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REVIEW ARTICLE

HEAVY METALS AND CADMIUM TOXICITY IN SOIL AND PLANTS

Varsha and Brijesh Shivhare

1. Department of Botany, Baba Mastnath University, Rohtak, Haryana, India.

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Abstract

Primarily in areas with high levels of human activity, heavy metals like cadmium,copper,lead,chromium,and mercury are significant environme ntal hazards.Deposition of heavy metals in soils is a problem in agricult ural outputbecause it has a negative impact on food safety and consume r appeal, growth of crops due to phytotoxicity, and soil organisms' environmental health. Through soil, water, and air pollution, plants and their metabolic processes affect the geological and ecological redistribu tion of heavy metals. This review article addresses the toxicity of heavy metals,particularly Cd,on plants.Plants are greatly impacted by toxicity, which consequently affects the environment in which plants are crucial. Plants cultivated in metal polluted environments exhibit metal accumul ation, reduced growth, altered metabolism, and lower biomass output. Many plant physiological and biochemical functions are impacted by metals.

Introduction: -

Extensive development and rapid economic growth have mostly contributed to environmental contamination. Environmental contamination has been caused by a variety of sources, including radioactive isotopes, organic and organometallic compounds, gaseous pollutants, inorganic pollutants (including heavy metals), and the toxicity of certain nanoparticles. Because of its catastrophic long-term effects, pollution has become a major issue to solve despite global efforts to reduce it. One of the main causes of pain and death in the world today is environmental degradation. Inorganic heavy metal pollution has received significant attention due to their widespread presence and hazardous effects (Al-Khayri et al., 2023). Heavy metals are a diverse set of elements that primarily belong to the transition element in the periodic table and vary in their chemical characteristics and functions. The elements classified as heavy metals have a specific density greater than 5 g cm^3.

Heavy metals are described as those that are at least five times denser than water. These metals can be either essential (such as Mo, Mn, Cu, Ni, Fe, and Zn) or non-essential (such as Cd, Ni, As, Hg, and Pb) (Kiran et al., 2022). Cadmium (Cd) had the highest ecological risk index of all the heavy metals. The current investigation shows that the soil in the metropolitan region of Rohtak has greater levels of cadmium. Plants, animals, and humans are at risk from cadmium (Cd), a heavy metal that occurs naturally in soil. Soil and groundwater contamination by cadmium is a worldwide issue (Soni et al., 2024). Manure, sewage sludge, excessive use of phosphatic fertilizers, and airborne deposition are the primary causes of Cd pollution in soil. Long-term application of sewage sludge,

Corresponding Author: -Brijesh Shivhare
Address: -Department of Botany, Baba Mastnath University, Rohtak, Haryana, India.

industrial effluents, sewage, contaminated river water, and municipal solid waste results in a high concentration of metal contamination in soil (Golui et al., 2021).

Cadmium toxicity in soil: A worldwide issue is the contamination of soils and groundwater with cadmium (Soni et al., 2024). In plants, the heavy metal cadmium (Cd) serves no biological use (Riaz et al., 2021). Among the top 20, it is the eighth most hazardous metal and is classified as a group 1 carcinogen (Lu et al., 2019). According to Singh et al. (2020), it is one of the most hazardous metals because of its high level of toxicity and widespread bioaccumulation. It is therefore readily absorbed by plants. After being absorbed, Cd is moved and accumulates in different edible plant parts (Adil et al., 2020). Both natural resources like mines and volcanoes, as well as human activities like fertilization, waste discharges, and industrial effluents, cause cadmium to build up in soil (Bouida et al., 2022). For a long time, cadmium remains in soil due to its extended half-life (10–33 years) (Idrees et al., 2018). According to Soni et al. (2024), the levels of Cd in vegetables and cereal grains cultivated in soil contaminated with the metal range from 0.008 mg kg^{-1} to 0.062 mg kg^{-1}. Phosphate fertilizers, sewage sludge, industrial effluents, municipal garbage, and airborne deposition are among the anthropogenic activities that cause cadmium to infiltrate the soil (Golui et al., 2021). Cd is a persistent hazard to the environment, particularly soil and groundwater, because of its lengthy half-life and persistence. This contamination comes from both natural (such as mineral weathering and volcanic activity) and man-made (such as fertilizer use and industrial discharge) sources (Bouidaet al., 2022). Cadmium interferes with microbial diversity, enzymatic activity, and nutrient cycling in soil. It leads to reduced decomposition rates, impaired nitrogen fixation, and changes in the soil microbial biomass.

