



Original Article

## The destructive effects of heavy metals on plant health, soil quality, and agricultural productivity

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### Abstract

Heavy metal contamination poses a significant threat to plant health, soil quality, and agricultural productivity. This review explores the sources, physiological impacts, and biochemical mechanisms underlying heavy metals toxicity in plants. Common heavy metals of concern include cadmium (Cd), lead (Pb), mercury (Hg), nickel (Ni), chromium (Cr), copper (Cu), and zinc (Zn), which originate from both natural processes and anthropogenic activities including industrial emissions, fertilizers, pesticides, and wastewater irrigation. Excessive accumulation of these elements disrupts plant metabolism by generating reactive oxygen species (ROS), leading to oxidative stress, enzyme inhibition, membrane damage, and impaired photosynthesis. Experimental studies show that cadmium and nickel stress significantly alter antioxidant enzyme activities—such as catalase, peroxidase, and superoxide dismutase—indicating a defensive response to oxidative imbalance. Morphological symptoms of metal toxicity include chlorosis, stunted growth, reduced yield, and reproductive failure. In addition to direct plant effects, heavy metals disturb soil microbial communities, alter pH, and inhibit processes like nitrogen fixation and decomposition. Effective mitigation requires regular soil monitoring, use of biochar and organic amendments, phytoremediation with hyperaccumulator plants, and balanced nutrient management. Understanding these interactions provides a foundation for sustainable soil management and the development of resilient crop systems in metal-polluted environments. This review synthesizes current understanding of heavy metal ecotoxicology in agricultural systems and emphasizes the need for integrated management approaches to ensure food safety and environmental sustainability.

**Keywords:** Heavy metals, Oxidative stress, Antioxidant enzymes, Phytotoxicity, Soil contamination, Phytoremediation

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### 1. Introduction

Heavy metals are naturally occurring elements in soils, typically defined as metallic elements with atomic numbers greater than 20 and possessing specific chemical properties, including cation formation and ligand binding capabilities.

Common heavy metals include nickel, lead, mercury, copper, chromium, and cadmium. Many natural and human sources can cause the accumulation of high concentrations of metals, which can be divided into natural, agricultural, industrial, urban, and transportation sources.

Heavy metals cause the formation of reactive oxygen species, which are products of aerobic metabolism and include compounds such as superoxide, hydrogen peroxide, and oxygen radicals that are produced during electron transfer reactions in mitochondria, chloroplasts, and peroxisomes, and if their concentration is not regulated, they cause damage to membrane proteins and DNA (Davey & et al, 2005).

Some ions, such as copper with strong reducing properties, as well as ions such as zinc and cadmium, are known to be initiators of membrane lipid peroxidation and inducers of reactive oxygen species production. The development of oxidative stress in plants exposed to heavy metal stress is mostly attributed to the imbalance created by the heavy metal between the production of oxygen-free radicals and their elimination by antioxidant defense mechanisms.

In a study on plants irrigated with municipal wastewater, it was found that calculated transfer factor and enrichment factor indexes in plants grown on the polluted soils are significantly higher than the control samples, which show the heavy metal enrichment in the contaminated samples (Mazhari & et al, 2019).

Overall, treated wastewater proved to be a promising alternative water and nutrient source for vegetable cultivation in water-limited areas like Neyshabur, enhancing productivity without immediate health risks, though continuous monitoring of cadmium accumulation is essential to prevent potential long-term soil and food safety issues (Keramati & et al, 2025). Soil contamination with heavy metals significantly reduced the amount of chlorophyll a and b, total chlorophyll, carotenoids, net photosynthesis, photosystem quantum chemical performance (PIABS), intercellular CO<sub>2</sub>, transpiration, and water use efficiency (Lajm Orak Rameh Chariy & et al, 2021).

## 2. Physiological and Biochemical Effects on Plants

### • The effect of heavy metals on plant enzymes

The results of experiments by Zhang & et al (2009), on forage mung bean and green mung bean plants showed that a concentration of 100  $\mu$ M cadmium increased the

production of peroxide anion, hydrogen peroxide, as well as the activity of plasma membrane-bound nicotinamide adenine dinucleotide phosphate (NADPH) oxidase and the activities of apoplastic and symplastic superoxide dismutase (SOD) and ascorbate peroxidase in the leaves of both plants.

