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Organic amendments for enhancing crop resilience under heavy metal stress: Mechanism, efficacy and implications for food safety

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Abstract

Contamination of agricultural soils by heavy metals impairs the food production system by affecting crop productivity, food chain and ecosystem functioning. However, the remedy for this problem is often assessed in terms of increased metal immobility rather than its impact on crops. In this review, available evidence regarding the effect of organic amendments, such as compost, manure, biochar, crop residue, biosolid and humic substances, on the resistance of crops to heavy metals is summarised. The review examines four aspects: changes in the soil chemical environment within the rhizosphere; physiological and molecular mechanisms of plant adaptation to heavy metal stress; microbiome interactions induced by organic amendments; and metal uptake by edible plant organs. Organic amendments usually decrease the availability of cationic heavy metals by elevating soil pH and cation exchange capacity (CEC), thereby enhancing adsorption and complexation with carboxyl and phenolic functional groups and shifting metals from exchangeable forms to oxidisable and residual pools. Such soil transformations result in alleviation of oxidative stress, maintenance of mineral balance and photosynthetic activity, as well as activation of antioxidants systems and metal transporters. However, efficiency of the treatment greatly depends on the type of amendment, dose, feedstock, soil type, crop species and metal itself. Some amendments may increase the mobility of oxyanions, introduce additional metals, disturb mineral balance and increase heavy metal concentrations in edible tissues. Collectively, these findings indicate the need to assess success of remediation in terms of crop tolerance, yield and product quality, in addition to heavy metal immobilisation.

Keywords: crop resilience; food chain safety; heavy metal bioavailability; soil remediation

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1. Introduction

The presence of heavy metals in agricultural soils has become a major concern for global food production systems. The non-biodegradable nature and their persistence in the environment have made their pollution a major worldwide issue. In order to meet the growing need for agricultural food production, agricultural soil needs to be managed carefully. However, more than 100000 ha of agricultural soils are affected by toxic elements (1, 2). It is exacerbated by both natural and human activities such as atmospheric deposition (3, 4), use of mineral fertilisers (5, 6), effluents from tanneries and metal finishing (7), endangering the soil and plant health. Studies have found that health risk from heavy metals was higher from the crop consumption than risk from soil exposure, which confirms the food chain as the main route of exposure to toxic metals in contaminated lands (8, 9). In this context, the term potentially toxic elements (PTEs) are used as an inclusive term encompassing the cationic metals cadmium (Cd), lead (Pb), nickel (Ni), zinc (Zn) and copper (Cu), the metalloid arsenic (As) and the redox-active element chromium (Cr). The term heavy metals is used only where a cited source specifically restricts its use to metallic cations.

Excess concentrations of toxic metals affect several physiological processes in plants. It results in accumulation of reactive oxygen species (ROS), causing damage to lipids, proteins and nucleic acids and reduction in chlorophyll and photosynthetic capacity (10, 11). Toxicity is highly dose and metal specific. For

example, excess total copper concentration (> 90 mg kg^{-1}) impaired photosystem II efficiency, nitrate reductase and carbonic anhydrase activities and reduced tissue content of nitrogen, phosphorus and potassium (NPK), which shows close connection between photosynthetic failure and nutrient depletion in mustard (12). However, plants have a multilayered defence system to maintain and restore normal physiological functions during exposure to toxic metals. Ions entering cytoplasm are deactivated by ligands like glutathione, phytochelatin, metallothionein and transported to vacuoles or peripheral tissues (13).

Among the other tools of remediation, organic amendments occupy a specific position, as they affect both chemistry of toxic metals and conditions for crop growth. It includes animal manure, municipal biosolid, green manure, crop residue, food and manufacturing waste, compost and biochar (14). Performance of each amendment is metal-specific (15) and each amendment has a unique mechanism for heavy metal immobilisation which also depends on other soil physicochemical characteristics (16). Inclusion of organic amendments reduce the usage of inorganic fertilisers with increased fertility, structure and microbial balance (9). Additionally, these soil chemical changes have both positive effect (17); and negative effect (18) on crop growth. Hence, selection of amendments should be important criteria for successful remediation of heavy metals along with improved crop growth.

Therefore, the present review attempts to understand the effect of organic amendments on the crops grown in the contaminated lands. It synthesises information from the mechanistic, physiological and quantitative aspect related to organic amendments and its impact on cereals, horticulture and plantation crops, grown in fields affected with Cd, Pb, Cr(III)/Cr(VI), As, Ni, Zn and Cu. It examines the effects of organic amendments at three connected levels viz., rhizospheric bioavailability and speciation, plant physiological and molecular response and transfer to the product with health risk indexes. Throughout, crop resilience is used in the operational sense defined in Section 2.3 and is distinguished from tolerance and from immobilisation efficiency.

Literatures were retrieved from Scopus, ScienceDirect and Google Scholar, covering publications from 2000 to 2025, with earlier work retained where it remains the primary source for a mechanism. Search strings combined amendments (organic amendment, compost, vermicompost, biochar, manure, humic substance, crop residue, green manure), contaminants (heavy metal, toxic element, Cd, Pb, Cr) and plant response (crop resilience, tolerance, bioavailability, uptake, antioxidant, health risk). Peer reviewed original studies and reviews published in English that reported at least one soil chemical, plant physiological, plant uptake or dietary risk endpoint under an organic amendment treatment were selected. Approximately 112 records were screened in full text and for synthesis of the manuscript.

Heavy metals toxicity and resilience mechanisms

Sources and pathways

Heavy metals reach agricultural soils through both geogenic weathering and a diverse suite of anthropogenic activities including, mining, smelting, transport, agrochemicals and irrigation whose relative importance shifts by region and element (19). Once deposited, their transfer into crops is governed less by total soil burden than by the pathway of entry and the identity of the receiving crop and no single pathway dominates across elements. Three different types of quantities are reported in the literature i) the absolute concentrations measured in soil, water, or fertilisers, ii) the contribution of a source to total inputs at the national level and iii) the enrichment from a specific source relative to the local background. The regional datasets presented below were compiled using different boundaries, time periods and analytical methods. Therefore, they are not directly comparable and are presented as independent examples of different source profiles rather than as a ranking of sources.

Studies in China have shown that atmospheric deposition supplied 43–85 % of As, Cr, mercury (Hg), Ni and Pb, while livestock manure accounted for roughly 55, 69 and 51 % of Cd, Cu and Zn inputs respectively (3). Net inputs of Cr, Ni and Zn rose by 52.9, 59.7 and 20.6 % under pressure from fossil-fuel combustion, manufacturing and waste incineration, whereas Cd, Cu and Hg declined by 46.7, 25.2 and 50.4 % following tighter control of feed additives and fertiliser quality (4). In France, metal toxicity are in the order of Zn > Cu > Cr > Pb > Ni > As = Mo > Se > Cd > Hg with manure, mineral fertilisers and pesticides as the dominant contributors (5). Fertiliser-borne metal inputs may originate from the raw materials used in fertiliser production. Across 196 phosphate fertiliser samples from 12 European countries, the mean Cr and Cd concentrations of 89.5 and 7.4 mg kg^{-1}, correlating with P content and fertiliser delivery of Cd, As and Cr matched or exceeded deposition (6). Irrigation also shifts the elemental signature. In Nigeria, soil concentrations followed Cr (81.77 mg kg^{-1}) > Pb (19.91) > As (13.23) > Cd (3.25), a sequence repeated in the irrigation water and transmitted into harvested tissue, with spinach exceeding cabbage because a greater share of absorbed metal was redistributed to aboveground organs (7) (Fig. 1, Table 1).

Impacts of heavy metals on plant growth, physiology and yield

At toxic concentrations, heavy metals converge on a common set of injuries, although primary biochemical lesion pathways differ substantially among redox active metals (e.g., Cu and Cr, which directly trigger Fenton-like reactions) and non-redox active metals (e.g., Cd and Pb, which bind sulfhydryl groups and displace essential cofactors). They disrupt pigment biosynthesis, light capture, electron transport and Calvin cycle enzymes while triggering ROS and oxidative stress (21). These lesions translate into measurable losses of germination, root and shoot growth, photosynthetic performance and

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ultimately yield. The dose-response pot studies reveal the rapid impact of heavy metals. Copper added to soil at 90 mg kg^{-1} reduced root length of *Brassica juncea* by 40.5 % and decreased shoot fresh weight by 37.0 %, chlorophyll content by 25.0 %, net photosynthesis by 38.6 %, stomata conductance by 39.2 %, Fv/Fm ratio by 23.2 % and ΦPSII by 25.3 %, increasing at the same time the value of non-photochemical quenching by 27.8 %, indicating the energy was redirected from carbon fixation to the thermal dissipation (12). Carbon and N assimilation mechanisms worked in unison, decreasing activity of rubisco and nitrate reductase by 22.4 and 25.5 % correspondingly, along with increasing accumulation of malondialdehyde, superoxide and hydrogen peroxide by 38.8, 26.2 and 25.6 %, respectively and depletion of macronutrients (N, P and K) in plant tissues. It results in the inhibition of photosynthesis under metal stress conditions, which is not limited to processes occurring within the chloroplasts but also involves impaired uptake of essential macronutrients. Values from single species pot trials under controlled watering and fertility are treated here as indicative of mechanism rather than as field transferable dose response coefficients.

