is generally less mobile and tends to accumulate predominantly in roots, although limited translocation to shoots and pods may occur under certain soil conditions (Ghori *et al.* 2019).

Copper and zinc, unlike cadmium and lead, are essential micronutrients required for normal plant growth and metabolic functioning. However, excessive concentrations can induce toxicity, disrupt physiological processes, and impair tissue development (Prasad *et al.* 2016). While plants possess regulatory mechanisms to maintain homeostasis of these essential elements, elevated soil concentrations may overwhelm these systems and lead to excessive accumulation.

The distinct physicochemical properties and plant interactions of individual metals necessitate metal-specific management strategies for effective remediation and risk reduction in contaminated production systems (Gupta *et al.* 2016).

Heavy metal bioavailability and uptake in French bean tissues are governed by soil chemical properties, metal speciation, plant physiological dynamics, and the intrinsic characteristics of individual metals, underscoring the importance of both individual and integrated management approaches for ensuring crop safety and consumer health.

Effects of Organic Amendments on the Immobilization of Heavy Metals

The application of organic amendments significantly alters the biological, chemical, and physical properties of soils, thereby playing an important role in the detoxification and immobilization of heavy metals in contaminated environments. These amendments reduce heavy metal bioavailability through several mechanisms, including precipitation, adsorption, complexation, and microbially mediated transformations (Sharma and Nagpal 2017). However, the effectiveness of these amendments varies depending on application rate, amendment quality, and prevailing soil conditions. A critical understanding of both their benefits and limitations is therefore essential for effective management.

1. Biochar

Biochar is a carbon-rich material produced through the pyrolysis of plant biomass under oxygen-limited conditions and has gained considerable attention as a soil amendment for the remediation of heavy metal-contaminated soils (Tu *et al.* 2020). Its effectiveness in reducing heavy metal bioavailability is largely attributed to its alkaline nature, which promotes the precipitation of metals as hydroxides and carbonates, thereby reducing their solubility and mobility.

In addition, biochar possesses a large surface area, porous structure, and abundant functional groups, all of which enhance its capacity to adsorb and immobilize metal ions (El-Naggar *et al.* 2017). Beyond heavy metal immobilization, biochar also improves soil cation exchange capacity, soil structure, water-holding capacity, and microbial abundance through enhanced biogeochemical interactions (Bandara *et al.* 2019).

The efficiency of biochar is strongly influenced by the feedstock material used and the conditions maintained during the pyrolysis process. Poorly prepared biochar may retain contaminants or release residual heavy metals into the soil system (Murtaza *et al.* 2024). Furthermore, excessive application may increase dissolved organic carbon in the soil, which under certain conditions can enhance the mobility of specific metals rather than suppress it (Liu *et al.* 2022). This highlights the importance of standardized production and appropriate application rates.

2. Compost

Compost is widely preferred by farmers because of its capacity to improve soil structure, enhance water-holding capacity, and supply essential nutrients. In contaminated soils, compost contributes to heavy metal immobilization mainly through adsorption and complexation processes facilitated by the release of functional organic groups (Urra *et al.* 2019).

Compost also stimulates microbial activity by supplying organic substrates, which promotes particle flocculation and aggregation, thereby reducing metal mobility and improving crop growth conditions (Liu *et al.* 2021).

Despite these benefits, compost application is not without limitations. Since compost is often prepared from multiple raw materials, contamination risk depends heavily on source quality. Organic materials originating from contaminated waste streams may themselves contain heavy metals and other pollutants. Moreover, decomposition processes release dissolved organic carbon, which under favorable conditions may increase the solubility and mobility of certain metals, thereby facilitating translocation within plant tissues (Sui *et al.* 2026). These limitations underscore the need for careful assessment of feedstock quality before field application.

3. Farmyard Manure

Farmyard manure consists of accumulated animal waste, including urine, droppings, and trampled feed residues, and is widely used to improve soil fertility while contributing to heavy metal immobilization (Sikka *et al.* 2025).

The organic matter released from farmyard manure facilitates the formation of stable organo-metal complexes through complexation processes, thereby reducing the availability of heavy metals in the soil solution (Dotaniya *et al.* 2022). In addition, farmyard manure improves soil aggregation, enhances moisture retention, and promotes microbial abundance, all of which contribute to reduced metal mobility and lower plant uptake (Irin and Hasanuzzaman 2024).

However, the quality of farmyard manure is highly dependent on its source. Manure derived from livestock exposed to contaminated feeds and water sources may contribute substantial loads of metals such as copper and zinc, especially under repeated long-term application (Aziz *et al.* 2017). During mineralization, some metals previously bound to organic fractions may also be released back into the soil solution, increasing their availability in the rhizosphere.

4. Green Manures

Green manures contribute to heavy metal immobilization through both direct and indirect mechanisms. These amendments are typically derived from fresh plant biomass, often fast-growing leguminous species with high vegetative mass (Hussain *et al.* 2021).

Upon decomposition, green manures release organic matter that contains functional groups capable of binding heavy metal ions and forming relatively stable organo-metal complexes, thereby reducing their concentration in the soil solution (Stancampiano *et al.* 2023). Some plant species used as green manure may also accumulate heavy metals within their tissues and sequester them in vacuoles, temporarily restricting their movement within the soil–plant system.

Furthermore, the decomposition of green manure improves the soil biological environment, stimulating microbial activity that can transform metals from more bioavailable forms into less accessible fractions (Kweza 2020).

Nevertheless, the effectiveness of green manures depends on factors such as decomposition rate, environmental conditions during mineralization, and plant species used. During decomposition, the release of humic substances and organic acids may, under some conditions, increase metal solubility and enhance uptake rather than immobilization (Chen *et al.* 2022). Additionally, species with strong phytoaccumulation characteristics may reintroduce previously accumulated metals into the soil after decomposition, which may counteract remediation efforts.

Organic amendments offer considerable potential for reducing heavy metal bioavailability while simultaneously improving soil quality and crop productivity. However, their effectiveness is strongly dependent on amendment source, quality, application rate, and soil conditions, underscoring the need for site-specific management strategies.

Effects of Inorganic Amendments on the Immobilization of Heavy Metals

Inorganic amendments are widely used as rapid and effective options for reducing heavy metal concentrations in degraded soils, particularly by smallholder farmers. Unlike organic amendments, which often rely on complexation and biologically mediated mechanisms, inorganic amendments primarily reduce heavy metal bioavailability through physicochemical processes such as adsorption, precipitation, and pH modification (Guo *et al.* 2020). These amendments play a critical role in stabilizing heavy metals within the soil matrix, thereby reducing their transfer into the edible tissues of French beans. Their effectiveness, however, is strongly influenced by the type of metal involved, soil characteristics, and the rate of amendment application (Gul *et al.* 2019).

1. Lime

Lime is among the most commonly used inorganic soil amendments for reducing heavy metal concentrations in contaminated soils, particularly in acidic production systems. Its primary mechanism of action is the increase of soil p^H, which reduces the solubility of metals such as lead, cadmium, and copper. Under elevated p^H conditions, many metals precipitate as hydroxides and carbonates, thereby reducing their mobility and plant availability (Sun *et al.* 2009).

In addition to p^H-mediated precipitation, lime application can enhance cation exchange capacity and increase the adsorption of metal ions onto soil particles, further reducing their uptake by plants. In French bean production systems, liming therefore plays an important role in minimizing heavy metal translocation from the soil to edible tissues (Cui *et al.* 2024).

Despite these benefits, excessive reliance on lime may result in over-alkalinization of soils, which can induce deficiencies of essential nutrients such as phosphorus, iron, and manganese, ultimately affecting crop productivity. Moreover, liming primarily immobilizes heavy metals rather than removing them from the soil system, meaning contamination may persist over extended periods, especially under changing environmental conditions (Moghal *et al.* 2019). Its effectiveness may also decline in highly buffered soils where p^H changes are less pronounced.

2. Phosphates

Phosphorus-rich amendments are widely used to immobilize heavy metals, particularly lead, through the formation of stable and insoluble metal–phosphate compounds. For example, lead may precipitate as lead phosphate minerals, thereby reducing its mobility and bioavailability (Peiris *et al.* 2023).

Phosphorus also reduces heavy metal availability by competing for adsorption sites within the soil matrix, thereby limiting the binding and movement of certain metals. Through these precipitation and competitive adsorption processes, phosphatic amendments can effectively reduce heavy metal uptake within the root zone of French bean production systems (Campillo-Cora *et al.* 2020).

However, phosphorus-based amendments also present important limitations. Excessive application may lead to nutrient imbalances and environmental concerns such as eutrophication of nearby water bodies. In addition, some phosphatic fertilizers may themselves contain trace amounts of heavy metals, which can contribute to soil contamination under repeated use (Abebe *et al.* 2022). Their performance is also influenced by soil p^H and ionic competition, which determine the stability of formed metal–phosphate compounds (Liu *et al.* 2022).

3. Gypsum

Gypsum, also known as calcium sulfate, is another important inorganic amendment used to improve soil physical, chemical, and biological properties while contributing to the reduction of heavy metal bioavailability (Dubrovina *et al.* 2021).

Unlike lime, gypsum does not directly alter soil pH to a significant extent (Minato *et al.* 2023). Instead, its role in heavy metal management is largely mediated through calcium-driven ion exchange and improvements in soil structure. By enhancing soil aggregation, permeability, and infiltration, gypsum reduces surface runoff and erosion, thereby limiting metal movement across the soil profile.

The calcium ions supplied by gypsum also compete with heavy metal cations for exchange and adsorption sites on soil particles, which may reduce heavy metal uptake and improve French bean productivity under contaminated conditions (Moyne and Sterckeman 2023).