Apoplastic guaiacol peroxidase activity was significantly induced in leaves of both species, especially in green mung bean exposed to 100  $\mu$ M cadmium. With increasing cadmium concentration, the activities of antioxidant enzymes such as ascorbate peroxidase, guaiacol peroxidase, and glutathione reductase increased with increasing cadmium concentration; however, catalase (CAT) activity decreased in bean plants (Bhardwaj & et al, 2009).

Also, a decrease in catalase activity and an increase in hydrogen peroxide have been reported in wheat seedlings (Karamet & et al, 2014) under cadmium stress. In maize plants, the activities of CAT, ascorbate peroxidase, glutathione reductase, and guaiacol peroxidase enzymes increased in both the shoot and roots of plants treated with nickel sulfate with increasing concentration of this metal. The activity of guaiacol peroxidase enzyme was higher in the root, which was directly in contact with the heavy metal nickel, than in the shoot, and the activities of other enzymes were higher in the shoot than in the root (Pourakbar & Ebrahimzadeh, 2013).

Research also showed that with increasing lead concentration in the environment, the production of hydrogen peroxide as an indicator of oxidative stress, the production of flavonoids, and the activity of the peroxidase enzyme in alfalfa shoots and roots increased (Gholich & et al, 2015). Vermicompost can help immobilize heavy metals in contaminated soils through binding processes, while simultaneously improving plant growth by providing essential nutrients. This makes it a valuable amendment for phytoremediation strategies. (Jadia & Fulekar, 2008).

The increase of these metals in the environment causes effects such as disruption of seed germination, disruption of mitosis, induction of chlorosis and necrosis in leaves, reduction of photosynthesis and respiration, water imbalance, and changes in plant hormonal balance (Table 1).

**Table 1.** Specific effects of heavy metals on plants

Metal	Early Signs	Advanced Signs
Cadmium	Yellowing between veins in young leaves	Brown edges of leaves, stunted plants.
Lead	Purple leaves due to phosphorus deficiency	Root fragility, delayed maturation
Copper	Leaf curling and abnormal darkening of green leaves	Browning of leaves, reduced root branching

Plants growing in soils contaminated with heavy metals face several problems:

- Impaired nutrient absorption – for example, excess zinc reduces the absorption of iron and manganese, causing symptoms of their deficiency.
- Reduced photosynthesis – Lead and cadmium inhibit chlorophyll production and reduce the rate of photosynthesis by up to 40%.
- Enzyme disruption – Heavy metals react with vital plant enzymes, disrupting energy production and DNA repair pathways.
- Oxidative stress – Increased metals cause the production of free radicals and damage cell membranes.
- Reduced fruit yield – In cereals, cadmium reduces pollen fertility, and in fruit trees, lead disrupts pollen tube growth, leading to reduced fruit size and malformation.
- These effects are usually irreversible and severely reduce farm productivity.

Symptoms of heavy metal toxicity in plants are essential. Field diagnosis is difficult because the symptoms of heavy metals sometimes resemble those of element deficiencies.

Introducing the most important heavy metals in agricultural soils and soil ecosystems

**1. Cadmium (Cd)** – usually introduced into the soil through phosphate fertilizers. Cereal crops such as rice transfer cadmium to the grain, which is important for food safety standards.

**2. Lead (Pb)** – binds to soil organic matter but severely disrupts the root system. In root crops such as carrots and potatoes, it is transferred to the skin of the crop.

**3. Arsenic (As)** – sometimes present in groundwater, and prolonged irrigation can cause it to accumulate in the soil and reduce the plant's tolerance to drought.

**4. Mercury (Hg)** – although less common, it enters the atmosphere from gold mining or coal burning, and from there it is deposited in soils. Even very small amounts can harm plants.

**5. Chromium (Cr)** – especially the hexavalent form of chromium (Cr VI) is very dangerous. It is sourced from leather tanning wastewater and some dyes.

**6. Zinc (Zn)**- This metal plays a role as an activator and cofactor of some vital plant enzymes, including carbonic polymerases, RNA anhydrases, dehydrogenases, alkaline phosphatases, phospholipases, and sugar, nucleic acid, and lipid metabolism, plant photosynthesis, and auxin biosynthesis as a growth-promoting hormone. Some researchers believe that zinc maintains the

integrity of cell membranes by protecting proteins and membrane lipids from free radicals and other products of intracellular reduction reactions. In addition, this metal, along with copper, forms the main part of the superoxide dismutase enzyme, which is a free radical scavenger.