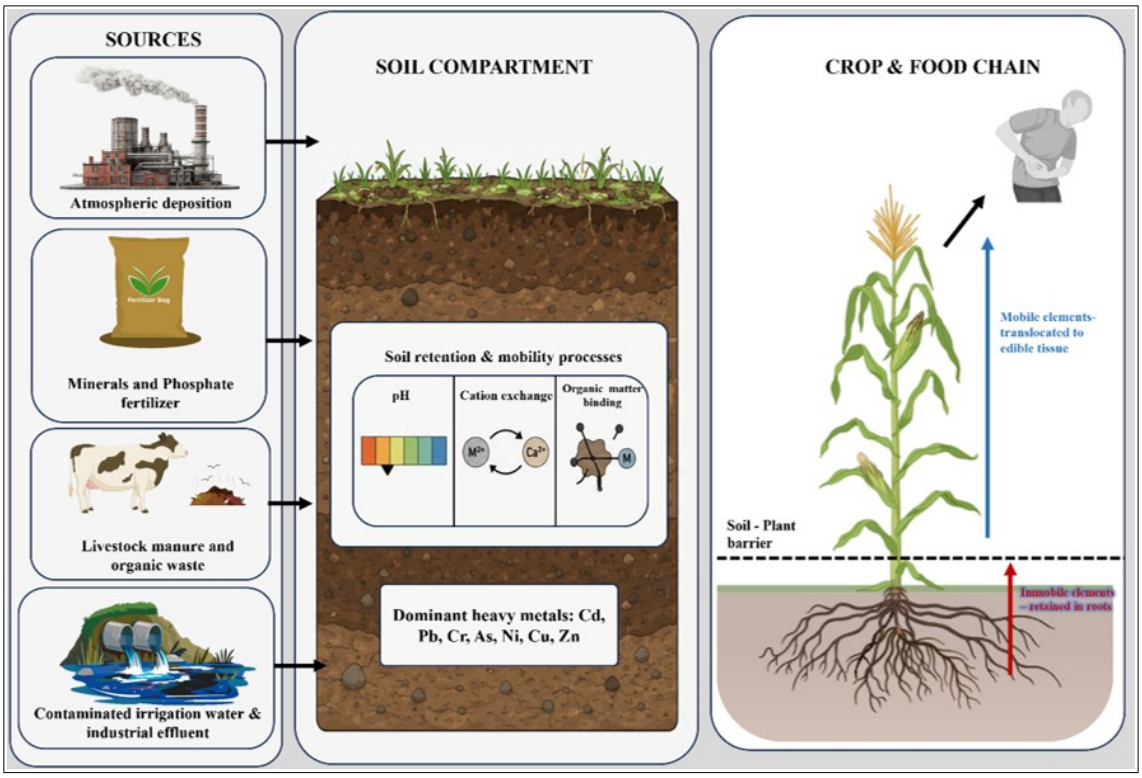


Fig. 1. Sources, pathways and representative concentrations of heavy metals reaching agricultural soils and crops.

Table 1. Sources, pathways and representative concentrations of heavy metals in agricultural soils and irrigation water

Metal(s)	Dominant source category	Region / system	Representative concentration or input share	Reference
PTEs	Mixed anthropogenic (global stock)	Worldwide contaminated sites	> 10 million sites; > 100000 ha of arable land affected	(1)
Zn; Cu; Pb; Cd	Mixed anthropogenic emissions	Global annual loading	About 1350000; 939000; 783000; 22000 t yr^{-1}, respectively	(20)
PTEs	Mixed (LUCAS survey)	European Union agricultural soils	6.24 % of samples affected; about 137000 km^2 requiring assessment	(2)
As, Cr, Hg, Ni, Pb	Atmospheric deposition	Chinese farmland, 1999–2005	43–85 % of total input	(3)
As, Cr, Hg, Ni, Pb	Atmospheric deposition	Chinese farmland, 2006–2015	80–94 % of total input	(4)
Cd; Cu; Zn	Livestock manure	Chinese farmland, 1999–2005	55 %; 69 %; 51 % of total input, respectively	(3)
Cd; Cu; Zn	Livestock manure	Chinese farmland, 2006–2015	20 %; 63 %; 44 % of total input, respectively	(4)
Cr; Ni; Zn	Net anthropogenic input (industry, combustion, waste)	Chinese farmland, 2006–2015 vs. 1999–2006	+52.9 %; +59.7 %; +20.6 % change in net input	(4)

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Metal(s)	Dominant source category	Region / system	Representative concentration or input share	Reference
Cd; Cu; Hg	Net anthropogenic input (post-regulation decline)	Chinese farmland, 2006–2015 vs. 1999–2006	46.7 %; -25.2 %; -50.4 % change in net input	(4)
Cd, Cr	Mineral fertiliser (predominant source)	French agricultural soils	Predominantly attributable to mineral fertilisation, more than any other source category	(5)
Cr; Cd	Phosphate fertiliser	196 samples, 12 European countries	Mean 89.5 mg kg^{-1} Cr; 7.4 mg kg^{-1} Cd	(6)

PTEs: potential toxic elements; Zn: zinc; Cu: copper; Pb: lead; Cd: cadmium; As: arsenic; Cr: chromium; Hg: mercury; Ni: nickel.

Responses are highly non-monotonic, thus making thresholds hard to define. Cadmium exposure impaired water photolysis and electron transfer and increased thermal dissipation in lettuce seedlings (10 and 20 mg kg^{-1}) (22). Similar measurements in the pseudo-metallophyte *Arabidopsis halleri* and *Arabidopsis arenosa* as model systems revealed decrease in chlorophyll and increase in anthocyanin under both Cd and Zn, decrease in the flow of the trapped energy and number of active reaction centers after five days of Cd treatment, along with the noticeable species divergence with Cd accumulating three times more in *A. arenosa* leaves and Zn in *A. halleri* (20). Germination is also metal specific. *Brassica napus* seed germination decreased to 56.7 % under Pb and 43.3 % under Cd at 300 mg L^{-1}, with translocation factor less than one in all soil conditions, thus pointing to the root retention rather than shoot transfer (23) (Table 2).

Table 2. Physiological, biochemical and molecular responses of crop and model plant species to heavy metal stress

Species (crop/model status)	Metals	Physiological / molecular endpoint	Quantified effect	References
Brassica juncea (crop)	Cu, 90 mg kg^{-1} (Soil, 30 DAS)	Growth (root length, shoot fresh mass)	↓40.48 % (root length); ↓37.04 % (shoot mass)	(12)
Brassica napus (crop)	Pb / Cd, 300 mg L^{-1}	Seed germination	↓ to 56.67 % under Pb; ↓ to 43.33 % under Cd	(23)
Rice (cereal proxy)	Cd (Soil, 4 months)	Grain yield, *OsNramp5* knockout	11 % of wild-type yield (due to impaired Mn uptake)	(24)
Brassica juncea (crop)	Cu 90 mg kg^{-1}, (Soil, 30 DAS)	Photosynthesis (net rate, chlorophyll, Fv/Fm, ΦPSII, NPQ)	*Pn* ↓38.64 %; Chl ↓25.01 %; ΦPSII ↓25.31 %; NPQ ↑27.77 %	(12)
Lactuca sativa (crop)	Cd, 1-5 to 10-20 mg kg^{-1} (Soil)	Relative chlorophyll; PSII donor/acceptor sides	Hormetic stimulation at low dose; inhibited at high dose	(21)
Arabidopsis arenosa / *A. halleri* (model, non-crop)	Cd and Zn (Hydroponic, 5 d)	Leaf Cd and Zn partitioning	Cd ~3-fold higher in *A. arenosa*; Zn ~3-fold higher in *A. halleri*	(20)
Brassica juncea (crop)	Cu, 90 mg kg^{-1} (Soil, 30 DAS)	Carbon/nitrogen assimilation (Rubisco, nitrate reductase)	Rubisco ↓30.69 %; nitrate reductase ↓25.51 %	(12)
Brassica juncea (crop)	Cu, 90 mg kg^{-1} (Soil, 30 DAS)	Oxidative damage (MDA, $O_2\cdot^-$, H_2O_2)	MDA ↑38.81 %; $O_2\cdot^-$ ↑26.20 %; H_2O_2 ↑25.57 %	(12)
Canna indica (model, non-crop)	Cr, 100 mg kg^{-1} (21 d)	Antioxidants (SOD, APX, POD, GSH) vs. oxidative markers (MDA, ROS)	SOD, APX, POD, GSH ↑; MDA & ROS ↑ concurrently	(25)
Multiple (mechanism synthesis)	Cd, Ni, Co, Mn, Fe, Zn	Vacuolar sequestration (ABC transporters, CDF proteins)	Sequestration of PC-Cd and free cations into vacuole	(26, 27)
Rice (cereal)	Cd	Vacuolar sequestration, *OsHMA3* overexpression	Grain Cd ↓; no yield penalty; 5 ZIP genes up; Zn maintained	(28)
Rice (cereal)	Cd	Node-to-grain transfer, *OsLCT1*	RNAi suppression decreases Cd accumulation in rice	(29)
Solanum tuberosum (crop)	Zn, + *Bacillus* inoculation	Antioxidant gene expression	SOD, CAT, APX, DHAR, GR expression upregulated	(30, 31)
Solanum lycopersicum (crop)	Cd + PGPR inoculation	Antioxidant transcripts	*SOD*, *POD* and *PPO* transcript abundance upregulated	(32)
Sedum alfredii (model, non-crop)	Cd + endophyte inoculation	Metal-transporter families	*SaHMA*, *SaNRAMP* and *SaZIP* upregulated	(33)
Triticum aestivum (crop)	Cd + *Azospirillum brasilense*	Transporter regulation	*TaTM20* expression modulated	(34)

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Species (crop/model status)	Metals	Physiological / molecular endpoint	Quantified effect	References
Canna indica (model, non-crop)	Cr, 100 mg kg^{-1} (21 d)	Time-resolved transcriptome + metabolome	16247 DEGs and 38 metabolites staged across 12 pathways	(25)

↑/↓ = percentage increase/decrease relative to untreated controls. DAS: days after sowing; Pn: net photosynthetic rate; Fv/Fm: PSII maximum quantum efficiency; ΦPSII: PSII effective quantum yield; NPQ: non-photochemical quenching; MDA: malondialdehyde; ROS: reactive oxygen species; SOD: superoxide dismutase; CAT: catalase; POD: peroxidase; APX: ascorbate peroxidase; DHAR: dehydroascorbate reductase; GR: glutathione reductase; GSH: reduced glutathione; PC: phytochelatin; CDF: cation diffusion facilitator; DEG: differentially expressed gene; PGPR: plant growth-promoting rhizobacteria; Cu: copper; Pb: lead; Cd: cadmium; Zn: zinc; Cr: chromium; Ni: nickel; Co: cobalt; Mn: manganese; Fe: iron; As: arsenic.

