

Heavy Metal Accumulation in Agricultural Soils and its Consequences for Crop Plants and Food Safety

Manju M. George 

Department of Botany, Union Christian College (Autonomous) Aluva, Ernakulam District, Kerala – 683 102, India

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*Corresponding Author: **Manju M. George** | Email Address: manju@uccollege.edu.in

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Abstract

The accumulation of heavy metals and metalloids in agricultural soils is a permanent threat to soil health, crop productivity and food safety. Cadmium, lead, arsenic, mercury, chromium, nickel and copper enter agricultural land from geogenic weathering, atmospheric deposition, mining, industrial activities, phosphate fertilisers, pesticides, livestock manures, sewage sludge and irrigation with wastewater. Being non-biodegradable elements, repeated inputs can increase soil concentrations over time, both total and bioavailable. Their impact on crops is highly dependent on soil pH, organic matter, redox conditions, texture, microbial activity and crop species. Excess metals affect seed germination, root growth, nutrient uptake, photosynthesis, water relations and enzyme function, usually through oxidative stress and disruption of essential metal homeostasis. Different crops have different capacities to absorb and translocate metals. Leafy vegetables, rice and some root crops can accumulate worrying levels of cadmium, arsenic or lead. Dietary exposure to contaminated crops is associated with nephrotoxicity, neurotoxicity, cardiovascular effects, developmental toxicity and cancer risk. Good management includes source control, routine testing of soil and crops, pH and organic-matter management, safe irrigation water, low-accumulating cultivars, and site-specific remediation. This review summarises sources, soil processes, plant responses, food chain transfer, health risks and mitigation methods of heavy metals in agricultural systems.

Keywords: agricultural soils; heavy metals; cadmium; arsenic; lead; crop uptake; food safety; phytoremediation; bioavailability.

1. Introduction

Agricultural soils are a medium of production, a sink for contaminants originating from waste and a pathway for contaminants into the human food chain. There is a particular concern for heavy metals and metalloids like cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), chromium (Cr), nickel (Ni), copper (Cu) and zinc (Zn), as they are persistent in the soil, cannot be degraded biologically and accumulate in plants and animals [16, 8]. Some elements such as Cu, Zn, Ni and Cr are essential micronutrients at low concentrations but become toxic when bioavailable levels exceed plant tolerance thresholds [11, 1].

This is a global issue because agricultural intensification often leads to an increase in metal inputs. Soil loading can be contributed to by phosphate fertilisers, metal-based pesticides, irrigation with contaminated water, biosolids, livestock manures, atmospheric deposition from traffic and industry, and emissions from mining or smelting. Anthropogenic activities are particularly important in peri-urban and industrialised farming areas where the use of wastewater for irrigation and proximity to emissions sources may lead to high loads of contaminants [16, 3].

The key food-safety issue is not just the total concentration of a metal in soil, but the bioavailable fraction, the part that is available for plant uptake and subsequent transfer to edible tissues. The fraction is strongly governed by soil pH, organic matter, clay content, redox potential, microbial activity and rhizosphere chemistry [7, 15]. Therefore, two soils with similar total metal levels may represent very different risks for crops and consumers.

A review of the major sources and behaviour of heavy metals in agricultural soils, their effects on crop physiology and yield, their transfer into food crops, the human health risk, and practical prevention and remediation measures.

2. Sources of Heavy Metals in Agricultural Soils

2.1 Natural and geogenic sources

Heavy metals are naturally present in soils as constituents of parent rocks and minerals. Weathering of metal-rich shales, volcanic materials, sulphide deposits and mineralised bedrock can release As, Cd, Pb, Ni, Cr and other elements into soil profiles [1]. In some areas naturally high background concentrations, particularly of As, Ni, Cr or Pb, can mean that agricultural soils exceed guideline values even in the absence of major local pollution.

Rapid increases in contamination are seldom attributable to natural inputs only, but these inputs do provide the baseline against which anthropogenic additions can be measured. Geogenic contamination is especially relevant in areas where crops are grown on alluvial plains, mining-impacted catchments or soils developed from metal-rich parent materials [16, 8].