**7. Nickel (Ni)**- Therefore, it is likely that crop plants in different regions of the world, and also in our country, are exposed to nickel toxicity, and their growth and yield are reduced. Some studies have shown that high environmental nickel concentrations significantly reduce root and shoot growth compared to control plants. It has also been reported that heavy metal stress increases cell wall lignification, making the wall stiffer and more inflexible (Lebelo et al., 2021). This phenomenon could be a possible reason for the reduction in the longitudinal growth of roots and shoots in the presence of nickel (Gajewska & Sklodowska, 2007). One of the reasons for the reduction in the fresh weight of roots and shoots seen in the 800  $\mu\text{M}$  nickel treatment could be the reduction in the water content of the root and shoot tissues induced by nickel stress (Gajewska & Sklodowska, 2005).

### 3. How do heavy metals enter the soil?

There are various ways for soil to become contaminated with heavy metals.

**1. Atmospheric sediments and industrial dust** – Metal smelting industries, coal-fired power plants, and busy roads emit fine particles containing lead, cadmium, and nickel over long distances.

**2. Fertilizers and pesticides** – Some low-quality phosphate fertilizers contain cadmium, and copper fungicides can raise copper concentrations above the permissible limit if used repeatedly.

**3. Irrigation water** – The use of river or canal water contaminated with municipal or industrial wastewater is a continuous source of arsenic, mercury, and chromium to the farm.

**4. Animal manure and sewage sludge** – Some of these sources, especially if not quality-controlled, can introduce large amounts of zinc or lead into the soil.

**5. Old contamination** – Historical use of pesticides containing lead or arsenic (Fig. 1).

To permanently control and monitor heavy metal pollution, for effective long-term management of heavy metal pollution, the following practices are recommended:

**1. Accurate diagnosis** – Perform a “Soil Health + Heavy Metals” test annually, especially if you operate near industrial areas or use cheap fertilizers.

**2. Dilution and stabilization** – If metal levels are rising, use high-calcium biochar or iron oxide-rich

compounds. These can reduce up to 70% of the metals available to the plant.

**3. Cleanup with metal-absorbing plants** – Plant metal-absorbing plants such as Indian mustard or sunflower between planting seasons to absorb metals and remove them from the soil with harvest.

**4. Balanced and targeted nutrition** – Proper nutrition with elements such as zinc and silicon reduces cadmium absorption. A complete calcium and magnesium program limits the transfer of lead to the aerial parts. Using NPK fertilizers with amino acid chelates helps to better absorb beneficial elements in competition with metals.

**5. Leaf compost** can also be used to remove heavy metals from wastewater due to its ion exchange capacity, and due to its high organic matter content, it can retain contaminants for a long time. Leaf compost can remove high levels of dissolved metals and reduce their toxicity because various types of leaves and bark provide a surface for absorbing heavy metals.

Incorporating vermicompost with soil and potting soil can lead to increased plant growth (Atiyeh & et al, 2001). In general, planting media can reduce the toxicity of these elements to plants due to the complex formation between heavy metal ions and soil organic matter (Perminova & Hatfield, 2005).



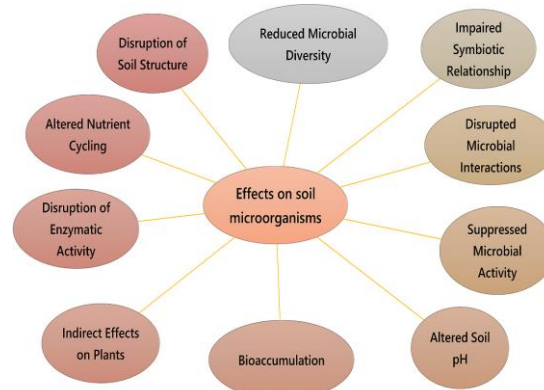
**Fig 1.** Ways of heavy metals entering the soil. Heavy metals enter the soil from natural sources such as rock erosion and volcanic activity, as well as from human sources such as industries, sewage, fertilizers, and contaminated fuels. The accumulation of these elements in the soil over time causes a decrease in fertility, environmental pollution, and threatens the health of humans and living organisms.