Plant defence and resilience mechanisms

In evaluating plant performance, it is critical to distinguish operational states viz., stress response (immediate metabolic shift to injury), tolerance (ability to survive elevated metal concentrations without dying), resistance (preventing metal entry or systemic translocation), recovery (repairing tissues post-stress) and crop resilience. Here, crop resilience is operationally defined as the capacity of an agricultural crop to sustain vegetative growth, reproductive capacity, nutritional quality and yield under metal exposure while maintaining edible-tissue metal burdens. To withstand the heavy metal injury, plants performs a layered defence that spans enzymatic and non-enzymatic antioxidants, metal binding ligands, transporter controlled sequestration and support from rhizosphere microbiota (26).

Antioxidant induction is near universal but should not be read as evidence of successful protection. Elevated antioxidant enzyme activity above control levels can reflect severe cellular oxidative stress rather than effective physiological acclimation. In Cu stressed *B. juncea*, superoxide dismutase (SOD), catalase (CAT) and guaiacol peroxidase (POX) activities rose by 30.2, 28.2 and 32.3 % (12). Under Cr, SOD, ascorbate peroxidase (APX) activity, peroxidase (POD) activity and glutathione (GSH) in *Canna indica*, but so did malondialdehyde (MDA) and ROS (25). Ascorbate peroxidase modulates H_2O_2 for signalling while CAT detoxifies the excess generated under stress, with monodehydroascorbate reductase (MDHAR) and glutathione reductase sustaining regeneration through the ascorbate-glutathione cycle (26).

Chelation converts a signalling problem into a storage problem. Phytochelatin and metallothionein bind cytosolic metal and vacuolar ATP-binding cassette transporters (ABC) transporters translocate phytochelatin Cd complexes across the tonoplast (27), while cation diffusion facilitator proteins shift Cd, Ni, Co, Mn, Fe and Zn from cytosol to vacuole (26). Transporter level control determines whether that sequestration protects the grain. Rice offers the best resolved case. OsNramp5 knockouts lost the capacity to take up both Mn and Cd but suffered reduced growth and grain yield, particularly at low Mn (24), whereas OsHMA3 overexpression raised root Cd, lowered shoot Cd and constitutively upregulated five ZIP-family genes that maintained shoot Zn tolerance gained without a nutritional or yield penalty (28). This contrast is precisely the distinction between tolerance and resilience. A third node governs final delivery. OsLCT1, expressed most strongly at reproductive stages and mediating efflux of Cd along with K, Mg, Ca and Mn (28), whose RNAi suppression reduces Cd reaching grain (29).

Rhizosphere bacteria reinforce these systems from outside the plant. *Bacillus* inoculation improved Zn tolerance in potato through upregulated SOD, CAT, APX, dehydroascorbate reductase (DHAR) and glutathione reductase (GR) (30) and plant growth-promoting rhizobacteria (PGPR) strains enhanced tomato antioxidant capacity under Cd via SOD, POD and polyphenol oxidase (PPO) transcripts (32). Bacteria also reach the transport machinery directly, with inoculation of *Sedum alfredii* upregulating *SaHMA*, *SaNRAMP* and *SaZIP* families (33), *Azospirillum brasilense* modulating *Tatm20* in wheat and inoculation suppressing Cd induced *PCS* and F-box expression in *Sulla coronaria* (35), an instructive reminder that microbially conferred resilience can mean less stress signalling (Fig. 2).

Omics and systems-level insights into crop plant tolerance

Advances in genomics, transcriptomics, proteomics and metabolomics have reframed metal tolerance as a coordinated, network-level programme rather than the action of any single gene (26). Read together, these datasets expose both the temporal choreography of the stress response and the subcellular compartmentation that ultimately limits detoxification. Multi-omics work resolves tolerance as a temporally staged programme rather than a fixed trait. Exposure of *Canna indica* to 100 mg kg^{-1} Cr for 21 days yielded 16247 differentially expressed genes and 38 differential metabolites across twelve pathways in a clear succession. Carbohydrate metabolism through the galactose, starch and sucrose pathways at day 7, phytohormone signal transduction and MAPK cascades at day 14 and glutathione metabolism with phenylpropanoid biosynthesis at day 21 (25). Sampling at a single time point therefore risks capturing only one phase of a moving response. Compartmentation emerges as the organising principle at the systems level, because endomembrane reorganisation alters membrane permeability, storage capacity and detoxification independently of transcriptional regulation, so that trafficking dynamics rather than gene expression alone set the limits of translocation and hyperaccumulation (13).

Candidate gene discovery has followed accordingly, implicating WRKY transcription factors across Pb and Cd responses, *BnaCn.ABCC3* in rapeseed vacuolar sequestration of PC-Cd complexes and *ZmZIP3*, *ZmHMA3* and *ZmHMA4* loci in maize (26).

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In rice, transporter-level characterisation of *OsNramp5*, *OsHMA3* and *OsLCT1* has been carried through to grain Cd outcomes (24, 28, 29). Beyond these cases, much of the mechanistic omics literature derives from model or non-food species. *Canna indica* is an ornamental wetland macrophyte, *Sedum alfredii* is a hyperaccumulator and the Arabidopsis populations discussed above are metallicolous ecotypes. Findings from these systems are treated here as hypotheses about crop behaviour and are labelled as such wherever they appear, rather than as direct evidence; their translation requires validation in the target crop, under realistic soil exposure, with harvested-organ metal concentration as the endpoint.

Organic amendments

Classification

Organic amendments are materials of organic origin applied to improve soil health and crop growth. Organic amendments can be classified based on their source, processing method and functional properties. Classification by source separates agricultural residues, including livestock manure and cereal straw, from municipal organic wastes such as sewage sludge, with the former having the ability to increase the soil fertility and the later acting as immobilising material (36). Processing provides a second criterion. Composting transforms degradable organic waste into humus, which results in a slower but more stable nutrient release, aggregate formation, better water retention and passivation of hazardous compounds prior to incorporation into soil (36). On the other hand, pyrolysis yields biochar, a chemically distinct, aromatic and largely non-mineralisable product. Functional use provides a third axis. Farmyard and poultry manures are applied mainly as fertilisers, while biochar and engineered composts are applied to control contaminants.

Source and processing labels are nonetheless weak predictors of behaviour in contaminated soil and a classification based on measurable physicochemical properties is more useful for amendment selection. Six parameters carry most of the predictive weight. The C : N ratio governs whether an amendment supplies or immobilises mineral nitrogen and therefore whether metal immobilisation is achieved at the cost of nutrient deficiency. Carbon rich materials that widen soil C : N from about 12 : 1–32 : 1 provoke N deficiency even while improving water retention. Amendment pH and acid-neutralising capacity determine the liming effect of an amendment. This effect increases soil pH and promotes the pH-dependent sorption of cationic metals, making alkaline biochar and lime-blended manures particularly effective in acidic soils (15). Cation exchange capacity (CEC) sets the density of exchange sites available for cationic metal retention. Dissolved organic C acts in the opposite direction for some elements, because soluble organic ligands can mobilise metals and compete with oxyanions for sorption sites and it also drives microbial reduction of Cr(VI) to Cr(III) (16). Specific surface area and porosity, maximal in pyrolysed materials, determine physical sorption capacity and the persistence of that capacity over time (36). Finally, the abundance and type of oxygen containing functional groups, principally carboxyl and phenolic groups, control complexation strength and its pH dependence.