2.2 Fertilizers, manures, and agrochemicals

Phosphate fertilisers are a known diffuse source of Cd and in some deposits of Pb and As, as phosphate rock can contain these impurities [5, 8]. Repeated application for a long time can gradually increase the Cd content in soil, particularly in highly fertilised systems with low pH.

Livestock manures and composts may contain Cu and Zn from feed additives and also variable amounts of Cd, Pb, As and other elements depending on feed, bedding and processing [1, 3]. Biosolids derived from sewage sludge are a source of nutrients and organic matter, but if wastewater streams are polluted they can contain Cd, Pb, Hg, Cr, Ni and Cu [1, 15].

Historically, sources of Pb, As, Cu, Hg and other metals have included pesticides, fungicides, and soil amendments. While many highly persistent metal-based pesticides have been restricted, legacy contamination is still relevant in old orchards, vineyards and intensively treated fields [16, 8].

2.3 Irrigation water and wastewater

Irrigation with raw or partially treated municipal, industrial, or mining-impacted wastewater is one of the most direct pathways for transfer of metals to agricultural land. Wastewater from domestic, industrial and stormwater sources can contain Cd, Pb, Cr, Cu, Zn, Ni and As, and repeated application can result in accumulation of these in surface soils where roots are concentrated [16, 9]. Higher concentrations of Pb, Cd, Cr, Cu and Zn have been found in crops grown on land irrigated with wastewater [9].

Groundwater can also be a source of As, particularly in alluvial and deltaic environments where reducing geochemical conditions favour arsenic mobility. Flooded rice systems are especially vulnerable because anaerobic conditions can enhance arsenic mobility and uptake [15, 5].

2.4 Atmospheric and industrial deposition

Metals are emitted in particle form from industrial emissions, the combustion of fossil fuels, mining, smelting, waste incineration and road traffic and deposited on soil and plant surfaces. Such deposition is generally related to Pb, Cd, Hg, Cr, Ni and Cu [Zwolak et al., 2019, Jayakumar et al., 2021]. Such fields may therefore receive both diffuse atmospheric inputs and local contamination from adjacent highway, smelter, coal-fired plant and industrial cluster sources.

Atmospheric deposition can also directly contaminate edible parts of plants through foliar deposition in addition to increasing soil reservoirs. This distinction is important for food safety as washing may reduce deposits on the surface but cannot remove metals incorporated into plant tissues [16, 9].

3. Behaviour and Bioavailability in Soil

3.1 Total concentration versus bioavailability

The total soil metal concentration is an indicator of total contaminant load but is not a good predictor of plant uptake. Metals occur in different operationally defined pools, i.e. soluble and exchangeable, carbonate- and oxide-bound, organic-bound and residual mineral forms.

Soluble and exchangeable fractions are generally most available to plants and microbes, while residual fractions are relatively stable [7, 15].

So, bioavailability is the key variable in risk assessment. It is affected by metal speciation, soil solution chemistry, root exudates, microbial transformations, and plant uptake physiology [7, 15]. For example, a soil may contain a high total concentration of Pb but present limited risk if the metal is strongly bound to organic matter or iron oxides.

3.2 Soil pH and redox conditions

Soil pH is one of the most important controls on metal solubility and mobility. Many cationic metals, e.g. Cd, Zn, Ni, Cu, and Pb, have enhanced solubility and availability under acidic conditions, with a decrease in adsorption and an increase in desorption from exchange sites [7, 15]. Thus, liming of acidic soils can decrease the bioavailability of Cd and Pb by increasing pH and enhancing precipitation or adsorption, but the effectiveness varies with metal, soil type and initial pH [15].

The redox potential is particularly important in paddy rice systems. Flooding decreases oxygen in the soil and may reduce sulphate to sulphide, which may immobilise some metals as metal sulphides; however, reducing conditions may also mobilise arsenic by reducing arsenate to the more mobile arsenite form [15, 5]. Water management has therefore crop-specific consequences. Drainage may reduce As uptake in rice but may increase the availability of Cd under some conditions.

3.3 Organic matter, clay, and microbial processes

Soil organic matter interacts with metal ions through adsorption, complexation and cation-exchange processes, which often reduce their mobility and bioavailability [7, 15]. Thus, organic amendments such as compost, farmyard manure and biochar can immobilise metals, improve soil structure and support microbial communities, but the net effect depends on their own metal content and the soil context [15, 4].