Gypsum is particularly beneficial in sodic soils, where it improves root penetration and plant resilience by ameliorating soil physical constraints. Nevertheless, compared with lime and phosphate amendments, its effectiveness in heavy metal immobilization is often relatively lower and may require repeated applications to maintain its benefits over time.

4. Mineral Additives

Mineral-based amendments possess high adsorption capacities and are widely used in the immobilization of heavy metals in soils. Common examples include zeolites, bentonite, iron oxides, and manganese oxides (Zhang and Pu 2011).

These materials primarily function through adsorption and cation exchange mechanisms, owing to their large surface area and abundance of reactive binding sites. For example, iron oxides are particularly effective in binding metals such as cadmium, lead, and arsenic, while zeolites efficiently adsorb cationic heavy metals because of their high cation exchange capacity and porous structure (Yuna 2016).

The incorporation of mineral additives therefore improves metal retention in soils and reduces bioavailability within the rhizosphere, thereby minimizing uptake by French bean roots. A major advantage of these amendments is their stability and metal-specific performance across a wide range of soil conditions.

However, their application may be limited by relatively high costs, and their adsorption sites may become saturated over time, leading to reduced effectiveness. In addition, unlike organic amendments, mineral additives contribute little to improvements in soil organic matter and biological activity, which may limit their broader agronomic benefits (Kumar *et al.* 2017).

Inorganic amendments offer rapid and effective mechanisms for heavy metal stabilization, although their long-term performance and agronomic suitability depend strongly on soil conditions, amendment type, and application strategy.

Comparative Performance of Organic and Inorganic Soil Amendments in Heavy Metal Immobilization

Considerable attention has been directed toward the use of soil amendments as practical strategies for immobilizing heavy metals in contaminated agricultural soils, particularly within French bean production systems (Table 3). Both inorganic and organic amendments have demonstrated varying degrees of effectiveness in reducing heavy metal bioavailability, although their performance differs depending on soil conditions, metal type, and amendment characteristics (Zhao and Imran 2024).

A comparative evaluation of these amendment groups reveals important differences in their mechanisms of action, speed of response, long-term stability, agronomic benefits, and associated limitations. Inorganic amendments such as lime, phosphates, gypsum, and mineral additives generally provide rapid immobilization through chemical stabilization mechanisms, including precipitation, adsorption, and ion exchange (Rocco *et al.* 2018)

In contrast, organic amendments such as biochar, compost, manure, and green manure typically exert their effects through gradual physicochemical and biologically mediated processes. These

Table 3: Comparison of Organic and Inorganic Amendments in Heavy Metal Immobilization

Dimension	Inorganic Amendments (lime, phosphates, gypsum, mineral additives)	Organic Amendments (biochar, compost, manure, green manure)
Speed of action	Fast (days to weeks); immediate chemical stabilization	Slow to moderate (weeks to months); gradual physicochemical and biological processes
Persistence	Moderate; effects may decline without repeated application	High; longer-term stability through persistent organic matter
Soil health benefits	Limited, mainly chemical immobilization	High improves structure, water retention, nutrient cycling, and microbial activity.
Contamination risk	Low when clean materials are used	Variable; depends on feedstock quality
Cost/accessibility	Generally low and widely available	Moderate; biochar may be costly, but compost and manure are more accessible.
Suitability by soil type	Acidic, sandy, and low-clay soils	Soils with low organic matter and poor biological activity
Effectiveness by metal type	Strong for Cd, Pb, Zn	Strong for Cd, Zn; moderate for Pb and Ni

include complexation, chelation, adsorption, and enhancement of soil biological activity. Although their response may be slower, they often provide longer-term improvements in soil quality and ecosystem function (Fadeyi *et al.* 2026).

Importantly, organic amendments confer broader soil health benefits, including improvements in soil structure, moisture retention, nutrient cycling, and microbial abundance, whereas inorganic amendments are generally more limited to chemical stabilization functions (Ali *et al.* 2025).

The relative effectiveness of these amendments also varies by metal type. Inorganic amendments are often particularly effective for immobilizing cadmium, lead, and zinc, while organic amendments may provide stronger long-term control of cadmium and zinc, with variable performance for lead and nickel depending on amendment source and soil environment (Ibrahim *et al.* 2026).

The choice between organic and inorganic amendments should be guided by site-specific soil conditions, target metal species, economic feasibility, and desired duration of remediation.

Integrated Amendment Strategies and Synergistic Effects

Integrated soil amendment strategies often provide superior outcomes in reducing heavy metal bioavailability compared with the application of single amendments alone (Huang *et al.* 2016). The synergistic effects of these combined approaches arise from the interaction of physical, chemical, and biological mechanisms that collectively enhance heavy metal immobilization, improve soil health, and support crop productivity. However, the effectiveness of integrated systems may be compromised by inappropriate application rates, poor timing, and the use of low-quality amendment materials, all of which reduce their remediation potential (Table 4).

1. Organic Matter and Lime Combinations

Organic amendments such as farmyard manure, compost, and green manures are important sources of organic matter in agricultural soils. When combined with lime, these amendments are generally more effective in immobilizing heavy metals than when applied individually.

Lime primarily reduces heavy metal solubility through an increase in soil p^H, which promotes precipitation of metals as hydroxides and carbonates. In contrast, organic amendments contribute to immobilization through adsorption processes and the formation of stable organo-metal complexes, particularly via humic substances and other reactive organic fractions (Aggarwal *et al.* 2025).

The combined use of organic matter and lime also improves soil structure, enhances nutrient retention, and promotes microbial abundance, thereby contributing to both soil restoration and reduced heavy metal uptake in degraded soils (Qaswar *et al.* 2020). Nevertheless, the efficiency of this combination depends on soil-specific conditions. For example, soils with high buffering capacity may limit the p^H-modifying effect of lime, thereby reducing its effectiveness in heavy

Table 4: Comparative Summary of Studies on Integrated Soil Amendments and Heavy Metal Reduction in Crop Systems

Study Type	Crop / System	Amendment Applied	Target Metal(s)	Key Soil Response	Effect on Plant Uptake	Effect on Yield	Key Interpretation
Field study	French bean/ legumes	Compost + lime	Cd, Pb	↑ pH, ↑ organic matter	↓ Cd and Pb uptake	↑ Yield	An integrated approach more effective than single amendments
Pot experiment	Vegetable crops	Biochar	Cd, Zn	↓ Available metals, ↑ CEC	Significant reduction in uptake	Moderate yield increase	High adsorption-mediated immobilization
Field study	Leafy vegetables	Farmyard manure	Cu, Zn	↑ Organic matter, variable metal content	Variable depending on manure quality	↑ Yield	Potential contamination risk if the manure source is polluted
Controlled study	Legumes	Lime	Cd, Pb	↑ pH, ↓ metal solubility	Reduced uptake	Neutral to slight increase	Greater effectiveness under acidic soil conditions
Field trial	Mixed cropping system	Phosphate fertilizer	Pb	Formation of insoluble Pb compounds	Significant reduction in Pb uptake	↑ Yield	Highly effective for Pb immobilization
Pot experiment	Horticultural crops	Biochar + fertilizer	Cd, Zn	Synergistic improvement in soil properties	Strong reduction in uptake	Highest yield response	Best-performing integrated combination
Field study	Irrigated vegetables	Compost + biochar	Multiple metals	Improved structure and organic matter	Reduced bioavailability	↑ Yield	Demonstrates potential long-term benefits

metal stabilization. In acidic soils with low organic matter content, the integration of both organic and inorganic amendments is often particularly beneficial (Najafi and Jalali 2016).

2. Organic Matter and Fertilizer Combinations

The integration of organic amendments with synthetic fertilizers provides a balanced approach for simultaneously managing plant nutrition and heavy metal risks. Synthetic fertilizers supply essential nutrients required for optimal French bean growth, while organic matter contributes to heavy metal immobilization through adsorption and complexation mechanisms (Singh *et al.* 2023).

Enhanced biomass production resulting from improved nutrient supply may also contribute to a dilution effect, whereby heavy metal concentrations in plant tissues are reduced as a result of increased growth and dry matter accumulation, thereby lowering the risk of excessive metal accumulation in pods (Wang *et al.* 2016).

However, excessive use of synthetic fertilizers, particularly phosphorus-based fertilizers, may under certain conditions contribute additional heavy metals or alter soil chemistry in ways that increase metal solubility and bioavailability. Therefore, careful optimization of fertilizer type, application rate, and amendment combinations is essential for maximizing crop productivity while minimizing heavy metal uptake (Nzihou and Sharrock 2010).

3. Biochar and Mineral Amendments

The combined use of biochar with mineral amendments such as iron oxides, manganese oxides, phosphates, and lime has been shown to substantially reduce heavy metal uptake in crops.

Mineral amendments primarily function through adsorption, precipitation, and ion exchange processes that reduce metal mobility in soils (Mensah *et al.* 2022). Biochar complements these processes through its large surface area, porous structure, and abundance of functional groups, all of which enhance adsorption and complexation of metal ions.

This integrated approach has demonstrated superior performance in reducing metals such as copper, zinc, and cadmium compared with the use of individual amendments alone (Branzini and Zubillaga 2012).

The effectiveness of these combinations is strongly influenced by soil type and environmental conditions. Clay soils generally possess greater adsorption capacity than sandy soils, although sandy soils may benefit substantially from biochar addition through improved aggregation and enhanced sorption capacity (Du *et al.* 2023). Soil pH and metal-specific chemistry also play important roles in determining remediation efficiency.

4. Synergy and Context-Specific Responses

Integrated amendment systems often outperform sole amendment applications because they simultaneously exploit physical, chemical, and biological mechanisms involved in soil restoration and heavy metal immobilization (Karer *et al.* 2015).