#### 4. Organic modifiers

Unfortunately, because the composition of leaf compost is not known, there can be different absorption rates for different leaves and woody species present in it. The efficiency of leaf compost depends entirely on the seasonal species present in the compost at any given time and in each part of it (Jadia and Fulekar, 2008).

#### 5. Effects of HMs on soil microorganisms

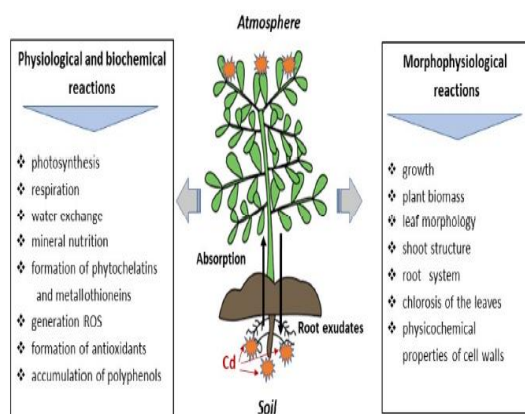
Soil microbes also play an important role in maintaining the soil's pH. Too high or too low soil pH disturbs the microorganisms. HMs found in soil can cause shifts in soil pH. Certain heavy metals, like aluminum, have the potential to acidify the soil, resulting in a decrease in pH. This fluctuation in pH can have consequences for the viability and functioning of soil microorganisms, as different species have varying levels of tolerance to pH changes. Changes in soil pH can also affect the accessibility and movement of HMs within the soil, intensifying their impact on microorganisms. One of the studies shows that contamination of soil with Pb results in soil acidification (Collin & et al, 2022). Contamination with lead inhibits nitrogen fixation and affects photosynthesis in plants (Porter, 1981). Similarly, it inhibits the activity of mycorrhizal fungi and soil enzymes. Short-term additions of N and P are sensitive to communities of soil microbes and enzymatic activities (Collin & et al, 2022). Another study conducted on the effect of soil amendments on trace elements indicates that HMs like Cd have a toxic effect on microorganisms. Contamination with Cd reduces the soil pH, which has toxic effects on soil bacteria, fungi, and earthworms (Ukalska-Jaruga & et al, 2022). This contamination affects nitrogen cycling. Similarly, high levels of Cu and Zn in the soil increase the soil pH slightly, which disrupts microbial communities, especially bacterial communities involved in decomposition (Sazykin et al, 2023). Some microorganisms, such as arbuscular mycorrhizal fungi, can accumulate zinc (Fig. 2) (Begum & et al, 2019).



**Fig 2.** The effect of heavy metals on the activities of internal soil microorganisms. The presence of heavy metals in soil can cause cytotoxicity, reduce the growth and activity of beneficial microorganisms, and alter the structure of the microbial community. These elements disrupt vital processes such as respiration, enzyme production, and decomposition of organic matter, causing a decrease in the ability of microbes to participate in the nutrient cycle and reducing soil fertility.

Heavy metals affect plant physiology, including photosynthesis, relative water respiration, accumulation of polyphenols, and nutrients. Heavy metals affect plant

morphology, including plant growth, biomass, leaf surface area, root and stem morphology, and leaf chlorophyll (Fig 3).



**Fig 3.** Heavy metals affect plant physiology and morphology

Additionally, its effect includes an increment in toxicity level. It has an impact on the physiological and biochemical functions of plants, which in turn affects photosynthesis by lowering the production of chlorophyll, compromising enzymatic activity, and impeding nutrient uptake. This leads to stunted plant growth and development and lower crop yields (Ejaz & et al, 2023). Additionally, HMs can cause oxidative stress in plants. They can engender ROS that can damage cellular structures, interrupt customary metabolic functions, and damage aquatic organisms (Singh & Kalamdhad, 2011). Oxidative stress can lead to cell membrane damage, protein degradation, and DNA alterations, ultimately impacting plant growth and crop productivity.

## Declarations

### Data and code availability

This article is a review and the content is presented with citation of the source.

### Conflicts of interest

The author announced that they have no known conflicts of interest that could have appeared to influence the work reported in this manuscript.

### Ethical approval

This paper is neither under Review nor published elsewhere.

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