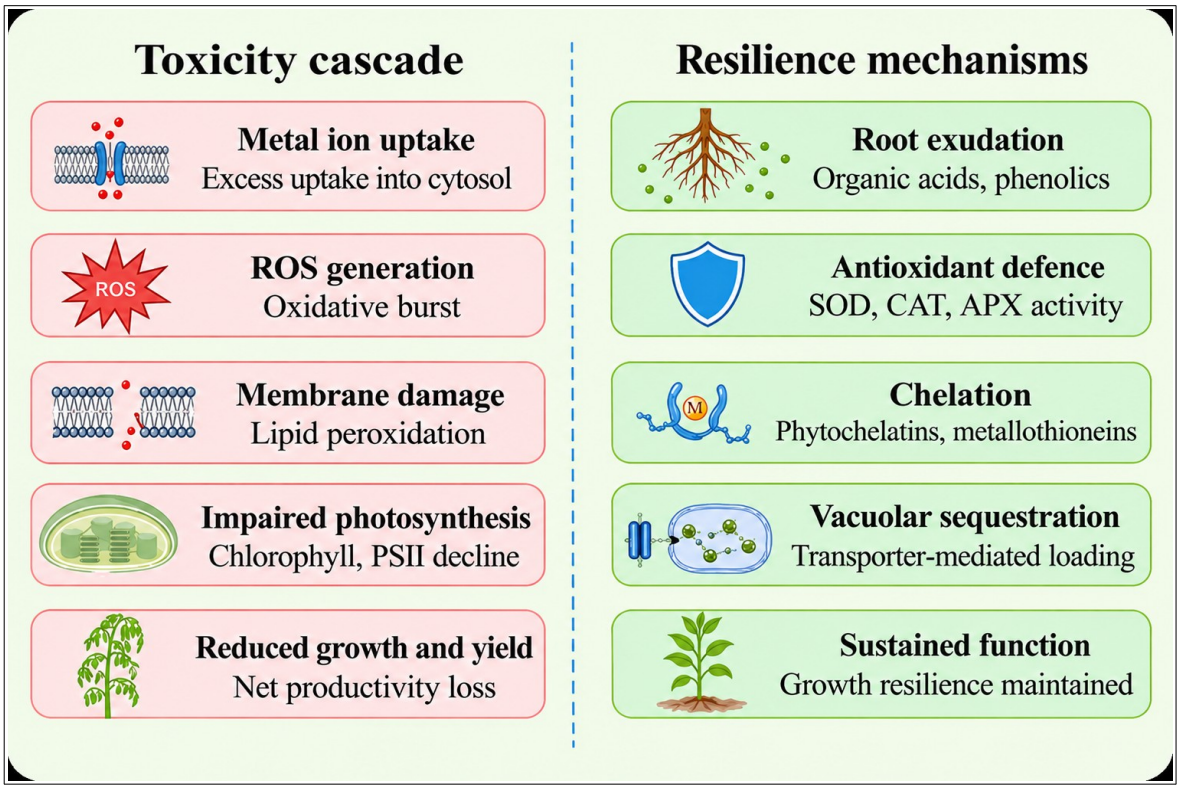


Fig. 2. Cellular and molecular mechanisms of heavy metal toxicity and resilience in crop plants.

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The rate at which these materials are applied matters as much as their identity, since the same amendment can either increase or decrease metal accumulation depending on dose. Sewage sludge, municipal solid waste compost and garden waste compost applied at 25–100 Mg ha^{-1} to an acidic mine soil altered soil chemical composition and metal mobility across that range (37), whereas long-term application of pig manure caused excessive Zn and Cu accumulation (38). High quality, well characterised organic wastes applied at rates matched to soil buffering capacity are therefore preferable on metal-contaminated land.

Physicochemical properties related to heavy metal mitigation

Retention of metals by organic matter proceeds through ion exchange, complexation and adsorption, with phenolic, carboxyl, carboxylate and amino moieties furnishing the binding sites (39, 40). Humic acid concentrates this chemistry with its carboxyl, alcoholic, carbonyl and phenolic groups, together with redox-active quinone functions, govern both metal complexation and interaction with soil colloids (41). Because deprotonation of these groups is pH-dependent, amendment driven pH shifts and cation exchange capacity operate as coupled rather than separate controls. Soils rich in organic matter, clay minerals and metal oxides carry higher cation exchange capacity (CEC) and greater sorptive surface and correspondingly lower cationic metal mobility (42).

Applying compost, compost + biochar and compost + humic acid combinations to sewage irrigated soil raised pH by 0.11–0.30 units and organic matter by 3.1–35.1 %, cut $CaCl_2$ extractable Cd by 33-48 % and shifted As, Cd, Zn and Cu out of easily exchangeable fractions into oxidisable and residual forms (43). Efficacy of each amendment is also element specific. Biochar, phosphates and liming materials immobilise Pb above 85 %, while compost, clay minerals and metal oxides remained below 65 %. In case for Cd, animal wastes, lime and biochar reached only 55–60 % and compost just 15 %. Biochar and compost exceeded 80 % for Cu. Zn immobilisation ranged between 70 and 77 % for animal wastes, lime and biochar against 25 % for phosphates (15). The numbers given are general average or trend taken from different studies. Because those studies used different soils, metal concentrations, amendment amounts and testing methods, the numbers should not be treated as exact or universally applicable values for a particular contaminated site (Table 3).

Table 3. Classification and key physicochemical properties of organic amendments relevant to heavy metal mitigation

Amendment class	Source / processing	Dominant functional groups / properties	Primary mode of action against metals	Reference(s)
Livestock manure (farmyard, poultry, pig)	Animal excreta; raw or field-applied	High organic matter; pH-raising capacity; labile carbon	pH adjustment and organic complexation; can itself import metals, antibiotics and resistance genes	(36, 38)
Green manure / crop residue (straw)	Plant biomass; incorporated or surface-applied	High organic carbon; readily decomposable	Organic complexation and pH modification; labile carbon may re-mobilise metals on decomposition	(44)
Compost	Aerobic composting of organic waste to stable humus	Humic substances; carboxyl and phenolic groups; complexation capacity	Surface complexation and ion exchange; passivates metals before soil entry via matured, stable organic matter	(36, 39)
Vermicompost	Earthworm-mediated processing of organic waste	Enriched humified organic matter; high sorption capacity	Strong reduction of metal bioavailability via complexation and sorption	(39)
Sewage sludge / biosolids	Municipal wastewater treatment residue	High organic matter; variable and often high native metal load	Organic binding; net benefit constrained by imported contaminant burden	(36, 45)
Biochar	Pyrolysis of biomass/crop residue	Large specific surface area, porosity; aromatic C; alkaline pH; surface functional groups	Surface adsorption, ion exchange and liming; resists mineralisation for durable immobilisation	(36)
Humic substances (humic/fulvic acid)	Extracted or concentrated humified fractions	Carboxyl, phenolic, hydroxyl, carbonyl and redox-active quinone groups	pH-dependent complexation with soil colloids; redox participation and metal chelation	(41)
Organic amendments (general, redox-active)	Organic-carbon-rich materials	Dissolved organic carbon (DOC) supply	Microbial/chemical reduction of Cr(VI) into sparingly soluble Cr(III), scaling with soil DOC	(16)
Mixed / engineered formulations (e.g. compost-biochar, manure-biochar)	Combined organic + pyrolysed inputs	Combined sorption surface, CEC and pH buffering	Complementary immobilisation with improved persistence over single amendments	(18)
Soil organic matter context (amendment-modified)	In situ organic matter, clay and oxide fractions	Elevated CEC and sorptive surface area	Higher CEC lowers cationic metal mobility; governs pH-dependent sorption	(15, 42)

CEC: cation exchange capacity; DOC: dissolved organic carbon.

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Immobilisation measured as a reduction in the extractable fraction does not by itself establish permanent risk reduction. The metal remains in the soil and its partitioning between solid and solution phases can change in response to the same factors initially modified by the amendment. A decrease in pH caused by acidification, nitrification of amendment derived nitrogen, or loss of the liming effect can re-protonate carboxyl and phenolic groups and release cationic metals. Redox changes can have a similar effect. In flooded paddy soils, sulphide chemistry strongly influences Cd solubility, whereas this mechanism is less relevant under aerobic conditions; consequently, amendment performance may differ between water regimes (15). Progressive mineralisation of organic matter can also reduce the availability of binding sites and weaken metal retention over time. This decline is more pronounced for labile, readily decomposable materials than for pyrolysed materials, whose aromatic structures are more resistant to mineralisation (36). Immobilisation is therefore better understood as a potentially reversible condition that requires periodic verification rather than as a permanent transformation.

Effects of organic amendments on soil health and root-zone conditions

Chemical improvement and metal immobilisation frequently move together. In a highly acidic mine affected soil supporting perennial ryegrass, organic residues reduced the mobile fractions of Cu, Pb and Zn and those reductions correlated inversely with concurrent gains in pH, electrical conductivity, organic matter, N, available P and available K (37). Broader synthesis attributes such gains to improved aggregate stability, water-holding capacity, cation exchange capacity and nutrient use efficiency alongside stimulated microbial activity (44). Amendment addition increased pakchoi root and shoot fresh weight by 29–63 % and 39–85 %, while lowering root and shoot Cd by 21–44 % and 26–53 %, respectively (43).

On the other hand, long term field data temper this picture. Across five years on an acidic Alfisol tea plantation, chicken manure with and without biochar raised pH, total C and N and available P and K relative to chemical fertiliser, though only the manure + biochar combination reduced bulk density. Available Cd, Cr, Ni declined in the order, control > chemical fertiliser > manure > manure + biochar, yet available Cu, Zn, As and Pb rose under manure (18). It also indicated that heavy metal risk had almost no effect on tea yield but a marked negative effect on tea quality. A comparable dissociation appears between growth and immobilisation. Farmyard manure (FYM) at 5 % significantly improved the growth of *Pennisetum americanum* and *Sorghum bicolor*, whereas powdered activated carbon achieved the strongest reduction in metal bioavailability but depressed plant growth (46). Maximum immobilisation and maximum productivity are therefore not necessarily delivered by the same material maximum immobilisation and maximum productivity are therefore not necessarily delivered by the same material. Amendment specific trade-offs of this kind become visible only when efficacy is judged on four endpoints together, namely soil chemistry, plant uptake, yield and product quality and soil biological health, rather than on immobilisation alone.