These systems not only reduce heavy metal bioavailability but also improve soil health indicators such as microbial abundance, nutrient retention, and crop productivity. However, the magnitude of these benefits is highly context-dependent and varies according to environmental conditions, contamination levels, soil organic matter content, and soil p^H (Kwiatkowska-Malina 2017).

Soils with low cation exchange capacity and acidic conditions often exhibit stronger responses to amendment-based remediation than neutral or alkaline soils. In neutral soils, the combined use of mineral amendments and organic matter may provide more effective remediation outcomes (Nejad *et al.* 2021).

Integrated amendment strategies represent one of the most promising approaches for long-term mitigation of heavy metal risks in French bean production systems.

Impacts on Soil Properties, French Bean Growth, Yield, and Edible Tissue Contamination

Soil amendments exert significant effects on soil physicochemical and biological properties, plant growth performance, and the accumulation of heavy metals in edible plant tissues (Teodoro *et al.* 2019). Understanding these effects is essential for the development of evidence-based strategies aimed at reducing heavy metal risks while simultaneously enhancing crop productivity and food safety. Such information is particularly important for researchers, practitioners, and policymakers involved in the design of sustainable soil management interventions.

1. Changes in Soil Physical and Chemical Characteristics

The mobility and uptake of heavy metals are strongly influenced by changes in soil physical and chemical properties induced by amendment application. Organic amendments such as farmyard manure, green manure, and compost improve soil aggregation, increase cation exchange capacity, and enhance soil organic matter content (Khadim *et al.* 2024). These modifications increase the adsorption capacity of soils and promote the retention of metal ions, thereby reducing their mobility and bioavailability.

Similarly, biochar application contributes to heavy metal immobilization, particularly in acidic soils, where metals are often precipitated as hydroxides and other less soluble forms (Jia *et al.* 2021).

Soil p^H and heavy metal speciation are also strongly influenced by inorganic amendments such as lime and gypsum. Liming increases soil p^H, which promotes the precipitation and immobilization of heavy metals, thereby reducing their availability for plant uptake. Likewise, phosphorus-rich fertilizers may facilitate the formation of insoluble phosphatic metal complexes, particularly for metals such as lead (Gómez and Ruiz 2023).

Gypsum contributes primarily through improvements in soil structure, water infiltration, and soil chemical balance. The combined use of organic and inorganic amendments often generates synergistic effects that enhance both soil quality and heavy metal stabilization, making these integrated strategies highly suitable for sustainable crop production systems (Hassoune *et al.* 2020).

2. Effects on Plant Growth and Yield

The application of both organic and inorganic soil amendments has been shown to improve French bean production systems through enhanced soil fertility and reduced heavy metal stress.

Organic amendments improve root development by enhancing soil structure, increasing nutrient availability, and improving water-holding capacity and moisture retention, all of which contribute to better plant growth and establishment (Hassoune *et al.* 2020).

Several studies have reported that amendments such as biochar, compost, and lime improve crop performance indicators, including pod number, pod weight, biomass accumulation, and overall yield.

Integrated amendment strategies, such as biochar combined with mineral additives or lime combined with organic matter, often produce stronger improvements in soil health and crop performance than single amendments, thereby supporting sustainable production systems (Meena and Prakasha 2021).

Improved pod quality and increased marketable yield also have important socioeconomic implications, as they may enhance farmer income and improve livelihoods, particularly among smallholder farmers dependent on French bean production (Mahapatra *et al.* 2024).

3. Accumulation of Heavy Metals in Edible French Bean Pods

Because French bean pods constitute the edible portion consumed by humans, the accumulation of heavy metals in pods is of critical concern for food safety and public health (Lane *et al.* 2026).

The use of both organic and inorganic amendments has significantly contributed to the reduction of heavy metal accumulation in French bean tissues through mechanisms such as adsorption, complexation, ion exchange, and precipitation (Rizwan *et al.* 2020).

However, reduced uptake does not necessarily imply complete elimination of contamination risk. Soil conditions may change over time, and continuous cropping or repeated amendment use may create conditions that increase metal solubility and facilitate renewed uptake within the rhizosphere (Norouzi and Akbari 2026).

The concentration of heavy metals in plant tissues is influenced by several interacting factors, including metal type, soil characteristics, and amendment properties. For example, cadmium and lead tend to become more bioavailable under acidic soil conditions because of increased solubility and reduced complex formation, which enhances their uptake by plants (Chibuike and Obiora 2014).

Therefore, while soil amendments play an important role in reducing heavy metal mobility, continuous monitoring remains essential to ensure sustained effectiveness. Overreliance on amendment-based immobilization without periodic reassessment may allow previously stabilized metals to become reavailable in soils over time (Shakti and Pandey 2024). A conceptual summary of the major contamination pathways, immobilization mechanisms, integrated amendment strategies, and their effects on soil and crop performance is presented in Fig. 1.

Food Safety, Human Health Risks, and Regulatory Considerations

The accumulation of heavy metals such as lead, copper, and cadmium in edible plant tissues poses significant risks to human health through food chain transfer (Goni *et al.* 2024). Understanding the maximum permissible limits (MPLs) and key human health risk indices, including estimated daily intake and hazard quotient, is essential for evaluating the risks associated with contaminated food consumption. Consequently, safeguarding consumers requires effective soil health management and sustainable soil amendment strategies that minimize metal transfer into edible tissues.

1. Permissible Limits

Maximum permissible limits (MPLs) for heavy metals in food products are established by both national and international food safety agencies to protect human health. According to the European Food Safety Authority, the maximum permissible limits in legumes are 0.2 mg kg^{-1} for cadmium, 0.1 mg kg^{-1} for lead, and 10 mg kg^{-1} for copper (Ahmad and Goni 2009).

Consumption of legume products containing metal concentrations above these thresholds may expose consumers to serious health risks, including kidney dysfunction, neurological disorders, developmental impairment, and other chronic health complications. These contaminants reach humans indirectly through enrichment and transfer along the food chain (Wei and Cen 2020).

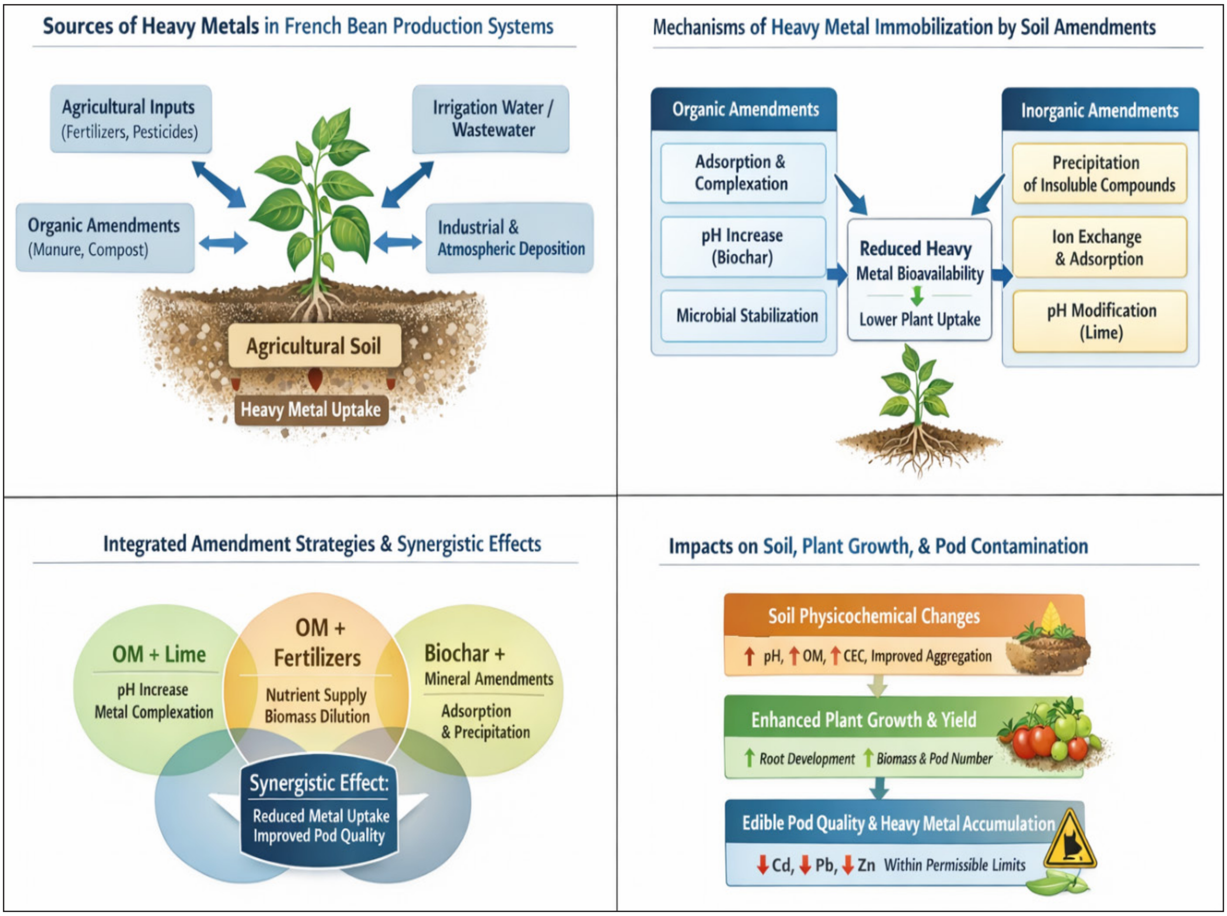

Fig. 1: Conceptual framework illustrating major sources of heavy metals in French bean production systems, mechanisms of immobilization by soil amendments, integrated amendment strategies, and their effects on soil properties, plant growth, and edible pod contamination

The application of carefully selected soil amendments plays an important role in maintaining heavy metal concentrations within acceptable limits. Several studies have reported that combinations such as biochar and lime are effective in keeping heavy metal concentrations in edible tissues within recommended safety thresholds.