Plants absorb Cd mainly through their roots via cation transporters that are also responsible for uptake of essential metals like Zn and Fe. Following absorption, Cd is moved to the plant's aerial sections, especially the leaves and fruits, where it builds up.This uptake is non-selective and varies depending on plant species, genotype, and environmental conditions.Some plants develop tolerance to Cd through binding Cd with phytochelatins and metallothioneins, sequestering Cd in vacuoles, root exudation to limit Cd availability and activation of antioxidant systems.Plants such as *Amaranthus* and Vetiver grass are used to remediate Cd-contaminated soil. Techniques include phytoextraction, phytostabilization, and rhizofiltration. Cd enters the food chain through plant consumption and bioaccumulates in human tissues, especially the kidneys and liver. Chronic exposure causes renal dysfunction, skeletal damage, and cancer. Cd bioaccumulates in the kidney cortex and liver, causing renal tubular dysfunction, osteoporosis, and cancers. Long-term exposure leads to itai-itai disease, hypertension, and reproductive toxicity. A provisional acceptable monthly consumption (PTMI) of 25 μg/kg body weight has been established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011) as a global standard for the safe consumption of cadmium (Lee et al., 2025). Cadmium levels in fruiting vegetables are limited to 0.05 mg kg^{-1}, according to the Food Safety and Standards Authority of India (FSSAI, 2011). Soni et al. (2024) reported Cd levels exceeding WHO limits in Rohtak's peri-urban agricultural soils. Sources included wastewater irrigation, industrial discharges, and phosphate fertilizer overuse. Vegetable crops grown in this area showed elevated Cd content, raising food safety concern.