Additional sorption sites are provided by clay minerals and iron, aluminium and manganese oxides. Soils with fine texture and high clay and oxide contents tend to bind metals more compared to sandy soils with low organic matter content [7, 15]. Soil microbes affect the fate of metals in terms of pH modification, chelator production, redox condition modification, and metal species transformation that can immobilise or mobilise the contaminants [7, 4].

4. Uptake, Translocation, and Accumulation in Crops

Like other plants, they take up metals from the soil solution via their roots. Metals can enter cells through transport pathways normally used by essential ions; for instance, Cd can utilise transporters involved in uptake of Zn, Fe, Mn or Ca, while arsenate can enter via phosphate transport pathways [11, 15]. Once in root, metals may be stored in vacuoles, bound to cell walls, detoxified by phytochelators or metallothioneins or transported to shoots through xylem [11, 10].

Distribution of metals in plant organs is very important for food safety. Many plants show a high retention ability of a high proportion of Pb in the roots, thus limiting its transfer to the shoots, while Cd is relatively mobile and can be accumulated in the leaves, grains and other edible tissues [11, 9]. Arsenic accumulation is especially relevant in rice grain, where inorganic arsenic is the form of greatest toxicological concern [15, 5].

Accumulation depends greatly on crop type. Leafy vegetables are often more cadmium-rich than fruiting vegetables because leaves receive a large amount of translocated metal from the roots and also intercept atmospheric deposits. Root and tuber crops may contain Pb and As in the edible underground organs, and cereals such as rice may contain Cd and As in grain [16, 9]. Cultivar differences also matter, and low-accumulating cultivars can be selected for contaminated areas [9].

5. Effects on Crop Plants

5.1 Germination, growth, and yield

Toxic concentrations of heavy metals inhibit seed germination, root elongation, shoot growth, biomass, flowering and yield. Roots are generally a first target as they are the first contact zone with soil contaminants. Metal stress can reduce the root length, reduce the lateral-root formation, damage the root tips and impair the water and nutrient absorption [11, 1].

Yield losses are caused by the combined effects of reduced photosynthesis, nutrient imbalance, impaired water relations and cellular damage. Cd, Pb, Hg and As are particularly associated with reduced growth and yield as they disturb the cellular homeostasis and interfere with photosynthesis and nutrient uptake [9, 11]. The degree of effects depends upon the concentration of metal, time of exposure, soil properties and the tolerance mechanism of crop.

5.2 Photosynthesis and chlorophyll

Heavy metals often decrease chlorophyll content and photosynthetic efficiency. They can inhibit biosynthesis of chlorophyll, promote degradation of chlorophyll, injure chloroplast, and inhibit the activity of photosystem II [11, 10]. Among them, Cd and Pb are especially known to reduce carbon dioxide fixation and degrade chlorophyll resulting in chlorosis and poor growth [10].

Reduced photosynthesis reduces carbohydrate supply for growth and grain filling. It can reduce tillering, grain number, grain weight and harvest index in cereals, whereas it can reduce leaf area, fruit set and marketable yield in vegetables [11, 1].

5.3 Oxidative stress and cellular damage

One of the most important mechanisms of metal toxicity is the overproduction of reactive oxygen species (ROS) such as superoxide, hydrogen peroxide and hydroxyl radicals. Metals can induce ROS directly through redox cycling, as with Cr and Cu, or indirectly through disruption of electron transport, antioxidant defences and mitochondrial function [11, 10].

ROS damage lipids, proteins, nucleic acids and membranes. To counter oxidative stress, plants initiate the activation of antioxidant enzymes such as superoxide dismutase, catalase, peroxidase, glutathione reductase, and ascorbate peroxidase, as well as non-enzymatic antioxidants like glutathione, ascorbate, and phenolic compounds [11, 10]. When metal stress overwhelms these defences, oxidative damage contributes to chlorosis, necrosis, reduced growth, and reproductive failure.

5.4 Nutrient imbalance and enzyme inhibition

Heavy metals compete with vital nutrients for sites of uptake and transport. Cd can affect the nutrition of Zn, Fe, Mn and Ca; Pb can interfere with the uptake of Ca and other minerals; and As can affect the phosphate metabolism [11, 1]. The deficiencies that result can mimic symptoms of metal toxicity or aggravate symptoms such as chlorosis, necrosis, stunted root growth and reduced yield.