Interaction between organic amendments and plant associated microbiota

The effect of amendments on the microbiome mainly comes from changes in the substrates supplied to and the chemistry of the rhizosphere, with labile C amendment leading to microbial growth and enzyme action (44). The community structure changes accordingly instead of just growing larger. Organic fertiliser application to reclaimed maize land led to increases in Proteobacteria, Actinobacteria and Ascomycota and reductions in Acidobacteria, Gemmatimonadetes, Bacteroidetes, Verrucomicrobia, Basidiomycota and Chytridiomycota by 13.89–38.87 % (47). However, direction of change depends on the presence of other substances besides the organic matter. Since the community structure of bacteria and fungi in the tea plantation was found to increase only in the absence of biochar addition, with soil physicochemical properties accounting for 14.3 and 23.6 % variation of bacteria and fungi communities respectively and available K and P being the major driver of bacterial community (18). If such plant growth promoting rhizobacteria develop in these amended soils, their influence is not due to sorption either. Siderophore production enables the use of insoluble Fe^{3+} and conversion of it to plant-available Fe^{2+}, 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity reduces ethylene formation that would inhibit root growth and organic acids and biosurfactants released change the metal partitioning in the roots (48). Furthermore, these microorganisms also interfere with the plant's physiology (32). Thus, organic amendments act more as habitat engineers rather than inert sorbents.

Mechanisms and efficacy in enhancing crop resilience

Rhizosphere immobilisation and speciation shifts

In the rhizosphere, the future of a given contaminant is essentially decided and organic amendments affect it through a number of concurrent chemistries, as opposed to a dominant one. Through ion exchange, surface complexation, precipitation and adsorption, metals are redistributed from soil solution to solid phases, thereby reducing the amount available for root uptake (15). The oxygen containing functional groups of humified organic matter, especially the carboxyl and phenolic groups, deprotonate as pH increases and provide negatively charged sites that complex cationic metals to form stable metal-organic complexes (41). This complexation is not only a reduction in mobility but also represents a change in speciation. Treatment of multi element contaminated soil using green manure + compost, compost + biochar and compost + humic acid led to the immobilisation of As, Cd, Zn and Cu to oxidisable and residual fractions, while increasing soil pH by 0.30 units and reducing $CaCl_2$ extractable Cd by 33–48 % (43). Since the exchangeable and carbonate bound fractions are the ones most easily

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intercepted by plant roots, this is how their immobilisation results in decreased uptake. The redistribution nevertheless remains conditional on the pH, redox and organic matter conditions that produced it and reverses as those conditions change

Speciation control becomes critical in the case of redox active elements. For example, organic carbon acts as an electron donor, facilitating microbial and chemical reduction of highly toxic and mobile Cr(VI) to less soluble Cr(III), with the degree of reduction depending on the concentration of dissolved organic carbon (16, 36). In case of As, compost + humic acid amendment immobilised the cationic metals, increased the available As, as competitive sorption and complexing of dissolved organic matter could displace the oxyanions (43). An amendment chemistry that protects a crop against Cd or Pb will therefore not necessarily protect the same crop against As or Cr and multi-element sites require each target element to be evaluated separately (Fig. 3).

Nutrient status and ionic balance

Immobilisation is one of the effects of organic amendments on plant roots. Another equally important effect is the modification of the ionic environment in which roots function. Residue application to acid mine soil increased pH, electrical conductivity, organic matter, N, available P and available K, along with decreasing mobile Cu, Pb and Zn contents in parallel trends, forming mirror images of one another (37). It is important from a mechanistic point of view that several toxic ions use transporters used by other minerals as well, thus increasing the concentration of the competitors reduces the pathway of toxic metal penetration. An example of the inverse process can be seen in Cu-stressed *B. juncea*, in which copper deficiency decreased tissue N, P and K contents and the activity of nitrate reductase (12). Thus, replacing the depleted nutrient pool is one of the tasks organic amendments fulfil. Humic substances extend this function into the plant itself, acting on root plasma membrane H^+-ATPase activity, which acidifies the apoplast and energises secondary nutrient transport, on nitrate and phosphate uptake systems and on auxin-like signalling that promotes lateral root proliferation and thus exploration of a larger soil volume; these effects are expressed even in the absence of a stress treatment (41).

Plant physiological and antioxidant responses

Where amendments reduce the effective metal dose, the subsequent physiological recovery occurs via the injury pathway in reverse, with increased photosynthetic capacity, membrane stability and growth occurring in parallel. This approach is justified because metal toxicity results initially from oxidative damage quantified through malondialdehyde content and electrolyte leakage and reduced photochemical efficiency (12). Humic acid application to Cd stressed strawberry improved Cd toxicity by increasing membrane stability and proline (41, 49). In wheat, the application of straw derived humic acid reduced oxidative stress under Cd stress while retaining biomass (41, 47). These results indicate that the mechanism behind the effect is based on an integrated antioxidant rather than enzyme response. Humic acid selectively affects the antioxidant system. In pepper, it increased the activity of SOD, CAT and POD along with proline and chlorophyll, while in beans it increased SOD and glutathione reductase, but decreased CAT and ascorbate peroxidase (50). This variation indicates that the role of amendments is to retune the balance between hydrogen peroxide production, signalling and detoxification via the ascorbate glutathione cycle. It is important to note that physiological improvement can be due not only to the biochemical stimulation, but also to lower metal load, therefore improvement in chlorophyll and biomass levels usually correlates with reduction in tissue metal concentration.

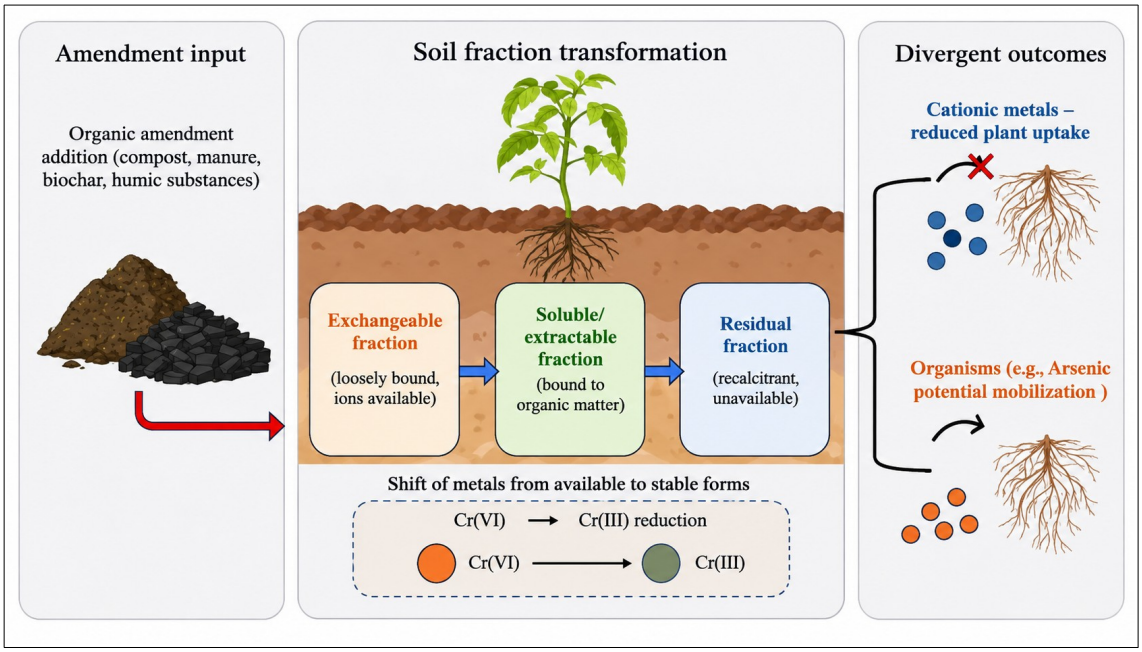


Fig. 3. Rhizosphere-level mechanisms by which organic amendments alter heavy metal bioavailability and speciation.

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Signalling of stress responsive genes and microbiome/bio stimulant synergy

On the regulatory level, amendments affect the same circuits responsible for coordination of the metal responses. Temporal profiling of *Canna indica*, an ornamental wetland macrophyte, revealed that the exposure to Cr resulted in consecutive involvement of carbohydrate metabolism, phytohormone signalling and mitogen-activated protein kinase (MAPK) cascades and finally glutathione metabolism and phenylpropanoid biosynthesis, which places hormone and MAPK signalling in the center of tolerance program (25). Redox active components of humic substances such as quinones participate in ROS scavenging and decrease the oxidative stress signal (41).

Resilience gains are often largest where amendments and microbial partners act together, but claims of synergy require a specific evidential standard. Synergy means that the combined treatment exceeds the sum of the individual treatments, which can be established only in factorial or fully comparative designs containing both single-inoculant and single-amendment controls. Many reported combinations lack such controls and demonstrate additive or merely co-occurring benefits. Arbuscular mycorrhizal fungi provide metal tolerance via multiple mechanisms cell wall binding, cytosolic chelation, vacuolar sequestration stabilised by polyphosphate, SOD induction and exudation of organic acids and glomalin which immobilises the metals in soil (51, 52). Co-inoculation of date palm growing in Pb contaminated soil with *Glomus* isolate and *Rhizobium leguminosarum* led to enhanced root growth, biomass and germination compared to any of the partners alone through the combination of nutrient acquisition and Pb transformation and detoxification (53, 54). Plant growth-promoting rhizobacteria support the same axes through siderophores production, ACC-deaminase mediated ethylene suppression and antioxidant/transporter genes up-regulation (48). Mechanistically, organic amendments prepare a soil microbiome environment for building resilience.

Comparative and quantitative synthesis across amendment types

Selecting the most suitable organic amendment depends on the environmental conditions and the type of contaminant, as no single amendment is universally effective. Biochar with its aromatic porous structure is not mineralised easily and is able to immobilise metals for long periods of time, while raw manure and straw provide easily mineralisable labile carbon that might result in remobilisation of metals when decaying. Repeated application of manure might introduce metals, antibiotics and resistance genes (38). The composting mitigates this problem by stabilising the organic matter and passivating metals before the soil entry (36). In summary, biochar and stabilised composts appear to be better options for immobilisation of cationic metals, such as Pb and Cu, especially in acidic soils due to the liming effect. Manure and humic amendment are particularly effective in soils where plant growth and antioxidant activity are limiting factors. The combined application of manure and biochar can further enhance soil fertility and improve the long term stability of immobilisation. However, these strategies should not be applied indiscriminately to oxyanions or multi element contamination, as their effectiveness must be evaluated for the specific contaminant mixture (Table 4).