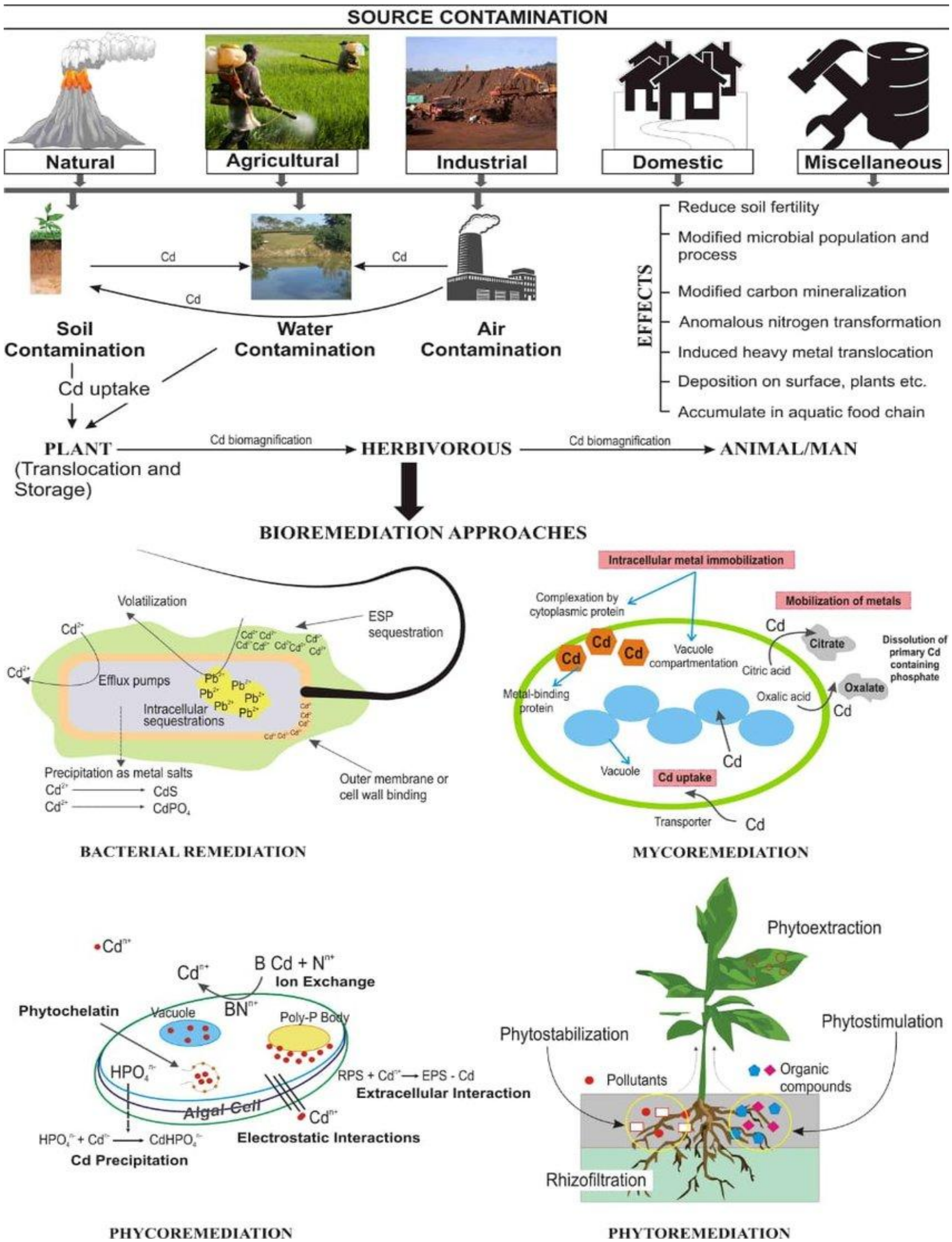

Fig.1: Overview of Cadmium toxicity (Kumar et al., 2021).

Major impact on plants: Certain plant species exhibit toxin resistance by containing accumulated metals in their roots or by tolerating elevated amounts of heavy metals in their tissue (Davis and Beckett, 1978). According to Boggess et al. (1978), plants' propensity to accumulate metal in their shoots can be linked to their sensitivity to metal toxicity. Hewitt (1966) postulated that elements with comparable physical and chemical characteristics would behave antagonistically in biological interactions. Reactive enzymatic and receptor proteins are displaced by elements of similar types, which also compete for the same transport and storage places in the cell. Copper toxicity may be inhibited by Cd, whereas selenium may work in concert with it. It can impact morphological, physicochemical, and structural alterations in plants, such as stomatal density, chlorosis, and suppression of lateral roots (Huybrechts et al., 2020). For instance, whereas Cd may inhibit the absorption of copper, selenium may work in concert with it. Cd toxicity often results in altered ion homeostasis, enhanced reactive oxygen species (ROS) generation, disruption of enzymatic activity, structural damage to mitochondria and chloroplasts and reduced crop yield and biomass.