Metals also bind to sulfhydryl groups and active sites of enzymes, inhibiting metabolic pathways. This can influence nitrogen metabolism, carbohydrate metabolism, antioxidant defence, and photosynthetic carbon fixation [11, 1]. Enzymes need specific metal cofactors and protein structures, thus even moderate metal stress can impede metabolic efficiency before any visible symptoms are exhibited.

5.5 Soil microbial and biochemical effects

Heavy metals affect not only plants but also soil organisms on which nutrient cycling depends. Heavy metal concentrations can reduce microbial biomass, alter community composition, inhibit enzyme activity, and reduce decomposition, nitrogen mineralisation, and other soil processes [7, 1]. This can have effects in reducing the supply of nutrients to crops and in weakening resilience in the soil ecosystem.

Microbial communities have different sensitivities. Some bacteria and fungi can tolerate or even transform metals, which can contribute to immobilisation or mobilisation depending on the species and conditions [4, 7]. Therefore, maintaining organic matter and balanced nutrient status can support microbial functions that help buffer metal stress.

6. Transfer to the Food Chain and Food Safety

6.1 Edible-tissue accumulation

Heavy metals enter the human food chain when crops accumulate contaminants in edible roots, tubers, leaves, fruits, seeds or grains. The amount of transfer depends on soil bioavailability, crop species and cultivar, plant organ, growth stage and agronomic management [16, 9]. Key exposure pathways are repeatedly identified as leafy vegetables, rice and some root crops due to their uptake and consumption [16, 9].

Rice in rice consuming areas deserves special attention. Flooded cultivation may enhance As mobility, and Cd can be accumulated in grain under aerobic or acidic conditions, making rice an important dietary source of both elements in affected areas [15, 5]. Vegetables grown in peri-urban gardens or wastewater irrigated fields may also have high levels of Pb, Cd, Cr, Cu and Zn [16, 9].

6.2 Regulatory limits and exposure assessment

Food-safety standards use maximum levels to limit contaminant concentrations in commodities. The Codex Alimentarius defines a maximum level as the highest concentration of a contaminant legally recommended for a food or feed commodity [5]. These limits are commodity-specific because crops differ in accumulation potential and consumption patterns.

Human exposure assessment commonly estimates chronic daily intake, hazard quotient, and cancer risk from measured concentrations in food and assumed consumption rates [9]. Cd and Pb are major non-carcinogenic and carcinogenic concerns, respectively, while inorganic As is treated as a significant carcinogenic risk. Hg, particularly methylmercury, is a major concern in aquatic foods, although agricultural crops can also contribute in contaminated settings [9, 5].

6.3 Human-health consequences

Chronic dietary exposure to heavy metals can cause multiple adverse health outcomes. Cd is associated with kidney damage, bone demineralization, and increased cancer risk; Pb affects neurodevelopment, hematopoiesis, blood pressure, and reproductive health; inorganic As is linked to skin lesions, cardiovascular disease, diabetes, and cancers; and Hg exposure

can damage the nervous system, kidneys, and developing fetus [10, 5].

Children, pregnant women, and nutritionally vulnerable populations face disproportionate risks because of higher relative food intake, developing organ systems, and greater susceptibility to neurodevelopmental effects [9]. Because contamination is often chronic and low-level, its health effects may be subtle, delayed, and difficult to attribute to a single food source without dietary and biomonitoring data.

7. Monitoring and Risk Assessment

Monitoring is the first step to good management. Soil testing should measure total concentrations and bioavailable fractions where possible, using appropriate extractants and taking into consideration pH, organic matter, texture and land-use history [7, 15]. Similarly, testing of crop tissue is important because it directly reflects the fraction of contaminant entering the food supply.

The risk assessment should take into account soil data, crop accumulation data, irrigation water quality, dietary consumption patterns and exposure of vulnerable populations. Indices such as bioconcentration factor, translocation factor, hazard quotient and lifetime cancer risk are useful for comparing crops, sites and management scenarios [9]. However these indices should be used with caution since they are dependent on assumptions about consumption, speciation and bioavailability.