Table 4. Comparative efficacy of organic amendments in reducing heavy metal bioavailability, plant uptake and edible-tissue concentrations

Amendment	Target metals	Soil / Crop system	Study type	% change in bioavailable metal or tissue concentration	Reference
Biochar (vs. compost/clay/oxides)	Pb	Multi-study comparison	Meta-synthesis	>85 % immobilised (biochar) vs. <65 % (compost, clay, oxides)	(15)
Animal waste, lime, biochar (vs. compost)	Cd	Multi-study comparison	Meta-synthesis	↓55-60 % immobilised vs. ~15 % (compost)	(15)
Biochar and compost (vs. phosphates)	Cu; Zn	Multi-study comparison	Meta-synthesis	Cu ≥ 80 %; Zn 70–77 % (animal waste/lime/biochar) vs. 25 % (phosphate, Zn)	(15)
Organic residues	Cu, Pb, Zn	Acidic mine soil, ryegrass	Pot	↓ mobile fractions, inversely correlated with pH/OM gains	(37)
Compost / compost–biochar / compost–humic acid	Cd	Multi-element soil, pakchoi	Pot	↓33-48 % ($CaCl_2$-extractable)	(43)
Farmyard manure	Heavy metal(loid)s	Mine-impacted soil, *Pennisetum*/*Sorghum*	Pot	Growth improved; modest bioavailability reduction	(46)
Powdered activated carbon	Heavy metal(loid)s	Mine-impacted soil, *Pennisetum*/*Sorghum*	Pot	Strongest bioavailability reduction, but growth depressed	(46)
Vermicompost	Cd; Cr; Pb; Mn	Mine-impacted soil, radish	Pot	↓32.5 %; ↓50.25 %; ↓44.50 %; ↓42.25 % (uptake)	(17)
Compost + biochar	Pb	Smelter soil, spinach/dill/lettuce	Pot	↓42 % (spinach); ↓44 % (dill); ↓57 % (lettuce, tissue)	(55)
Compost + biochar	Cd	Smelter soil, leafy vegetables	Pot	↓50 % (lettuce); ~↓25 % (other edible parts, tissue)	(55)
Compost/biochar formulation	Cd	Multi-element soil, pakchoi	Pot	Root ↓21–44 %; shoot ↓26–53 % (tissue)	(43)

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Amendment	Target metals	Soil / Crop system	Study type	% change in bioavailable metal or tissue concentration	Reference
Organo-limestone (chicken droppings + lime)	Cu; Co	Cu-contaminated market gardens, vegetables	Field	↓ soil-to-plant transfer; pH raised 5.43 into 7.26	(56)
Chicken manure + biochar	Cr; Cd; Ni	Acidic Alfisol, tea plantation	Field	↓ available Cr, Cd, Ni; yield and quality maintained	(18)
Chicken manure (alone)	Cu; Zn; As; Pb	Acidic Alfisol, tea plantation	Field	↑ available Cu, Zn, As, Pb (trade-off)	(18)
Compost (5 %, w/w)	Cr	Smelter soil, spinach/dill	Pot	↑357 % (spinach); ↑233 % (dill, tissue; trade-off)	(55)
Compost/biochar	Ni	Smelter soil, all vegetables	Pot	↑ uptake across all species (trade-off)	(55)
Organic amendments	Cr(VI)	Mineral soil	Incubation	Cr(VI) into Cr(III) reduction, scaling with soil DOC	(16)

Pb (lead); Cd (cadmium); Cu (copper); Co (cobalt); Cr (chromium); Ni (nickel); Zn (zinc); As (arsenic); Cr(III): trivalent chromium; Cr(VI) (hexavalent chromium); DOC: dissolved organic carbon.

Implications for crop production and food chain protection

Effects of organic amendments on metal concentrations in edible plant parts

The primary objective of organic amendment application to contaminated soils is to reduce the bioavailability of heavy metals in the rhizosphere, thereby decreasing their accumulation in the crop edible parts. For cationic metals, substantial evidence supports the effectiveness of this approach. In a controlled experiment using smelter contaminated sandy soil, wheat-straw biochar and green-waste compost moved cadmium almost entirely into the residual fraction, with about 75 % of soil Cd becoming residual for compost compared to 25 % in the control soil sample and the results were reflected in leaf and root reductions of approximately 50 % in Cd in lettuce and radish, as well as reductions of 42 % in lead in spinach, 44 % in dill and 57 % in lettuce (55). The degree of the reductions corresponded with the operational fraction redistribution and not with any change in the total metal content of the soil, highlighting the fact that speciation was key. Similarly oriented outcomes are found across crop types. Vermicompost decreased radish uptake of Cd, Cr, Pb and Mn by 32.5, 50.3, 44.5 and 42.3 %, respectively in mine contaminated soil (17) and blends of organo-limestones made up of chicken manure and lime reduced the transfer of Cu and Co in Congolese soils, while increasing pH from acid to neutral state (56).

These studies indicate that reliability varies systematically with the amendment + crop + metal combination rather than with amendment quality alone. The most dependable configuration is an alkaline or lime blended amendment, such as biochar, mature compost or organo-limestone, applied to an acidic soil contaminated with Cd or Pb and cropped with a species whose harvested organ is not the principal accumulation site. Reductions of roughly 40–60 % in edible tissue concentration are reported consistently across leafy vegetables and root crops in this configuration (17, 55, 56). Reliability declines where the harvested organ is the leaf and the metal is one that plants translocate efficiently, because leafy vegetables retain a higher proportional shoot burden than fruit or grain crops. It declines further for Cu and Zn, which are essential micronutrients whose uptake is homeostatically regulated, so that reductions in soil availability are partly buffered by the plant. Two configurations should be avoided. Any amendment rich in dissolved organic carbon applied where As is a co-contaminant and any high rate organic input on soils in which Cr and Ni already reside predominantly in residual forms. Since in both cases, the intervention offers little benefit and can increase mobility. For grain crops, no configuration should be assumed effective without measurement in the grain itself, because node level transporter control governs the final transfer step independently of rhizosphere availability (29).

The effectiveness of organic amendments is strongly dependent on the chemical form and behaviour of the target element. In the same leafy vegetable experiment that halved Cd and Pb, neither biochar nor compost had any effect on the amount of Cr and Ni, since 90 % of Cr in the soil was already present in the residual fraction (55). Further information is provided by studies on non-food and bioenergy crops. In Cd contaminated soil, the application of bone meal and manure reduced Cd bioavailability to *Jatropha*, which exhibited a high root bioconcentration factor and a translocation factor below 1, indicating limited Cd movement to above ground tissues. In contrast, cassava showed toxicity symptoms and poor adaptation under the same soil conditions (57). Reduction of Cd to roots is positive outcome for bioenergy plant, but not necessarily a protective one for root vegetable, thus the partitioning of element within the plant should be considered in light of the harvested part.

Human health risk indices and regulatory thresholds in amended systems

The risk to human health is assessed using dietary exposure and risk assessment metrics, including daily intake, hazard quotient (HQ), carcinogenic risk (CR) and total hazard quotient (THQ). These are derived from toxicological reference values and exposure parameters and are not obtained by comparing measured tissue

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concentrations with food standards. Estimated daily intake (EDI) is calculated from the measured concentration in the edible portion, the consumption rate and body weight. Hazard quotient is the ratio of EDI to the element-specific oral reference dose and THQ sums HQ values across elements or food items to estimate the aggregate non-carcinogenic burden. Carcinogenic risk is the product of chronic daily intake and the oral cancer slope factor and is applied only to elements classified as carcinogenic. An HQ or THQ above unity indicates a potential non-carcinogenic health concern and carries no implication for cancer risk, which is a separate, incremental probability metric conventionally judged acceptable between 1×10^{-6} and 1×10^{-4}. Maximum levels in food are a distinct regulatory instrument and should be cited as such: the codex alimentarius general standard for contaminants and the corresponding Commission Regulation (EU) 2023/915 set maximum Cd concentrations of 0.20 mg kg^{-1} fresh weight for leaf vegetables and 0.10 mg kg^{-1} for root and tuber vegetables, with maximum Pb concentrations of 0.30 and 0.10 mg kg^{-1} for the same categories. While the Food and Agriculture Organization / The World Health Organization (FAO/WHO) provisional tolerable monthly intake for Cd is 25 µg kg^{-1} body weight. Compliance with a maximum level and an HQ below unity are therefore separate tests and an amended crop may satisfy one while failing the other (58).

Depending on the nature of the amendments, these metrics may shift either way. When immobilisation is effective, organic amendments can reduce the human health risks. Vermicompost reduced the health risk index associated with radish consumption grown in mine contaminated soil (17). However, the health risk indices for Pb and Cd remained above the acceptable threshold (health risk index (HRI) > 1) even after treatment in the most heavily contaminated soil. It indicated that although the risk was reduced, it still posed an unacceptable health hazard. Studies involving repeated applications of amendments provide more relevant evidence for evaluating its performance. Over two cultivation cycles, sewage sludge, swine manure and municipal compost did not change the trace element concentrations in the bulk soil. But it increased the trace element concentrations in lettuce and radish compared to soil with chemical fertiliser, resulting in 1.4–1.8 fold increase in the adult THQ for lettuce and a 1.3–1.9 fold increase for radish roots (58). Repeated applications of organic amendments increased, rather than decreased, dietary exposure to trace elements. These findings highlight that the ultimate indicator of remediation is the concentration of metals in edible plant tissues and the associated dietary intake, rather than the reduction of extractable metal concentrations in soil alone.