2. Transfer Factor (TF)

The transfer factor (TF) is an important index used to assess the movement of heavy metals from soil into plant tissues such as roots, shoots, and pods (mg kg^{-1}) (Ullah *et al.* 2026).

The transfer factor is calculated as:

$$TF = \frac{\text{Concentration in plant tissue}}{\text{Concentration in soil}}$$

A transfer factor greater than one indicates that the plant accumulates higher concentrations of a given heavy metal relative to its concentration in soil, whereas a transfer factor less than one suggests relatively lower uptake and accumulation within plant tissues.

Studies in French bean production systems have shown that lead often exhibits lower transfer factors because of its strong retention in root tissues, while cadmium tends to exhibit higher transfer factors owing to its greater mobility in soils and efficient translocation within plant tissues (Saadaoui *et al.* 2022).

The use of soil amendments such as phosphate materials and biochar has been shown to reduce heavy metal bioavailability, resulting in lower concentrations and reduced transfer factors in French bean pods.

3. Hazard Quotient and Daily Intake

The potential health risk associated with the consumption of contaminated food is commonly assessed using indices such as Estimated Daily Intake (EDI) and Hazard Quotient (HQ) (Ain *et al.* 2023).

The hazard quotient is calculated as:

$$HQ = \frac{EDI}{RfD}$$

where *EDI* represents the estimated daily intake, and *RfD* is the reference dose for the specific heavy metal under consideration.

The units of EDI are typically expressed as mg kg^{-1} body weight day^{-1}.

An HQ value greater than one indicates a potential health risk to consumers, whereas values below one generally indicates low risk.

For example, children are often more susceptible to heavy metal exposure because of their lower body weight and relatively higher intake per unit body mass, making them particularly vulnerable to contaminants such as lead and cadmium (Mao *et al.* 2018).

These considerations further emphasize the need to maintain heavy metal concentrations in French bean pods within established permissible limits.

4. Differences Across Regulations

Regulatory thresholds for heavy metals in plant tissues vary across countries and regulatory bodies.

For legumes, the European Union sets maximum permissible limits of 0.1 mg kg^{-1} for lead and 0.2 mg kg^{-1} for cadmium (Timoracka 2019). However, some countries lack crop-specific thresholds and therefore rely on broader international food safety guidelines.

This variation highlights the importance of adopting robust risk assessment frameworks and site-specific management strategies to ensure compliance with both local and international market standards.

Effective regulation of heavy metals in food crops is therefore critical for ensuring food safety in both domestic and export markets (Latif *et al.* 2018).

It has been widely reported that soil amendment strategies are closely linked to maintaining heavy metal concentrations within maximum allowable limits in French bean pods and other edible tissues. A schematic representation of heavy metal uptake, pod accumulation, transfer factor, and associated human health risk indices is presented in Fig. 2.

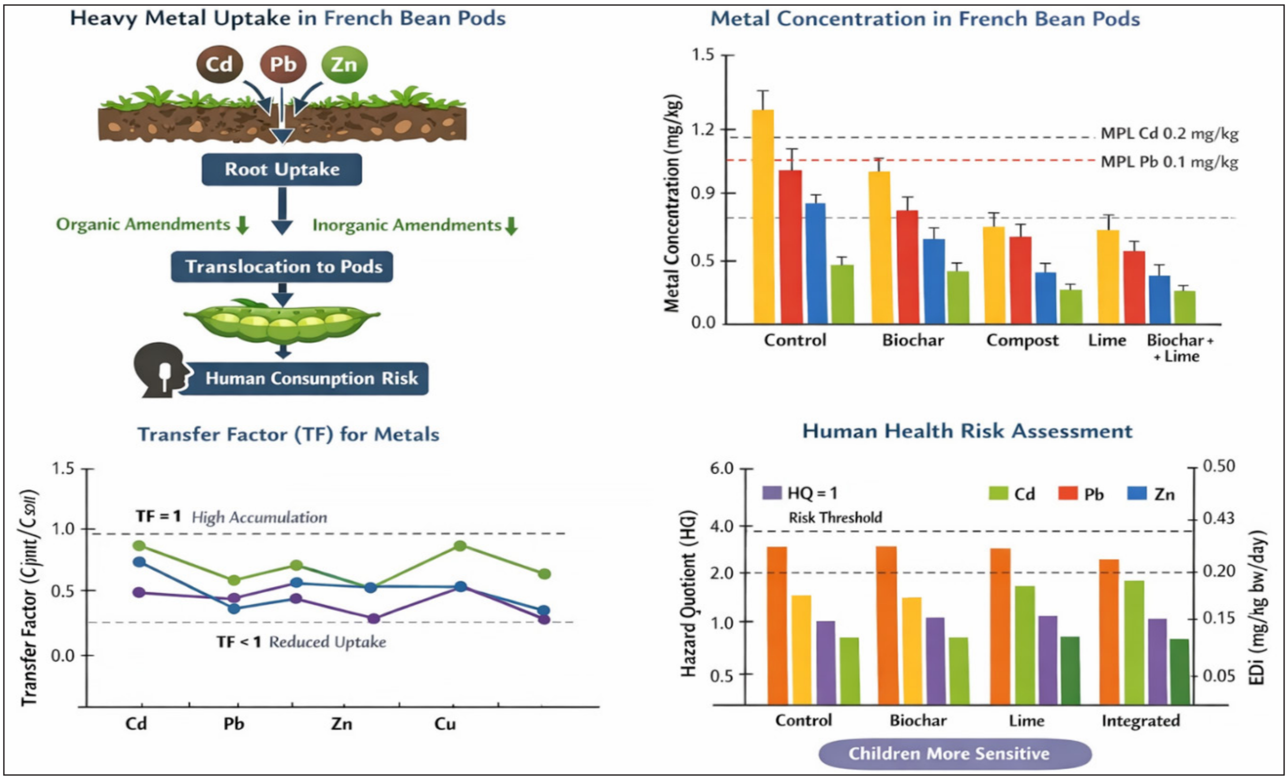

Fig. 2: Conceptual and analytical representation of heavy metal uptake, accumulation in French bean pods, transfer factor, and associated human health risk assessment under different soil amendment strategies

Knowledge Gaps and Future Research Priorities

Substantial progress has been made in understanding the role of soil amendments in the immobilization of heavy metals within soil–plant systems. Nevertheless, significant knowledge gaps remain, particularly in relation to French bean production systems. These limitations continue to constrain the development of fully optimized, evidence-based management strategies for safe and sustainable crop production.

A large proportion of existing studies has focused predominantly on leafy vegetables and cereal crops, with comparatively limited attention given to French beans. This is a notable gap considering the nutritional importance of French beans as a source of vitamins and their economic significance within both local and export markets. There is therefore a clear need for crop-specific studies aimed at understanding heavy metal uptake, translocation to pods, and the performance of different soil amendments specifically under French bean production systems.

Another major limitation lies in the predominance of short-term studies, often conducted within a single season and under poorly controlled or highly simplified experimental conditions. Such approaches may fail to capture long-term interactions among soil amendments, soil physicochemical properties, microbial dynamics, and crop responses. Long-term field-based studies are therefore essential for evaluating heavy metal stabilization dynamics, soil fertility trends, and crop performance across multiple growing seasons.

Current research also remains limited with respect to metal-specific responses, soil-type interactions, and French bean varietal differences. Many studies report the use of soil amendments without clearly defining specific target metals, optimal application rates, or crop genotype interactions. To maximize heavy metal immobilization while avoiding secondary challenges such as excessive alkalinity and nutrient imbalances, there is a need to establish crop- and site-specific amendment rates and combinations of both organic and inorganic materials.

In addition, most available studies are conducted under laboratory or pot conditions, which often do not adequately represent field realities. Field environments are inherently more complex because of spatial heterogeneity, fluctuating moisture regimes, and dynamic microbial processes, all of which can significantly influence amendment performance.

Despite frequent reporting of total heavy metal concentrations in soils, relatively few studies have focused on heavy metal speciation. A detailed understanding of metal fractions, including organic complexes, carbonate-bound forms, oxide-associated forms, and exchangeable pools, is critical for accurately predicting amendment effectiveness, transfer factors, and associated human health risks. Advanced analytical approaches such as X-ray spectroscopy and related spectrometric techniques should therefore be increasingly incorporated into future studies.

Another important research gap concerns the interaction between French bean cultivars and soil amendment strategies. Differences in root architecture, metal uptake capacity, and translocation to pods may vary considerably among cultivars, yet limited work has been undertaken to evaluate these interactions systematically.

Future research should therefore place greater emphasis on integrated amendment approaches that combine soil science, agronomy, plant physiology, and human health risk assessment to generate robust recommendations for sustainable agricultural systems.

CONCLUSION

Heavy metal accumulation in French bean tissues represents a significant threat to both crop productivity and food safety, largely driven by contamination of agricultural soils.

Current evidence indicates that both inorganic and organic soil amendments play important roles in the amelioration of heavy metal contamination through mechanisms such as complexation, adsorption, precipitation, enhancement of microbial activity, and modification of soil p^H.

Organic amendments, including green manure, farmyard manure, compost, and biochar, have been widely recommended because they provide relatively long-term and sustainable solutions for heavy metal immobilization while simultaneously improving soil quality.

Inorganic amendments such as lime, gypsum, phosphorus-based materials, and mineral additives contribute primarily through physicochemical stabilization processes that reduce metal mobility and plant uptake.

Importantly, the integration of organic and inorganic amendments often produces synergistic effects, resulting in improved soil health, reduced heavy metal bioavailability, enhanced crop productivity, and greater food safety compared with the use of single amendments.