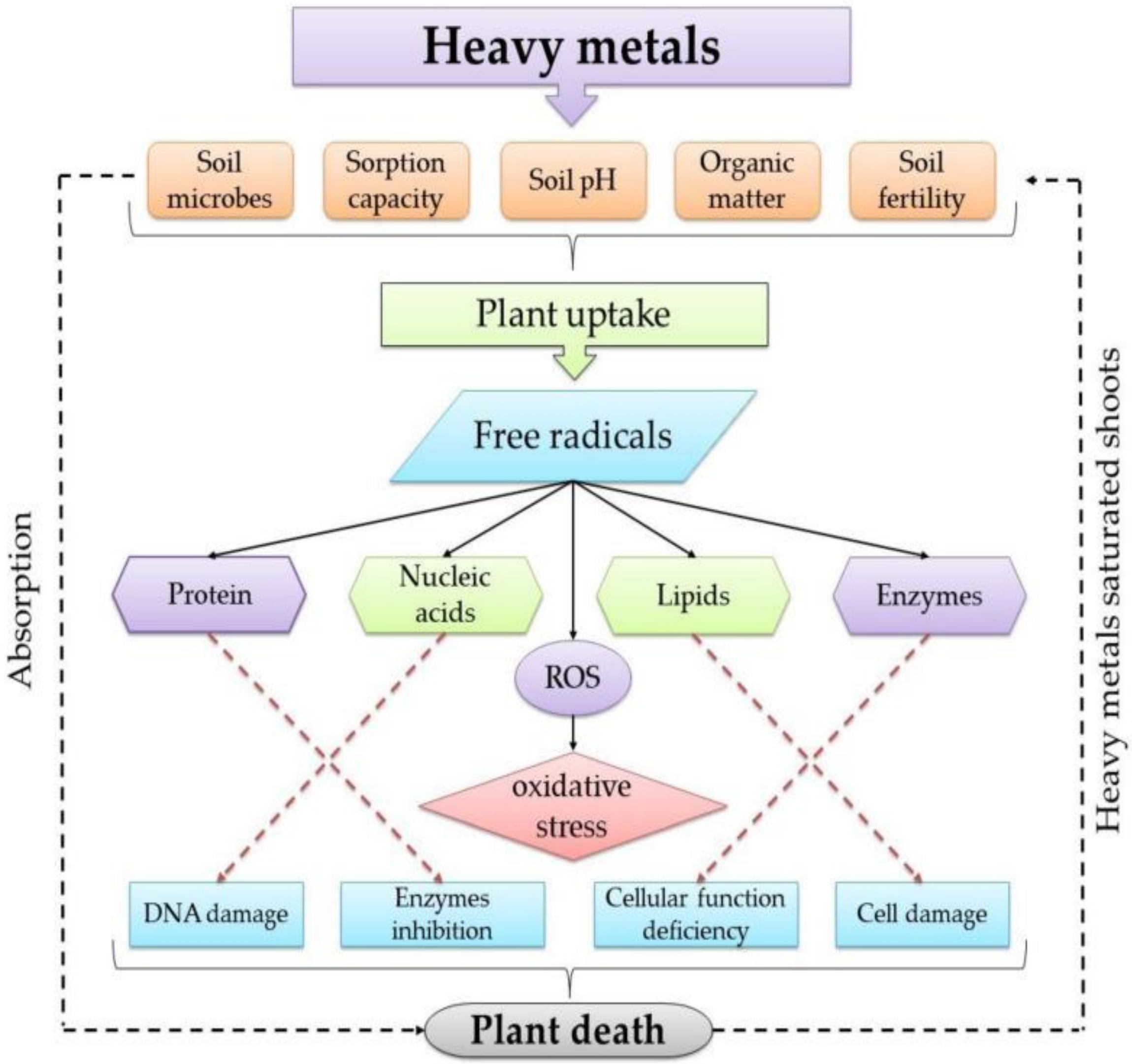

Fig. 2: Heavy metals and their effects in plants (Alengebawy et al., 2021).

Table 1: Effects observed in plants due to heavy metals.

S.No.	Metal studied	Plant studied	Effects Observed	References
1	Cd	Spinach, soybeans, lettuce, and curlycress	Leafy vegetables accumulated toxic levels of cadmium at low soil concentrations, while grains and fruit crops showed greater tolerance and lower Cd uptake.	Bingham et al.,1975

2	Cd	Maize, sorghum, pearlimillet, clusterbean, green gram and cowpea	Reduction in rice yield	Sarkunan et al.,1998
3	Cd, Pb, Zn, Cu, Cr and Ni	Wheat	Protein content decreased	Athar and Ahmad 2000
4	Cd (II), Cr (VI) and Cu (II)	*Convolvulus arvensis*	Reduction in root elongation but shoot is suitable for phytoremediation	Torresdey et al.,2004
5	Cd, Zn, Cu, Cr and Pb	Chickpea	Depletion of plant growth, chlorophyll, nodulation and nitrogen concentration in roots and shoots	Wani et al.,2007
6	Cd	Rice (*Oryza sativa* L.)	Predominance of photosynthetic rates, chlorophyll content, fluorescence efficiency and reduced nitrate reductase activity	Hussain et al.,2008
7	Cd and Pb	Mango	Predominance of photosynthetic rates, chlorophyll content, fluorescence efficiency and reduced nitrate reductase activity	Yang et al.,2010
8	Cd and Pb	Corn (*Zea mays*)	Phytoremediation	Mojiri,2011
9	Cd	*Amaranthus*, fenugreek and buckwheat	Reduction in dry matter yield	Joshi et al.,2011
10	Cd	Spinach	Decrease in dry matter	Dalir et al.,2013
11	Cd, Pb, Cr, Zn	Maize	-	Nacke et al.,2013
12	Cd	Bana grass, vetiver grass	No significant effect on chlorophyll content and photosynthetic rates but water content and leaf transpiration rate increased	Zhang et al.,2014
13	Cd	-	Altered mitochondrial function as a result of redox regulation being upset and more ROS being produced, whichinterferes with plant metabolism and damages membrane lipid	Gallego et al., 2012; Chen et al., 2018a, 2018b, 2018c; Huybrechts et al., 2020
14	Cd	Rice	Delays in plant growth and decreased yield	Mitra et al., 2018b
15	Cd	-	Plant physicochemical, morphological, and structural alterations, such as stomatal density, chlorosis, and lateral root inhibition	Bari et al., 2019; Huybrechts et al., 2020
16	Cd	Rice	variation in ion homeostasis through reduced water and mineral uptake, changed nitrogen metabolism, and restricted absorption of basic ions such as iron and magnesium	Afzal et al., 2019; Huybrechts et al., 2020
17	Cd	*Phaseolus lunatus*, Castor (*Ricinus communis)*	Effects on water transport, nutrition intake, enzyme activity, and photosynthesis	Ahmad et al., 2021a, Ahmad et al., 2021b; Rahul and Sharma, 2022
18	Cd	-	Effects on growth inhibition, wilting, chlorosis, leaf necrosis, decreased biomass, and yield	Shaari et al., 2022
19	Cd	*Brassica*	Plant death, reduced biomass output, and decreased plant growth	Li et al., 2023
20	Cd	Wheat	Compared to water control, enzyme activity	Ghosh et al.,2023