Trade-offs and unintended consequences

The clearest unintended consequence is that organic amendments are themselves carriers of trace elements. In the repeated application study, Zn, Cr, Ni and Cu in the sewage sludge exceeded contaminant limit values set for organo-mineral fertilisers, so each application delivered a metal load alongside its nutrients (58). Long term field experiments show that the accumulation of trace metals in soil can result from repeated applications of organic amendments. Simulations using the intermediate dynamic model for metals predicted that ecotoxicological critical limits under sewage sludge application had already been exceeded and would continue to be exceeded until 2100 in a 60 years old Swiss field experiment. While slight exceedance of Zn thresholds was also predicted in other treatments, compost amended plots were one of the only in which labile metal concentrations were not anticipated to decrease (59). Provenance and repetition therefore convert a remediation tool into a slow contamination source.

Agronomic and atmospheric trade-offs further complicate the management of heavy metal contamination. Carbon rich amendments widened the soil C : N ratio from 12 : 1 to as high as 32 : 1, provoking N deficiency even as they improved water retention (55) and heavy organic loading raises well recognised risks of nutrient surplus, salinity and altered greenhouse gas fluxes that must be weighed against immobilisation gains (60). Because pH, dissolved organic C and soil organic matter co-evolve over years, the same compost that binds Cd early may mobilise it later as organic matter turns over an interaction that only long term or model based accounting can expose. A defensible definition of safe amendment strategy consequently has to reconcile metal risk with nutrient balance, salinity and emissions rather than optimising for extractable metal alone.

Integration with good agricultural practices

The current limitations point toward amendments as one component of layered management rather than a standalone fix. Crop and cultivar choice is the first lever. Species differ sharply in accumulation and the bioenergy comparison showed jatropha and acacia tolerating Cd-contaminated soil that induced toxicity in cassava, indicating that non-food or low-accumulating species may be the appropriate land use where immobilisation cannot achieve food safe tissue levels (57). Moderate amounts of lime and organic amendments used together in food production systems can improve soil cation exchange capacity, stabilise pH dependent metal sorption and decrease metal transfer to crops. For instance, organo-limestone amendments reduced the transfer of Cu and Co in urban gardens in the Democratic Republic of the Congo. Nevertheless, it was pointed out that the effective amendment rates were too high, emphasising the need to exercise caution when extending successful experimental outcomes to field-scale applications (56). Complementary practices drawn from the salinity and metal stress literature combined biochar + compost or manure + biochar formulations, water management and root-zone conditioning can extend resilience benefits when matched to site conditions (60). There are two operating requirements. First, monitoring must span both soil and harvested food, since the repeated amendment evidence demonstrates that stable soil concentrations can coexist with rising edible tissue burdens and climbing hazard quotients (58). Second, amendment provenance

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requires screening against fertiliser contaminant limits before application, given documented exceedances in sludges and the long term accumulation they drive (59).

Decision thresholds can then be attached to these measurements. When edible tissue concentrations fall below the applicable maximum level and THQ remains below unity, amendment use continues under routine monitoring. When tissue concentrations lie within the maximum level but THQ approaches or exceeds unity, cultivar substitution toward low accumulating types and a change in the harvested organ are indicated before amendment rates are increased. When tissue concentrations exceed the maximum level despite two seasons of amendment at recommended rates, or where soil pH cannot be held above approximately 6.5 on Cd contaminated land, the site should be moved to non-food or bioenergy production. A rising extractable soil concentration under continued amendment or an amendment metal content above fertiliser limit values, should trigger immediate substitution of the amendment source.

The efficiency of organic amendments in lowering the transport of heavy metals varies depending on the element. For some metals (Cr and Ni), their effectiveness is limited and repeated applications without appropriate management may further increase metal exposure. However, they can successfully lower the uptake of some metals. As a result, organic amendments should be used in conjunction with a risk based, plant centered management framework that incorporates suitable crop selection, frequent soil and food monitoring and precise decision criteria for, when needed, removing highly polluted land from food production.

Challenges and future directions

Variability in amendment quality, composition and performance

The effects of feedstock, processing method and contamination level are so interconnected that an identical amendment type can both protect and poison a crop in different trials due to just a few parameters. It includes initial metal load, organic carbon concentration, pH buffer, ash content and the abundance of oxygen containing groups (15). Performance varies with amendment type and target metal together. Compost reduced Cd availability by about 15 % while biochar and animal-based amendments achieved 55–60 % and this ranking reorders for other elements, with compost performing strongly for Cu but weakly for Pb relative to biochar (15). Their implementation is made more difficult by the variation in amendment composition. While uneven application rates can restrict microbial activity and enzymatic activities that aid in metal immobilisation, organic supplements like manure and sewage sludge may also transfer trace metals into the soil (61). As a result, the lack of uniform physicochemical qualities affects amendment performance in addition to experimental settings. Therefore, suggestions for their agricultural usage would be more reliable if compost and biochar were categorised based on their useful qualities rather than where they came from.

Site and crop specific constraints

The efficiency of organic additions varies significantly depending on the characteristics of the soil, which limits the generalisability of suggestions. Since sorption, precipitation and complex formation depend on texture, mineralogy, CEC, organic matter concentration and redox potential, the same amendment can have contrasting effect in acidic and calcareous, upland and flooded soils (19). The differences between cationic metals and oxyanions make the issue more complex, as even after decades of pollution remnant, the application of vermicompost in the affected soil increased Cu, Zn, Cd and Pb immobility, but at the same time made Pb and As available, turning the procedure into a hazard for these elements (62). Similarly, redox conditions are crucial in paddy soil, as sulphide chemistry determines Cd solubility during the flooding, something unavailable in aerobic soils (15). Climate makes the picture even more complicated, as rainfall and temperature determine organic matter turnover, thus the persistence of any immobilising phase. However, most of the research is either carried out in lab conditions or in small plots that make generalisation to larger and climatically different fields doubtful (61). In other words, a universal recommendation cannot be reached or desired.

Long term stability of immobilisation and plant resilience effects

The long-term durability of organic amendments remains a serious concern, as promising short-term outcomes are not consistently sustained in the field. In an 8-year field experiment, red-mud + rape-straw cut plant Cd by 83.5 % in the early years but only 17.2 % by year eight, the decay tracking a gradual rebound in available soil Cd as the amendment's influence waned (63). This is not remobilisation in the catastrophic sense but a slow erosion of benefit that any single season trial would miss entirely, which cautions strongly against extrapolating pot scale efficacy to multiyear cropping. Cumulative inputs pose the mirror image risk. Over a trial exceeding 60 years, dynamic modelling projected that ecotoxicological critical limits were already exceeded under sewage sludge inputs and would remain so to 2100, with compost plots among the few where labile metal failed to decline (59). Stability therefore cuts both ways; the desirable immobilisation fades while the undesirable accumulation compounds and reconciling these opposed trajectories is a central unresolved challenge for repeated-application regimes.

Methodological and data gaps

Progress is hampered by methods that are neither standardised nor plant aware. Bioavailable metal is operationalised through a patchwork of extractants ethylenediaminetetraacetic acid (EDTA), $CaCl_2$, diethylenetriaminepentaacetic acid (DTPA), sequential fractionation whose results are not interconvertible, so cross study synthesis rests on unstable comparisons (15). Compounding this, amendment characterisation is rarely harmonised, plot sizes and trial durations are often

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too small to capture field behaviour and physiological endpoints are frequently omitted in favour of soil chemistry alone (61). A further blind spot is the scarcity of multi stress designs. Real agroecosystems impose metals alongside salinity, drought and nutrient imbalance, yet controlled studies typically isolate a single stress factor and the literature on amendments has only begun to address combined metal and salinity contexts (60). Chromium exposes these gaps most starkly. Its behaviour hinges on the Cr(III)/Cr(VI) couple, but amendment studies seldom resolve speciation, crop specific Cr responses in systems such as sugarcane remain thinly documented and integration of Cr work with sequential extraction or omics data is largely absent leaving the review's Cr focus supported more by mechanistic inference than by direct crop-level evidence.

Toward plant centric, omics guided, climate smart amendment strategies

The conceptual correction this field most needs is a shift of the evaluative endpoint from the soil to the plant. Reductions in extractable metal fractions and immobilisation efficiency are not the final objectives of remediation, but rather intermediate markers. Soil resilience, crop yield, nutritional quality and the safety of edible plant tissues should all be taken into consideration when assessing the long-term effectiveness of organic amendments. Therefore, rather than concentrating just on decreases in soil metal availability, recent assessments indicate the need to better understand soil–plant interactions (61).