These integrated strategies have also been associated with lower transfer factors, reduced heavy metal concentrations in edible tissues, and consequently lower risks to human health.

For maximum effectiveness, however, amendment rates and combinations must be carefully aligned with soil type, contamination level, and crop production conditions.

Despite recent advances, several uncertainties remain, particularly with respect to long-term field validation, French bean genotype responses, and amendment dose optimization. Additional research is still needed to better understand how environmental factors such as soil texture, microbial dynamics, and soil p^H interact with amendment performance under field conditions.

Furthermore, much of the available evidence remains derived from short-term experiments or from studies conducted on crops other than French beans, leaving a significant knowledge gap that must be addressed to better inform farmers, researchers, and policymakers.

Addressing these gaps will contribute substantially to the development of safer and more sustainable French bean production systems through improved soil physical, chemical, and biological conditions, ultimately supporting both agricultural productivity and consumer health.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

REFERENCES

Abbas, F., Siddique, T., Fan, R. and Azeem, M. 2023. Role of gypsum in conserving soil moisture, macronutrients uptake, and improving wheat yield in the rainfed area. *Water*, **15**(6): 1011.

Abebe, T.G., Tamtam, M.R., Abebe, A.A., Abtemariam, K.A., Shigut, T.G., Dejen, Y.A. and Haile, E.G. 2022. Growing use and impacts of chemical fertilizers and assessing alternative organic fertilizer sources in Ethiopia. *Applied and Environmental Soil Science*, *2022*, 1–14. https://doi.org/10.1155/2022/4738416

Aggarwal, M., Anbukumar, S., and Kumar, T.V. 2025. The relationship between pH, organic matter, and heavy metal concentrations in surface sediment of the Ganga River, India. *Water Environment Research*, **97**(8): e70160.

Ahmad, J.U. and Goni, M.A. 2009. Heavy metal contamination in water, soil, and vegetables of the industrial areas in Dhaka, Bangladesh. *Environmental Monitoring and Assessment*, **166**(1–4): 347–357.

Ain, S.N.U., Abbasi, A.M., Ajab, H., Faridullah, Khan, S. and Yaqub, A. 2023. Assessment of arsenic in Mangifera Indica (Mango) contaminated by artificial ripening agent: Target hazard quotient (THQ), health risk index (HRI), and estimated daily intake (EDI). *Food Chemistry Advances*, **3**: 100468.

Akbarpour, F., Gitipour, S., Baghdadi, M. and Mehrdadi, N. 2021. Correlation between chemical fractionation of heavy metals and their toxicity in the contaminated soils. *Environmental Earth Sciences*, **80**(21).

Al-Enzy, A.F., Ziydan, B.A. and Salih, M.A.A. 2025. Improvement of gypsum soil properties by adding organic and mineral fertilizers and its productivity for oil crops. *Kirkuk University Journal for Agricultural Sciences*, **16**(2).

Ali, A., Malik, Z., Basit, M.A., Dar, A., Zulfiqar, U., Sotiboldiyeva, D., Muminov, M., El-Beltagi, H.S. and Alqahtani, M.D. 2025. Integrating organic and inorganic amendments to enhance wheat growth, physiology and antioxidant activity while reducing cadmium accumulation. *BioMetals*, **39**(1): 389–408.

Ali, H., Khan, E. and Ilahi, I. 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, *2019*, 1–14. https://doi.org/10.1155/2019/6730305

Almotairy, H. 2024. Heavy metal contamination in soil: Implications for crop resilience and abiotic stress management. In *IntechOpen eBooks*. https://doi.org/10.5772/intechopen.114978

Aziz, M.A., Ahmad, H.R., Corwin, D.L., Sabir, M., Hakeem, K.R. and Öztürk, M. 2017. Influence of farmyard manure on retention and availability of nickel, zinc and lead in metal-contaminated calcareous loam soils. *Journal of Environmental Engineering and Landscape Management*, **25**(3): 289–296.

Bandara, T., Franks, A., Xu, J., Bolan, N., Wang, H. and Tang, C. 2019. Chemical and biological immobilization mechanisms of potentially toxic elements in biochar-amended soils. *Critical Reviews in Environmental Science and Technology*, **50**(9): 903–978.

Benalia, M.C., Youcef, L., Bouaziz, M.G., Achour, S. and Menasra, H. 2021. Removal of Heavy Metals from Industrial Wastewater by Chemical Precipitation: Mechanisms and Sludge Characterization. *Arabian Journal for Science and Engineering*, **47**(5): 5587–5599.

Blommaert, H., Aucour, A., Wiggenhauser, M., Moens, C., Telouk, P., Campillo, S., Beauchêne, J., Landrot, G., Testemale, D., Pin, S., Lewis, C., Umaharan, P., Smolders, E. and Sarret, G. 2022. From soil to cacao bean: Unravelling the pathways of cadmium translocation in a high Cd accumulating cultivar of Theobroma cacao L. *Frontiers in Plant Science*, **13**: 1055912.

Boahen, E. 2024. Heavy metal contamination in urban roadside vegetables: origins, exposure pathways, and health implications. *Discover Environment*, **2**(1).

Branzini, A. and Zubillaga, M.S. 2012. Comparative use of soil organic and inorganic amendments in heavy metals stabilization. *Applied and Environmental Soil Science*, *2012*, 1–7. https://doi.org/10.1155/2012/721032

Campillo-Cora, C., Conde-Cid, M., Arias-Estévez, M., Fernández-Calviño, D. and Alonso-Vega, F. 2020. Specific adsorption of heavy metals in soils: individual and competitive experiments. *Agronomy*, **10**(8): 1113.

Chen, Q., Zhang, Z., Wang, Y., Mu, G., Wu, X., Liu, Y., Luo, W. and Wen, X. 2022. Remediation of soil contaminated by HeavyMetals using Biochar: Strategiesand Future Prospects. *Polish Journal of Environmental Studies*, **32**(1): 27–40.

Chibuike, G.U. and Obiora, S.C. 2014. Heavy metal polluted soils: Effect on plants and bioremediation methods. *Applied and Environmental Soil Science*, *2014*, 1–12. https://doi.org/10.1155/2014/752708

Cui, H., Zhao, Y., Hu, K., Xia, R., Zhou, J., Zhou, J., Zhou, J. and Zhou, J. 2024. Impacts of atmospheric deposition on the heavy metal mobilization and bioavailability in soils amended by lime. *The Science of the Total Environment*, **914**: 170082.

Demirela, G., Terzi, M.H. and Durgun, M.B. 2025. Heavy metal enrichments in rural environment soils, pollution dynamics, source identification, and the role of subsurface mineralizations. *Scientific Reports*, **15**(1): 35858.

Dixit, R., Wasiullah, Malaviya, D., Pandiyan, K., Singh, U., Sahu, A., Shukla, R., Singh, B., Rai, J., Sharma, P., Lade, H. and Paul, D. 2015. Bioremediation of Heavy Metals from Soil and Aquatic Environment: An Overview of Principles and Criteria of Fundamental Processes. *Sustainability*, **7**(2): 2189–2212.

Dongre, R. 2021. Chromium; Lead as Soil Pollutants: Insights on Toxicity Profiles and their Remediation. *Journal of Advanced Biotechnology and Bioengineering*, **9**(1): 1–16.

Dotaniya, M.L., Rajendiran, S., Saurabh, K., Saha, J.K., Dotaniya, C.K. and Patra, A.K. 2022. Immobilization of chromium bioavailability through application of organic waste to Indian mustard (*Brassica juncea*) under chromium-contaminated Indian soils. *Environmental Monitoring and Assessment*, **195**(1): 31.

Du, Y., Feng, Y. and Xiao, Y. 2023. Interaction between biochar of different particle sizes and clay minerals in changing biochar physicochemical properties and cadmium sorption capacity. *Journal of Cleaner Production*, **428**: 139348.

Dubrovina, T.A., Losev, A.A., Karpukhin, M.M., Vorobeichik, E.L., Dovletyarova, E.A., Brykov, V.A., Brykova, R.A., Ginocchio, R., Yáñez, C. and Neaman, A. 2021. Gypsum soil amendment in metal-polluted soils—an added environmental hazard. *Chemosphere*, **281**: 130889.

Egbueri, J.C., Agbasi, J.C., Khan, M.Y.A., Abba, S.I., Turki, A.F., and ElKashouty, M. 2025. Assessing the environmental, health, and food security implications of heavy metals in irrigation water: a Multi-Index Analytical Framework. *Analytical Letters*, **59**(3): 373–408.

Ejileugha, C., Onyegbule, U.O. and Osuoha, J.O. 2023. Use of additives in composting promotes passivation and reduction in bioavailability of heavy metals (HMS) in compost. *Reviews of Environmental Contamination and Toxicology*, **262**(1).

El-Naggar, A., Shaheen, S.M., Ok, Y.S. and Rinklebe, J. 2017. Biochar affects the dissolved and colloidal concentrations of Cd, Cu, Ni, and Zn and their phytoavailability and potential mobility in a mining soil under dynamic redox-conditions. *The Science of the Total Environment*, **624**: 1059–1071.

Fadeyi, O.J., Fabunmi, T.O., Olowe, V.I.O. and Adejuyigbe, C.O. 2026. Impact of Organic Amendment on the agronomic performance of selected improved sorghum (*Sorghum bicolor* L. moench) varieties in the humid tropics. *International Journal of Plant Production*, **20**(1).

Faizan, M., Alam, P., Hussain, A., Karabulut, F., Tonny, S.H., Cheng, S.H., Yusuf, M., Adil, M.F., Sehar, S., Alomrani, S.O., Albalawi, T. and Hayat, S. 2024. Phytochelatins: Key regulator against heavy metal toxicity in plants. *Plant Stress*, **11**: 100355.