In smallholder systems, practical monitoring may be restricted to high-risk fields like wastewater-irrigated plots, peri-urban gardens, fields near industrial or mining sources, acidic soils with phosphate fertilisers and rice lands in As-affected regions [16, 15].

8. Prevention and Remediation Strategies

8.1 Source control

The most sustainable approach is to prevent further metal inputs. Source control includes using low-Cd phosphate fertilizers, avoiding contaminated irrigation water, treating wastewater before agricultural use, testing manures and composts, restricting contaminated biosolids, and controlling industrial emissions [16, 5, 15]. Regulatory enforcement, waste segregation, and farmer education are essential because remediation alone cannot manage continuous recontamination.

8.2 Agronomic management

Agronomic measures can reduce metal bioavailability and crop uptake. Liming acidic soils can decrease Cd and Pb availability; adding organic matter or biochar can increase adsorption and complexation; balanced fertilization can reduce plant stress and limit excess uptake; and appropriate water management can alter As and Cd dynamics in rice systems [15, 4].

Crop selection is another practical tool. Farmers can avoid high-accumulating crops in contaminated fields, choose low-accumulating cultivars, and use crops with lower edible-tissue transfer where soil risk is moderate [9]. In severely contaminated land, food-crop production may need to be replaced with non-food crops, bioenergy crops, or phytoremediation systems.

8.3 Phytoremediation and bioremediation

Phytoremediation uses plants to extract, stabilize, or volatilize contaminants.

Phytoextraction removes metals through harvestable plant biomass; phytostabilization reduces mobility and erosion; rhizofiltration removes metals from water; and phytovolatilization converts certain forms, notably Hg and As species, into volatile forms under specific conditions [4, 15]. Hyperaccumulator plants can remove metals but often produce low biomass and may be unsuitable for food production.

Microbe-assisted remediation can enhance phytoremediation by improving plant growth, altering metal speciation, producing biosurfactants or organic acids, and promoting immobilization in the rhizosphere [4]. Biochar, compost, and other organic amendments can support these processes while also improving soil fertility, though amendments must be screened for their own contaminant content [15, 4].

8.4 Physical and chemical remediation

Physical and chemical approaches may be needed for heavily contaminated or high risk sites. These involve replacement of soil, deep ploughing for dilution of surface contamination, excavation and safe disposal, soil washing, immobilisation using lime, phosphate, iron oxides or biochar and electrokinetic treatment in specialised settings [15, 4]. Such methods can be expensive, and may disrupt soil structure, so are generally reserved for severe contamination, or small high value areas.

9. Research Gaps and Future Directions

Effective risk management is limited by several gaps. First, the crop-specific uptake data are heterogeneous across soils, climates and cultivars making generalisation of risk predictions difficult [9]. Second, many studies measure total soil concentrations but do not well characterise bioavailable or speciated fractions, despite these being better predictors of plant uptake and toxicity [7, 15].

Third, there are few long-term human health studies that link crop contamination, dietary exposure and clinical outcomes. Future research needs to integrate soil geochemistry, plant physiology, data from food monitoring, diet surveys and biomarkers of exposure. Fourth, climate change may alter the behaviour of metals through changes in temperature, flooding, drought, salinity, and organic matter decomposition. These interactions need to be investigated at the field scale [15, 9].

Finally, practical solutions must be available to smallholder farmers. The chances of adoption of low-cost soil testing, safe water supplies, locally available amendments, low-accumulating varieties and clear advisory thresholds are higher than that of expensive remediation technologies alone [15, 10].

10. Conclusion

Heavy metal accumulation in agricultural soils is a threat to crop productivity and food safety, through a chain of contaminant inputs, soil chemistry, and dietary exposure. Sources, mobility, plant behaviour and health effects of Cd, Pb, As, Hg, Cr, Ni, Cu and Zn vary but all may be hazardous when bioavailable concentrations exceed crop and food-safety thresholds.

The best response is an integrated one: avoiding new inputs, monitoring soil and crops, managing pH and organic matter, using safe irrigation water, selecting appropriate crops and cultivars and remediating only where necessary. Policies and farm advisories should emphasise site-specific risk assessment, since food safety is a matter of bioavailability, not total concentration. Thus, it is important to prevent the accumulation of metals in agricultural soils, not only for sustainable crop production, but also for public health in the long term.

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