A plant-centric framework makes this reorientation operational by specifying the causal chain that any amendment decision must traverse and the measurement that closes each link. The chain begins with contaminant identity and speciation, which determine whether sorption, complexation or redox transformation is the relevant mechanism and whether the element behaves as a cation, an oxyanion or a redox-active species. It proceeds to the joint properties of soil and amendment, with soil pH, texture, mineralogy, CEC, organic carbon and redox status on one side and amendment pH, C : N, CEC, surface area and functional group density on the other, which together set the achievable change in partitioning. Application rate and reapplication interval then determine the magnitude and persistence of that change and must be set against nutrient loading and imported contaminant burden rather than against immobilisation alone. The fourth link is metal bioavailability in the rhizosphere, measured through a consistently reported extractant and through fractionation rather than total content. The fifth is crop uptake and internal partitioning, which depends on species, cultivar and transporter-level control and determines how much of the available pool reaches the harvested organ. The sixth is yield and product quality, which registers whether resilience rather than mere tolerance has been achieved. The chain closes at dietary risk, expressed as edible tissue concentration against the applicable maximum level and as HQ, THQ and CR. Each link is both a measurement point and a potential failure point and an amendment strategy is defensible only when evidence exists at every link rather than at the first four alone (Fig. 4). Omics tools offer the connective tissue for this reorientation, since transcriptomic, proteomic, metabolomic and microbiome profiling can link amendment properties to the plant and microbial responses they provoke and surface biomarkers of genuinely effective interventions the staged Cr-response programme resolved in a model species illustrates the resolution such approaches provide (25).

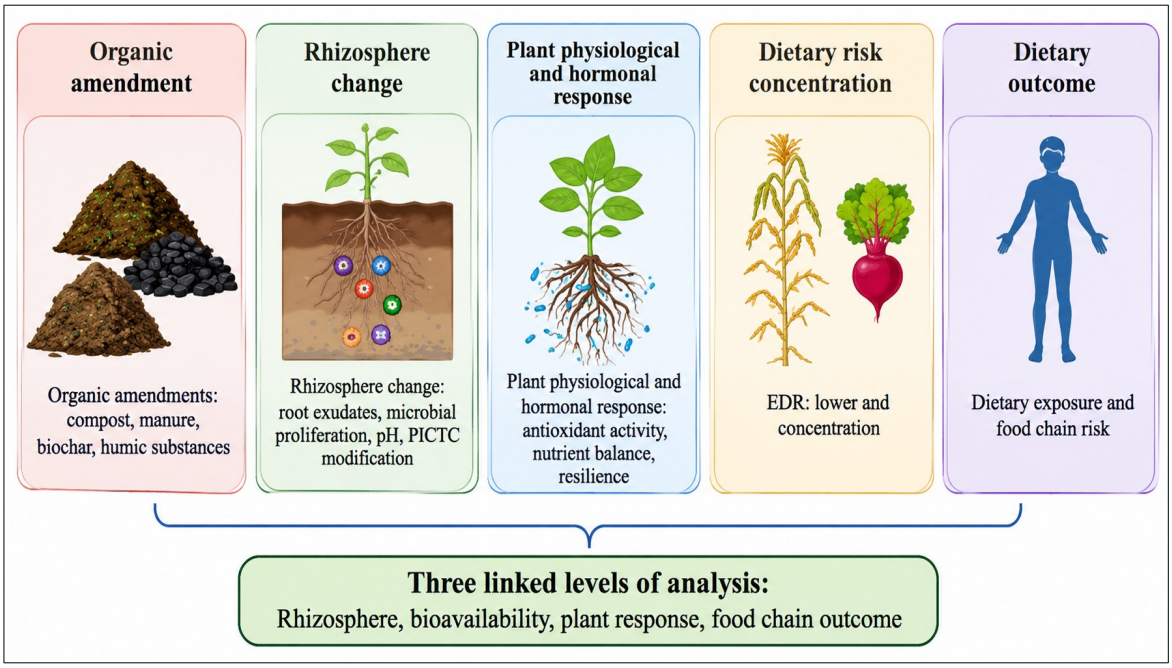


Fig. 4. Conceptual framework linking organic amendments to crop resilience and food chain safety.

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Four testable hypotheses follow directly from the gaps identified above and can be prioritised. The first is that amendment efficacy is predicted more accurately by measured functional properties, namely pH buffering, CEC, surface area and functional group density than by feedstock category. This is testable within 2–3 years through multi-site trials using characterised materials on standardised soils. The second is that transcriptional signatures of reduced effective metal dose predict edible tissue concentration more reliably than any single soil extractant, which requires paired omics and tissue measurement across three to five seasons. The third is that amendment + microbial combinations show true synergy only where the amendment relieves a specific microbial limitation, a proposition that demands factorial designs with single-factor controls and could be resolved within three years. The fourth is that the durability of immobilisation scales inversely with the labile carbon fraction of the amendment, a hypothesis testable only in field experiments maintained for 8–10 years and monitored for both available metal and edible tissue concentration. Short horizon work should concentrate on standardising characterisation and bioavailability protocols, because every subsequent synthesis depends on it. Medium horizon work on multi-stress and multi-element designs and on crop specific validation of omics derived markers and long horizon work on the decadal field trials that alone can settle questions of persistence and cumulative loading.

The most promising path forward is combinatorial: pairing amendments with breeding or selection of low-accumulating, metal-tolerant cultivars, with targeted bio stimulants such as PGPR, arbuscular mycorrhizal fungi and humic substances and with precision application that matches material and rate to the soil-crop-contaminant context (61). Genome editing and marker assisted selection extend this toolkit toward cultivars engineered for resilience under the environmental perturbations that climate change imposes (64). Because altered rainfall, temperature and CO_2 will reshape organic matter turnover and metal uptake simultaneously, amendment design cannot remain climate agnostic; a climate smart, plant centric framework is the logical synthesis of these strands.

Extension and farmer adoption

None of these advances will protect food chains unless they reach practice and the regulatory scaffolding remains uneven. Allowable metal concentrations in amendments and soils are inconsistently defined, so the same sludge may be compliant in one jurisdiction and prohibited in another, weakening the signal farmers receive about safe inputs (61). Closing this gap requires decision support tools that translate soil crop contamination data into concrete choices which amendment, at what rate, with what monitoring and crucially when to abandon food production in favour of non-food or remediation species. The persistent finding that immobilisation and soil environmental quality can diverge reinforces the need for such tools. In long-term Cd contaminated paddy, high amendment doses that lowered available Cd simultaneously suppressed microbial N cycling, so a treatment optimised for metal control degraded the soil's biological function (65).

Adoption barriers are economic, informational and institutional as much as technical. Organic amendments are bulky and transport and application costs rise steeply with distance from the feedstock source, which places high-rate treatments beyond the reach of smallholders in precisely the marginal landscapes where contamination and poverty coincide (60). The benefit is largely invisible at the farm gate, because reduced grain or leaf metal concentration produces no yield response the farmer can observe and attracts no price premium unless a certification or procurement scheme creates one. Soil and produce testing capacity is often absent or unaffordable, so farmers cannot verify either the contamination status of their land or the quality of the amendment they purchase. Insecure land tenure discourages investment in a treatment whose returns accrue over several seasons and labour demand competes with peak-season operations. Where regulation designates land as contaminated, farmers may reasonably fear devaluation and market exclusion and therefore avoid testing altogether.

The variety + irrigation + pH package developed for Cd contaminated paddy in China combines low accumulating cultivars, controlled flooding and liming and has been extended through pilot projects in Hunan Province and subsequently to other affected regions. Survey evidence from 447 farmers across 14 Cd polluted counties shows that adoption responds to guidance, constraint and incentive regulation and that technical understanding mediates that response, which identifies farmer training rather than mandate alone as the operative lever. At the other end of the intervention scale, the Japanese soil replacement programme in the Jinzu River basin, sustained from 1979–2012 across 863 ha under a polluter-funded, prefecture-administered scheme, reduced rice Cd to levels comparable with uncontaminated areas and illustrates both the effectiveness and the cost of engineering solutions where amendment-based management cannot achieve safe production. Building trust around interventions of this complexity depends on extension services, farmer field schools and participatory on-farm trials, coupled with subsidy or procurement instruments that make the invisible food safety benefit financially visible (60). The overarching message is one of qualified promise. Organic amendments are genuinely powerful instruments for immobilising metals and strengthening crop resilience, but they are neither self-sufficient nor universally safe and their value is realised only when embedded in an integrated, risk-based management strategy that keeps plant performance and food safety, rather than soil chemistry alone, at its centre.

2. Conclusion

Organic amendments should be viewed as tools for modifying the soil-microbe-plant system rather than simply as metal sorbents. Their effects arise from interacting changes in soil pH, cation exchange capacity, metal

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complexation, redox conditions, nutrient availability and biological processes. These mechanisms can reduce the mobility and plant uptake of several cationic metals and, in some cases, improve plant physiological performance under metal stress. However, their effectiveness is highly dependent on amendment properties, application rate, soil crop conditions and the chemistry of the target element. An amendment effective for Cd and Pb may have limited effects on Cr or Ni and may even increase the mobility of As under certain conditions.

Importantly, reductions in soil extractability or changes in metal fractionation cannot be assumed to represent reductions in human exposure. Evidence that repeated amendment application can increase edible-tissue concentrations and dietary hazard indices highlights the need to evaluate treatment success at the plant and food-consumption levels. Immobilisation should therefore be regarded as a potentially reversible process that can change with pH, redox conditions, organic-matter turnover and repeated cropping. Long-term performance must consequently be assessed under realistic field conditions rather than inferred solely from short-term laboratory or pot experiments.

Future research should focus less on developing new amendment materials and more on establishing consistent criteria for their characterisation, comparison and field evaluation. Harmonised measurements of amendment functionality, metal bioavailability, plant uptake and dietary exposure are needed to improve cross-study comparability. Multi season field trials should also incorporate variable soil conditions, repeated applications and multiple environmental stresses. Integrating these approaches with low accumulating cultivars, beneficial microbial partners and molecular indicators of metal exposure may further improve treatment reliability. Ultimately, the effectiveness of an organic amendment should be judged not only by its capacity to immobilise metals in soil, but by its ability to maintain low metal transfer to edible plant tissues and support the production of safe food over the relevant cropping timescale.

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Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Quillbot paraphrasing tool solely to improve the language of the text. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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