Fischer, G. and Fischer-García, F.L. 2023. Heavy metal contamination of vegetables in urban and peri-urban areas. An overview. *Revista Colombiana De Ciencias Hortícolas*, **17**(2).

Galal, T.M., Hassan, L.M., Ahmed, D.A., Alamri, S.A.M., Alrumman, S.A. and Eid, E.M. 2021. Heavy metals uptake by the global economic crop (*Pisum sativum* L.) grown in contaminated soils and its associated health risks. *PLoS ONE*, **16**(6): e0252229.

Ghori, N., Ghori, T., Hayat, M.Q., Imadi, S.R., Gul, A., Altay, V. and Ozturk, M. 2019. Heavy metal stress and responses in plants. *International Journal of Environmental Science and Technology*, **16**(3): 1807–1828.

Goldan, E., Nedeff, V., Barsan, N., Culea, M., Panainte-Lehadus, M., Mosnegutu, E., Tomozei, C., Chitimus, D. and Irimia, O. 2023. Assessment of Manure Compost Used as Soil Amendment—A review. *Processes*, **11**(4): 1167.

Gómez, A.A. and Ruiz, M.E.G. 2023. Heavy metal speciation, and the evaluation and remediation of polluted mine wastes and soils. In *IntechOpen eBooks*. https://doi.org/10.5772/intechopen.110412

Goni, M.A., Hosen, L., Khan, A.S., Abdullah-Al-Mamun, M., Khatun, M.J. and Siddiquee, T. 2024. Elevated uptake and translocation patterns of heavy metals in different food plants parts and their impacts on human health. *Biological Trace Element Research*, **203**(1): 512–534.

Gourkhede, P.H., Gore, A.K., Patil, M.G., Bhutda, P.O., Dhurgude, S.S., Pathrikar, D.T., Abdulraheem, M.I., Ch'ng, H.Y. and Rahimi, M. 2026. Long-term organic nutrient management in tomato enhances yield, quality, profitability, and soil health in a semi-arid conditions. *Scientific Reports*. https://doi.org/10.1038/s41598-026-41738-2

Gul, I., Manzoor, M., Hashmi, I., Bhatti, M.F., Kallerhoff, J., and Arshad, M. 2019. Plant uptake and leaching potential upon application of amendments in soils spiked with heavy metals (Cd and Pb). *Journal of Environmental Management*, **249**: 109408.

Gupta, N., Ram, H. and Kumar, B. 2016. Mechanism of Zinc absorption in plants: uptake, transport, translocation and accumulation. *Reviews in Environmental Science and Bio/Technology*, **15**(1): 89–109.

Hasan, S.A., Fariduddin, Q., Ali, B., Hayat, S. and Ahmad, A. 2019. Cadmium toxicity and tolerance in plants. *Elsevier eBooks*, **30**(2): 165–174.

Hassoune, H., Lachehab, A., Hajjaji, K.E., Mertah, O. and Kherbeche, A. 2020. Dynamic of heavy metals and environmental impact of waste Phosphogypsum. In *Microorganisms for sustainability* (pp. 57–77). https://doi.org/10.1007/978-981-15-6564-9_4

Hossain, M.A., Piyatida, P., Da Silva, J.A.T. and Fujita, M. 2012. Molecular mechanism of heavy metal toxicity and tolerance in plants: central role of glutathione in detoxification of reactive oxygen species and methylglyoxal and in heavy metal chelation. *Journal of Botany*, *2012*, 1–37. https://doi.org/10.1155/2012/872875

Huang, M., Zhu, Y., Li, Z., Huang, B., Luo, N., Liu, C. and Zeng, G. 2016. Compost as a Soil Amendment to Remediate Heavy Metal-Contaminated Agricultural Soil: Mechanisms, Efficacy, problems, and Strategies. *Water Air & Soil Pollution*, **227**(10).

Hussain, B., Li, J., Ma, Y., Chen, Y., Wu, C., Ullah, A. and Tahir, N. 2021. A Field Evidence of Cd, Zn and Cu Accumulation in Soil and Rice Grains after Long-Term (27 Years) Application of Swine and Green Manures in a Paddy Soil. *Sustainability*, **13**(4): 2404.

Ibrahim, N.Y.A., El-Khatib, A. and Mostafa, S. 2026. Biochar-mediated recovery of soil–wheat systems under heavy metal stress: toward sustainable development goals. *International Journal of Phytoremediation*, pp. 1–20. https://doi.org/10.1080/15226514.2026.2645912

Irin, I.J. and Hasanuzzaman, M. 2024. Organic Amendments: Enhancing plant tolerance to salinity and metal stress for improved agricultural productivity. *Stresses*, **4**(1): 185–209.

Jadaa, W. and Mohammed, H. 2023. Heavy Metals – Definition, Natural and Anthropogenic Sources of Releasing into Ecosystems, Toxicity, and Removal Methods – An Overview Study. *Journal of Ecological Engineering*, **24**(6): 249–271.

Jia, M., Yu, J., Li, Z., Wu, L. and Christie, P. 2021. Effects of biochar on the migration and transformation of metal species in a highly acid soil contaminated with multiple metals and leached with solutions of different p^H. *Chemosphere*, **278**: 130344.

Jorjani, S. and Karakaş, F.P. 2024. Physiological and biochemical responses to heavy metals stress in plants. *International Journal of Secondary Metabolite*, **11**(1): 169–190.

Kalkhajeh, Y.K., Huang, B., Hu, W., Ma, C., Gao, H., Thompson, M.L. and Hansen, H.C.B. 2020. Environmental soil quality and vegetable safety under current greenhouse vegetable production management in China. *Agriculture Ecosystems & Environment*, **307**: 107230.

Kaninga, B., Chishala, B.H., Maseka, K.K., Sakala, G.M., Young, S.D., Lark, R.M., Tye, A., Hamilton, E.M., Gardner, A. and Watts, M.J. 2020. Do soil amendments used to improve agricultural productivity have consequences for soils contaminated with heavy metals? *Heliyon*, **6**(11): e05502.

Karer, J., Wawra, A., Zehetner, F., Dunst, G., Wagner, M., Pavel, P., Puschenreiter, M., Friesl-Hanl, W. and Soja, G. 2015. Effects of biochars and compost mixtures and inorganic additives on immobilisation of heavy metals in contaminated soils. *Water Air & Soil Pollution*, **226**(10).

Khadim, M.D., Wesal, A.B. and Peezhand, A.W. 2024. Overview of the Impact of Compost on Bulk Density, Aggregate Consistency and Cation Exchange Capacity of Soils and its Consequential Effect on Crop Productivity. *Cognizance Journal of Multidisciplinary Studies*, **4**(6): 344–359.

Khalid, S., Shahid, M., Niazi, N.K., Murtaza, B., Bibi, I. and Dumat, C. 2016. A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of Geochemical Exploration*, **182**: 247–268.

Kim, Y., Lee, K., Lee, M. and Kim, K. 2022. Synergetic effect of complex soil amendments to improve soil quality and alleviate toxicity of heavy metal(loid)s in contaminated arable soil: toward securing crop food safety and productivity. *Environmental Science and Pollution Research*, **29**(58): 87555–87567.

Kumar, S.S., Kadier, A., Malyan, S.K., Ahmad, A. and Bishnoi, N.R. 2017. Phytoremediation and Rhizoremediation: Uptake, Mobilization and Sequestration of Heavy Metals by Plants. Int (pp. 367–394). https://doi.org/10.1007/978-981-10-6593-4_15

Kumar, V., Singh, J. and Kumar, P. 2019. Heavy metals accumulation in crop plants: Sources, response mechanisms, stress tolerance and their effects. In *Agro Environ Media - Agriculture and Ennvironmental Science Academy, Haridwar, India eBooks* (pp. 38–57). https://doi.org/10.26832/aesa-2019-cae-0161-04

Kushwaha, A., Rani, R., Kumar, S. and Gautam, A. 2015. Heavy metal detoxification and tolerance mechanisms in plants: Implications for phytoremediation. *Environmental Reviews*, **24**(1): 39–51.

Kweza, M. 2020. *Heavy metals in soil and vegetables of allotment gardens in the Cape Town environment*.http://etd.cput.ac.za/bitstream/20.500.11838/2989/1/Motuli_Kweza_209016868.pdf.-1.pdf

Kwiatkowska-Malina, J. 2017. Functions of organic matter in polluted soils: The effect of organic amendments on phytoavailability of heavy metals. *Applied Soil Ecology*, **123**: 542–545.

Lane, L., Wells, R., Vogel, C. and Reynolds, C. 2026. Improving food system outcomes with beans, peas and pulses: a prospective mapping review of research in the UK. *Public Health Nutrition*, **29**(1): e28.

Latif, A., Bilal, M., Asghar, W., Azeem, M., Ahmad, M.I., Abbas, A., Ahmad, M.Z. and Shahzad, T. 2018. Heavy Metal Accumulation in Vegetables and Assessment of their Potential Health Risk. *Journal of Environmental Analytical Chemistry*, **05**(01).

Li, F., Yang, H., Ayyamperumal, R. and Liu, Y. 2022. Pollution, sources, and human health risk assessment of heavy metals in urban areas around industrialization and urbanization-Northwest China. *Chemosphere*, **308**(Pt 2): 136396.

Lian, M., Wang, J., Ma, Y., Li, J. and Zeng, X. 2022. Influence of DOM and its subfractions on the mobilization of heavy metals in rhizosphere soil solution. *Scientific Reports*, **12**(1): 14082.

Liu, H., Zhou, Y., Qin, S., Awasth, S.K., Liu, T., Liu, H., Zhang, Z. and Awasthi, M.K. 2021. Distribution of heavy metal resistant bacterial community succession in cow manure biochar amended sheep manure compost. *Bioresource Technology*, **335**: 125282.

