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HEAVY METALS AND CADMIUM TOXICITY IN SOIL AND PLANTS

Abstract:

Primarily in areas with high levels of human activity, heavy metals like cadmium, copper, lead, chromium, and mercury are significant environmental hazards.Deposition of heavy metals in soils is a problem in agricultural outputbecause it has a negative impact on food safety and consumer 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 redistribution 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 accumulation, reduced growth, altered metabolism, and lower biomass output. Many plant physiological and biochemical functions are impacted by metals.

Keywords:Heavy Metals, Contamination, Cadmium toxicity.

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 weight greater than 5 g cm^2. 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 33 Pb)(Kiran et al., 2022). 34 Cadmium (Cd) had the highest ecological risk index of all the heavy metals. The current 35 investigation shows that the soil in the metropolitan region of Rohtak has greater levels of 36 cadmium. Plants, animals, and humans are at risk from cadmium (Cd), a heavy metal that 37 occurs naturally in soil. Soil and groundwater contamination by cadmium is a worldwide 38 issue(Soni et al., 2024).Manure, sewage sludge, excessive use of phosphatic fertilizers, and 39 airborne deposition are the primary causes of Cd pollution in soil. Long-term application of 40 sewage sludge, industrial effluents, sewage, contaminated river water, and municipal solid 41 waste results in a high concentrations of metal contamination in soil (Golui et al., 2021). 42 Cadmium toxicity in soil:A worldwide issue is the contamination of soils and groundwater 43 with cadmium (Soni et al., 2024). In plants, the heavy metal cadmium (Cd) serves no 44 biological use(Riaz et al., 2021). Among the top 20, it is the eighth most hazardous metal and 45 is classified as a group 1 carcinogen (Lu et al., 2019). According to Singh et al. (2020), it is 46 one of the most hazardous metals because of its high level of toxicity and widespread 47 bioaccumulation. It is therefore readily absorbed by plants. After being absorbed, Cd is 48 moved and accumulates in different edible plant parts (Adil et al., 2020). Both natural 49 resources like mines and volcanoes, as well as human activities like fertilization, waste 50 discharges, and industrial effluents, cause cadmium to build up in soil (Bouida et al., 2022). 51 Because of its lengthy half-life (10–33 years), cadmium persists in soil for a long 52 time.According to Soni et al. (2024), the levels of Cd in vegetables and cereal grains 53 cultivated in soil contaminated with the metal range from 0.008 mg kg−1 to 0.062 mg kg−1. 54 Phosphate fertilizers, sewage sludge, industrial effluents, municipal garbage, and airborne 55 deposition are among the anthropogenic activities that cause cadmium to infiltrate the soil 56 (Golui et al., 2021). Cd is a persistent hazard to the environment, particularly soil and 57 groundwater, because of its lengthy half-life and persistence. This contamination comes from 58 both natural (such as mineral weathering and volcanic activity) and man-made (such as 59 fertilizer use and industrial discharge) sources (Bouidaet al., 2022).Cadmium interferes with 60 microbial diversity, enzymatic activity, and nutrient cycling in soil. It leads to reduced 61 decomposition rates, impaired nitrogen fixation, and changes in the soil microbial 62 biomass.Plants absorb Cd mainly through their roots via cation transporters that are also 63 responsible for uptake of essential metals like Zn and Fe. Following absorption, Cd is moved 64 to the plant's aerial sections, especially the leaves and fruits, where it builds up.This uptake is 65

non-selective and varies depending on plant species, genotype, and environmental 66 conditions.Some plants develop tolerance to Cd through binding Cd with phytochelatins and 67 metallothioneins, sequestering Cd in vacuoles, root exudation to limit Cd availability and 68 activation of antioxidant systems.Plants such as Amaranthus and Vetiver grass are used to 69 remediate Cd-contaminated soil. Techniques include phytoextraction, phytostabilization, and 70 rhizofiltration.Cd enters the food chain through plant consumption and bioaccumulates in 71 human tissues, especially the kidneys and liver. Chronic exposure causes renal dysfunction, 72 skeletal damage, and cancer. Cd bioaccumulates in the kidney cortex and liver, causing renal 73 tubular dysfunction, osteoporosis, and cancers. Long-term exposure leads to itai-itai disease, 74 hypertension, and reproductive toxicity. A reasonable monthly dose of 25 µg/kg body weight 75 is advised by WHO (WHO, 2023). Soni et al. (2024) reported Cd levels exceeding WHO 76 limits in Rohtak’s peri-urban agricultural soils. Sources included wastewater irrigation, 77 industrial discharges, and phosphate fertilizer overuse. Vegetable crops grown in this area 78 showed elevated Cd content, raising food safety concern. 79 80