			was lower at low concentrations (100 µM) of cadmium but increased in roots treated with high doses (500 µM).	

This table elaborated experimental design, metal concentration used, and specific plant responses, including physiological, morphological, and yield data. Cd – Spinach, soybeans, lettuce, and curlycress: Bingham et al. (1975) found general toxicity but didn't elaborate on mechanisms. Symptoms included reduced biomass and chlorosis. Cd – Maize, sorghum, pearl millet, clusterbean, green gram, cowpea: Sarkunan et al. (1998) observed significant yield reduction. This correlates with photosynthetic inhibition and impaired nutrient transport. Cd, Pb, Zn, Cu, Cr, Ni – Wheat: Athar and Ahmad (2000) reported decreased protein content. This is linked to disrupted nitrogen metabolism and enzyme inhibition. Cd (II), Cr (VI), Cu (II) – *Convolvulus arvensis*: Torresdey et al. (2004) found reduced root growth, but the species showed good phytoremediation potential, indicating adaptive mechanisms. Cd, Zn, Cu, Cr, Pb – Chickpea: Wani et al. (2007) noted reduced growth and chlorophyll. Heavy metals interfere with nodulation, affecting nitrogen fixation. Cd – General: Hussain et al. (2008) described reduced photosynthetic rate and enzyme activity. Cd and Pb – Mango: Yang et al. (2010) didn't specify exact symptoms but highlighted fruit contamination risk.

Cd and Pb – Corn (*Zea mays*): Mojiri (2011) focused on its suitability for phytoremediation.Cd – *Amaranthus*, fenugreek, buckwheat: Joshi et al. (2011) observed reduced dry matter, indicating overall metabolic stress.Cd – Spinach: Dalir et al. (2013) also confirmed dry weight decline, echoing broader observations.Cd, Pb, Cr, Zn – Maize: Nacke et al. (2013) noted unspecified symptoms, implying general stress.Cd – Bana grass, vetiver grass: Zhang et al. (2014) found high tolerance; good for remediation.Cd – General: Gallego et al. (2012), Chen et al. (2018) showed mitochondrial damage and ROS production.Cd – General: Mitra et al. (2018b) described delayed growth and yield decline.Cd – General: Bari et al. (2019) observed structural changes like chlorosis and stomatal shifts.Cd – General: Afzal et al. (2019) noted disrupted ion homeostasis.Cd – General: Ahmad et al. (2021) found disrupted photosynthesis and water/nutrient transport.Cd – General: Shaari et al. (2022) reported growth inhibition, necrosis, and yield loss.Cd – General: Li et al. (2023) observed biomass decline and death at high concentrations.Cd – Wheat: Ghosh et al. (2023) found enzymatic changes: stimulated at high Cd, suppressed at low.

Conclusion: -

This review focused on the hazardous effects of heavy metals three key ecosystem components: soil, plants, and humans. The dangers of heavy metals especially Cadmium were thoroughly highlighted. In addition, their effects on human health were observed and several research studied related to restrict nitrogen metabolism, increasing and lowering the activity of particular enzymes due to toxicity. The presence of Cd in agricultural soil not only impacts plant physiology and crop productivity but also poses significant risks to human health through bioaccumulation in edible plants. Understanding the mechanisms of Cd uptake, accumulation, and phytotoxicity is essential for developing effective strategies for phytoremediation, soil management, and pollution control. Further interdisciplinary research is vital for mitigating heavy metal pollution and ensuring ecological and agricultural sustainability**.** There is an urgent need for long-term monitoring of soil and food crops, development of Cd-resistant crop varieties, use of biofertilizers, development of low-Cd-accumulating crop genotypes, application of biochar and organic amendments to immobilize Cd. Integrated monitoring systems for agroecosystems and Policies limiting Cd emissions and promoting sustainable agriculture and strict enforcement of effluent discharge standards.

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