Liu, M., Zhu, J., Yang, X., Fu, Q., Hu, H. and Huang, Q. 2022. Biochar produced from the straw of common crops simultaneously stabilizes soil organic matter and heavy metals. *The Science of the Total Environment*, **828**: 154494.

Liu, Z., Xu, Z., Xu, L., Buyong, F., Chay, T.C., Li, Z., Cai, Y., Hu, B., Zhu, Y. and Wang, X. 2022. Modified biochar: synthesis and mechanism for removal of environmental heavy metals. *Carbon Research*, **1**(1).

Long, Z., Huang, Y., Zhang, W., Shi, Z., Yu, D., Chen, Y., Liu, C. and Wang, R. 2021. Effect of different industrial activities on soil heavy metal pollution, ecological risk, and health risk. *Environmental Monitoring and Assessment*, **193**(1): 20.

Mahapatra, S., Singh, S. and Mishra, M. 2024. Economic benefits of NPK and organic amendments on green gram yield. *International Journal of Plant & Soil Science*, **36**(11): 477–485.

Mao, C., Song, Y., Chen, L., Ji, J., Li, J., Yuan, X., Yang, Z., Ayoko, G.A., Frost, R.L. and Theiss, F. 2018. Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. *CATENA*, **175**: 339–348.

Matisic, M., Dugan, I. and Bogunovic, I. 2024. Challenges in Sustainable Agriculture—The role of Organic Amendments. *Agriculture*, **14**(4): 643.

Meena, H.M. and Prakasha, H.C. 2021. The impact of biochar, lime and fertilizer on soil acidity and microbiological properties and their relationship with yield of rice and cowpea in an acidic soil of Southern India. *Journal of Plant Nutrition*, **45**(3): 358–368.

Mehmood, K., Ahmad, H.R., Abbas, R., Saifullah, and Murtaza, G. 2019. Heavy metals in urban and peri-urban soils of a heavily-populated and industrialized city: Assessment of ecological risks and human health repercussions. *Human and Ecological Risk Assessment an International Journal*, **26**(6): 1705–1722.

Mensah, A.K., Marschner, B., Shaheen, S.M. and Rinklebe, J. 2022. Biochar, compost, iron oxide, manure, and inorganic fertilizer affect bioavailability of arsenic and improve soil quality of an abandoned arsenic-contaminated gold mine spoil. *Ecotoxicology and Environmental Safety*, **234**: 113358.

Minato, E.A., Brignoli, F.M., Neto, M.E., Besen, M.R., Cassim, B.M.A.R., Lima, R.S., Tormena, C.A., Inoue, T.T. and Batista, M.A. 2023. Lime and gypsum application to low-acidity soils: Changes in soil chemical properties, residual lime content and crop agronomic performance. *Soil and Tillage Research*, **234**: 105860.

Moghaddam, V.K., Latifi, P., Darrudi, R., Askari, S.G., Mohammadi, A.A., Marufi, N. and Javan, S. 2021. Heavy metal contaminated soil, water, and vegetables in northeastern Iran: potential health risk factors. *Journal of Environmental Health Science and Engineering*, **20**(1): 65–77.

Moghal, A.A.B., Mohammed, S.A.S., Almajed, A. and Al-Shamrani, M.A. 2019. Desorption of Heavy Metals from Lime-Stabilized Arid-Soils using Different Extractants. *International Journal of Civil Engineering*, **18**(4): 449–461.

Mogire, E.O., Miriti, J., Gitari, H. and Gweyi-Onyango, J.P. 2024. Influence of irrigation and soil amendments on growth, yield, and quality of French beans in salt-affected soils. *International Journal of Bioresource Science*, **11**(2).

Mogire, O.E., Gweyi, J.P. and Miriti, J. 2025. Soil amendment and irrigation influence on growth, yield, quality and heavy metal uptake in French beans in Machakos County, Kenya (Master's thesis, Kenyatta University). Kenyatta University Repository. https://ir library.ku.ac.ke/items/82472e50-4778-4147-b7e4-d7acda048f44

Mohammadi, M., Dargahi, A., Almasi, A., Mousavi, S.A., and Mohammadi, P. 2025. Occurrence of microplastic, antibiotics, hormones, and heavy metals in livestock and poultry manure in west Iran. *Scientific Reports*, **15**(1): 27228.

Mokarram, M., Saber, A. and Sheykhi, V. 2020. Effects of heavy metal contamination on river water quality due to release of industrial effluents. *Journal of Cleaner Production*, **277**: 123380.

Moyne, C. and Sterckeman, T. 2023. Effect of calcium and trace metals (Cd, Cu, Mn, Ni, Zn) on root iron uptake in relation to chemical properties of the root-excreted ligands. *BioMetals*, **36**(5): 1013–1025.

Muimba-Kankolongo, A., Nkulu, C.B.L., Mwitwa, J., Kampemba, F.M. and Nabuyanda, M.M. 2022. Impacts of trace metals pollution of water, food crops, and ambient air on population health in Zambia and the DR Congo. *Journal of Environmental and Public Health*, *2022*(1): 4515115.

Murtaza, G., Ahmed, Z., Valipour, M., Ali, I., Usman, M., Iqbal, R., Zulfiqar, U., Rizwan, M., Mahmood, S., Ullah, A., Arslan, M., Rehman, M.H.U., Ditta, A. and Tariq, A. 2024. Recent trends and economic significance of modified/ functionalized biochars for remediation of environmental pollutants. *Scientific Reports*, **14**(1): 217.

Najafi, S. and Jalali, M. 2016. Effect of heavy metals on p^H buffering capacity and solubility of Ca, Mg, K, and P in non-spiked and heavy metal-spiked soils. *Environmental Monitoring and Assessment*, **188**(6): 342.

Neina, D. 2019. The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*, *2019*, 1–9. https://doi.org/10.1155/2019/5794869

Norouzi, S. and Akbari, G. 2026. Differential sensitivity and phytoremediation potential of faba bean (*Vicia faba* L.) cultivars irrigated with urban wastewater effluent. *Plant and Soil*. https://doi.org/10.1007/s11104-026-08346-5

Nunes, N., Ragonezi, C., Gouveia, C.S. and De Carvalho, M.Â.P. 2021. Review of Sewage Sludge as a soil Amendment in relation to Current International Guidelines: A Heavy Metal Perspective. *Sustainability*, **13**(4): 2317.

Nzihou, A. and Sharrock, P. 2010. Role of phosphate in the remediation and reuse of heavy metal polluted wastes and sites. *Waste and Biomass Valorization*, **1**(1): 163–174.

Obayes, K.H. 2022. Estimation of Soil Contamination with Heavy Metals in the Streets of Al-Diwaniyah City in Al-Qadisiyah Governorate, Iraq. *Nature Environment and Pollution Technology*, **21**(5(Suppl)): 2241–2248.

Ochmian, I. and Malinowski, R. 2024. Effect of Multi-Year Protection of Grapevines with Copper Pesticides on the Content of Heavy Metals in Soil, Leaves, and Fruit. *Agronomy*, **14**(8): 1677.

Pang, Y.L., Quek, Y.Y., Lim, S. and Shuit, S.H. 2023. Review on Phytoremediation Potential of Floating Aquatic Plants for Heavy Metals: A Promising approach. *Sustainability*, **15**(2): 1290.

Peiris, C., Alahakoon, Y.A., Arachchi, U.M., Mlsna, T.E., Gunatilake, S.R. and Zhang, X. 2023. Phosphorus-enriched biochar for the remediation of heavy metal contaminated soil. *Journal of Agriculture and Food Research*, **12**: 100546.

Periasamy, K., Selvaraj, P. S., Veeraswamy, D., Ettiyagounder, P., Tamilselvan, I., Kathirvel, S. and Karchiyappan, T. 2025. Alleviating soil salinity stress in castor (*Ricinus communis* L.): Synergistic effects of organic amendments and arbuscular mycorrhizal fungi on growth, yield, and antioxidant improvement under effluent contaminated ecosystem. *Desalination and Water Treatment*, **323**: 101295.

Prasad, R., Shivay, Y.S. and Kumar, D. 2016. Interactions of zinc with other nutrients in soils and plants - a review. *Indian Journal of Fertilisers*, **12**(5): 16–26.

Qaswar, M., Yiren, L., Jing, H., Kaillou, L., Mudasir, M., Zhenzhen, L., Hongqian, H., Xianjin, L., Jianhua, J., Ahmed, W., Dongchu, L. and Huimin, Z. 2020. Soil nutrients and heavy metal availability under long-term combined application of swine manure and synthetic fertilizers in acidic paddy soil. *Journal of Soils and Sediments*, **20**(4): 2093–2106.

Rani, N. and Singh, M. 2022. Remediation of soil impacted by heavy metal using farm yard manure, vermicompost, biochar and poultry manure. In *IntechOpen eBooks*. https://doi.org/10.5772/intechopen.105536

Rashmi, I., Roy, T., Kartika, K.S., Pal, R., Coumar, V., Kala, S., and Shinoji, K.C. 2020. Organic and Inorganic Fertilizer Contaminants in Agriculture: Impact on Soil and Water Resources. In *b* (pp. 3–41). https://doi.org/10.1007/978-3-030-41552-5_1

Rizwan, M.S., Imtiaz, M., Zhu, J., Yousaf, B., Hussain, M., Ali, L., Ditta, A., Ihsan, M.Z., Huang, G., Ashraf, M. and Hu, H. 2020. Immobilization of Pb and Cu by organic and inorganic amendments in contaminated soil. *Geoderma*, **385**: 114803.

Rocco, C., Seshadri, B., Adamo, P., Bolan, N.S., Mbene, K., and Naidu, R. 2018. Impact of waste-derived organic and inorganic amendments on the mobility and bioavailability of arsenic and cadmium in alkaline and acid soils. *Environmental Science and Pollution Research*, **25**(26): 25896–25905.

Saadaoui, W., Gamboa-Rosales, H., Sifuentes-Gallardo, C., Durán-Muñoz, H., Abrougui, K., Mohammadi, A., and Tarchoun, N. 2022. Effects of Lead, Copper and Cadmium on Bioaccumulation and Translocation Factors and Biosynthesis of Photosynthetic Pigments in *Vicia faba* L. (Broad Beans) at Different Stages of Growth. *Applied Sciences*, **12**(18): 8941.

Sarkar, S., Jaswal, A. and Singh, A. 2024. Sources of inorganic nonmetallic contaminants (synthetic fertilizers, pesticides) in agricultural soil and their impacts on the adjacent ecosystems. In *Elsevier eBooks* (pp. 135–161). https://doi.org/10.1016/b978-0-443-13993-2.00007-4

Selvi, A., Rajasekar, A., Theerthagiri, J., Ananthaselvam, A., Sathishkumar, K., Madhavan, J. and Rahman, P.K.S.M. 2019. Integrated Remediation Processes Toward Heavy Metal Removal/Recovery from Various Environments-A Review. *Frontiers in Environmental Science*, **7**.

Seshadri, B., Bolan, N. and Naidu, R. 2015. Rhizosphere-induced heavy metal(loid) transformation in relation to bioavailability and remediation. *Journal of Soil Science and Plant Nutrition*, *Ahead*, 0. https://doi.org/10.4067/s0718-95162015005000043

Shakti, P. and Pandey, A.K. 2024. Agricultural soil contamination due to industrial discharges: challenges for public health protection and food security. In *Elsevier eBooks* (pp. 21–42). https://doi.org/10.1016/b978-0-443-13993-2.00002-5

Sharma, A. and Nagpal, A.K. 2017. Soil amendments: a tool to reduce heavy metal uptake in crops for production of safe food. *Reviews in Environmental Science and Bio/Technology*, **17**(1): 187–203.

Sheng, D., Meng, X., Wen, X., Wu, J., Yu, H. and Wu, M. 2022. Contamination characteristics, source identification, and source-specific health risks of heavy metal(loid)s in groundwater of an arid oasis region in Northwest China. *The Science of the Total Environment*, **841**: 156733.

Sikka, R., Kalsi, A. and Kaur, P. 2025. Phytoremediation of Lead-Contaminated Soils Using Indian Mustard: Influence of Organic and Inorganic Amendments. *Bulletin of Environmental Contamination and Toxicology*, **114**(4): 63.

Singh, R., Kumar, A., Babu, S., Avasthe, R., Das, A., Rathore, S. S., Kumar, S., Singh, C., Sharma, V. and Bhupenchandra, I. 2023. Development of organic nutrients management system for profitable and soil-supportive French bean (*Phaseolus vulgaris* L.) farming in North Eastern Himalayas, India. *Frontiers in Sustainable Food Systems*, **7**.

Sinkovič, L., Blažica, V., Blažica, B., Meglič, V. and Pipan, B. 2024. How Nutritious Are French Beans (*Phaseolus vulgaris* L.) from the Citizen Science Experiment? *Plants*, **13**(2): 314.

Soltani-Gerdefaramarzi, S., Ghasemi, M. and Ghanbarian, B. 2021. Geogenic and anthropogenic sources identification and ecological risk assessment of heavy metals in the urban soil of Yazd, central Iran. *PLoS ONE*, **16**(11): e0260418.

Srivastava, V., Sarkar, A., Singh, S., Singh, P., De Araujo, A. S.F. and Singh, R.P. 2017. Agroecological Responses of Heavy Metal Pollution with Special Emphasis on Soil Health and Plant Performances. *Frontiers in Environmental Science*, **5**.

Stancampiano, L.M., Verrillo, M., Cangemi, S., Meignant, I., Spaccini, R., Piccolo, A. and Bridoux, M.C. 2023. The molecular composition of humic substances extracted from green composts and their potential for soil remediation. *Environmental Chemistry Letters*, **21**(5): 2489–2498.

Sterckeman, T. and Thomine, S. 2020. Mechanisms of cadmium accumulation in plants. *Critical Reviews in Plant Sciences*, **39**(4): 322–359.

Sui, F., Gao, Z., Qiang, C., Lu, H., Ma, J., Cui, L., Quan, G. and Yan, J. 2026. Mechanisms of Rice Rhizosphere Response to Soil Amendments Under Heavy Metal(loid) Stress- A Review. *Journal of Soil Science and Plant Nutrition*, **26**(1): 987–1006.

Sun, Y., Zhou, Q., Xie, X. and Liu, R. 2009. Spatial, sources and risk assessment of heavy metal contamination of urban soils in typical regions of Shenyang, China. *Journal of Hazardous Materials*, **174**(1–3): 455–462.

Teodoro, M., Trakal, L., Gallagher, B.N., Šimek, P., Soudek, P., Pohořelý, M., Beesley, L., Jačka, L., Kovář, M., Seyedsadr, S. and Mohan, D. 2019. Application of co-composted biochar significantly improved plant-growth relevant physical/chemical properties of a metal contaminated soil. *Chemosphere*, **242**: 125255.

Timoracka, M. 2019. Evaluation of transfer of heavy metals from the soil into the edible parts of bean. *International Multidisciplinary Scientific GeoConference SGEM . . .* https://doi.org/10.5593/sgem2019/3.2/s13.025

Tu, C., Wei, J., Guan, F., Liu, Y., Sun, Y. and Luo, Y. 2020. Biochar and bacteria inoculated biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil. *Environment International*, **137**: 105576.

Ullah, I., Akhtar, S., Adnan, M. and Nawab, J. 2026. Pollution level, occurrence, distribution, and risk assessment of potentially toxic elements using multivariate analysis and its phytoremediation in urban area of northwest Pakistan. *Soil and Sediment Contamination an International Journal*, 1–28. https://doi.org/10.1080/15320383.2026.2629614

Urra, J., Alkorta, I. and arbisu, C. 2019. Potential benefits and risks for soil health derived from the use of organic amendments in agriculture. *Agronomy*, **9**(9): 542.

Vasilachi, I.C., Stoleru, V. and Gavrilescu, M. 2023. Analysis of heavy metal impacts on cereal crop growth and development in contaminated soils. *Agriculture*, **13**(10): 1983.

Vasile, G., Tenea, A., Dinu, C., Iordache, A.M.M., Gheorghe, S., Mureseanu, M. and Pascu, L.F. 2021. Bioavailability, Accumulation and Distribution of Toxic Metals (As, Cd, Ni and Pb) and Their Impact on Sinapis alba Plant Nutrient Metabolism. *International Journal of Environmental Research and Public Health*, **18**(24): 12947.

Wang, Q., Chen, L., He, L. and Sheng, X. 2016. Increased biomass and reduced heavy metal accumulation of edible tissues of vegetable crops in the presence of plant growth-promoting Neorhizobium huautlense T1-17 and biochar. *Agriculture Ecosystems & Environment*, **228**: 9–18.

Wei, J. and Cen, K. 2020. Contamination and health risk assessment of heavy metals in cereals, legumes, and their products: A case study based on the dietary structure of the residents of Beijing, China. *Journal of Cleaner Production*, **260**: 121001.

Wen, J., Wu, Y., Li, X., Lu, Q., Luo, Y., Duan, Z. and Li, C. 2020. Migration characteristics of heavy metals in the weathering process of exposed argillaceous sandstone in a mercury-thallium mining area. *Ecotoxicology and Environmental Safety*, **208**: 111751.

Wu, W., Qu, S., Nel, W. and Ji, J. 2020. The impact of natural weathering and mining on heavy metal accumulation in the karst areas of the Pearl River Basin, China. *The Science of the Total Environment*, **734**: 139480.

Wu, Y., Li, X., Yu, L., Wang, T., Wang, J. and Liu, T. 2022. Review of soil heavy metal pollution in China: Spatial distribution, primary sources, and remediation alternatives. *Resources Conservation and Recycling*, **181**: 106261.

Wysokinski, A., Kuziemska, B. and Lozak, I. 2023. Heavy Metal Allocation to Pea Plant Organs (*Pisum sativum* L.) from Soil during Different Development Stages and Years. *Agronomy*, **13**(3): 673.

Yang, J., Sun, Y., Wang, Z., Gong, J., Gao, J., Tang, S., Ma, S. and Duan, Z. 2022. Heavy metal pollution in agricultural soils of a typical volcanic area: Risk assessment and source appointment. *Chemosphere*, **304**: 135340.

Yuna, Z. 2016. Review of the Natural, Modified, and Synthetic Zeolites for Heavy Metals Removal from Wastewater. *Environmental Engineering Science*, **33**(7): 443–454.

Zeng, F., Ali, S., Zhang, H., Ouyang, Y., Qiu, B., Wu, F. and Zhang, G. 2010. The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. *Environmental Pollution*, **159**(1): 84–91.

Zhang, M. and Pu, J. 2011. Mineral materials as feasible amendments to stabilize heavy metals in polluted urban soils. *Journal of Environmental Sciences*, **23**(4): 607–615.

Zhang, T., Liu, L., Feng, J., Hong, C., Wang, W., Guo, R., Zhu, W., Hong, L., Yao, Y. and Zhu, F. 2026. Quantifying Feed-to-Manure transfer of heavy metals and nutrients for precision pig production in China. *Agriculture*, **16**(3): 372.

Zhao, L. and Imran. 2024. Heavy metal mitigation in soil and plants using organic and inorganic amendments alone and in combination. *International Journal of Phytoremediation*, **27**(5): 606–623.