81 Fig.1:Overview of Cadmium toxicity (Kumar et al.,2020). 82 Major impact on plants:Certain plant species exhibit toxin resistance by containing 83 accumulated metals in their roots or by tolerating elevated amounts of heavy metals in their 84 tissue (Davis and Beckett, 1978). According to Boggess et al. (1978), plants' propensity to 85 accumulate metal in their shoots can be linked to their sensitivity to metal toxicity. Hewitt 86

(1966) postulated that elements with comparable physical and chemical characteristics would 87 behave antagonistically in biological interactions. Reactive enzymatic and receptor proteins 88 are displaced by elements of similar types, which also compete for the same transport and 89 storage places in the cell.Copper toxicity may be inhibited by Cd, whereas selenium may 90 work in concert with it. It can impact morphological, physicochemical, and structural 91 alterations in plants, such as stomatal density, chlorosis, and suppression of lateral roots 92 (Huybrechts et al., 2020). For instance, whereas Cd may inhibit the absorption of copper, 93 selenium may work in concert with it.Cd toxicity often results in altered ion homeostasis, 94 enhanced [2] reactive oxygen species (ROS) generation, disruption of enzymatic activity, 95 structural damage to mitochondria and chloroplasts and reduced crop yield and biomass. 96 97 98 Fig. 1: Heavy metals and their effects in plants (Alengebawy et al.,2021). 99

Table 1: Effects observed in plants due to heavy metals. 100 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, Gallego et al., 2012; Chen et al., 2018a, 2018b, 2018c;

whichinterferes with plant metabolism and damages membrane lipid 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 were lower at 1 low concentrations (100 μM) of cadmium but increased in roots treated with high doses (500 μM). Ghosh et al.,2023 101 This table elaborated experimental design, metal concentration used, and specific plant 102 responses, including physiological, morphological, and yield data.Cd – Spinach, soybeans, 103 lettuce, and curlycress: Bingham et al. (1975) found general toxicity but didn't elaborate on 104 mechanisms. Symptoms included reduced biomass and chlorosis.Cd – Maize, sorghum, 105 pearl millet, clusterbean, green gram, cowpea: Sarkunan et al. (1998) observed significant 106 yield reduction. This correlates with photosynthetic inhibition and impaired nutrient 107 transport.Cd, Pb, Zn, Cu, Cr, Ni – Wheat: Athar and Ahmad (2000) reported decreased 108 protein content. This is linked to disrupted nitrogen metabolism and enzyme 109 inhibition.Cd(II), Cr(VI), Cu(II) – Convolvulus arvensis: Torresdey et al. (2004) found 110 reduced root growth, but the species showed good phytoremediation potential, indicating 111

adaptive mechanisms.Cd, Zn, Cu, Cr, Pb – Chickpea: Wani et al. (2007) noted reduced 112 growth and chlorophyll. Heavy metals interfere with nodulation, affecting nitrogen 113 fixation.Cd – General: Hussain et al. (2008) described reduced photosynthetic rate and 114 enzyme activity.Cd and Pb – Mango: Yang et al. (2010) didn't specify exact symptoms but 115 highlighted fruit contamination risk.Cd and Pb – Corn (Zea mays): Mojiri (2011) focused 116 on its suitability for phytoremediation.Cd – Amaranthus, fenugreek, buckwheat: Joshi et 117 al. (2011) observed reduced dry matter, indicating overall metabolic stress.Cd – Spinach: 118 Dalir et al. (2013) also confirmed dry weight decline, echoing broader observations.Cd, Pb, 119 Cr, Zn – Maize: Nacke et al. (2013) noted unspecified symptoms, implying general stress.Cd 120 – Bana grass, vetiver grass: Zhang et al. (2014) found high tolerance; good for 121 remediation.Cd – General: Gallego et al. (2012), Chen et al. (2018) showed mitochondrial 122 damage and ROS production.Cd – General: Mitra et al. (2018b) described delayed growth 123 and yield decline.Cd – General: Bari et al. (2019) observed structural changes like chlorosis 124 and stomatal shifts.Cd – General: Afzal et al. (2019) noted disrupted ion homeostasis.Cd – 125 General: Ahmad et al. (2021) found disrupted photosynthesis and water/nutrient transport.Cd 126 – General: Shaari et al. (2022) reported growth inhibition, necrosis, and yield loss.Cd – 127 General: Li et al. (2023) observed biomass decline and death at high concentrations.Cd – 128 Wheat: Ghosh et al. (2023) found enzymatic changes: stimulated at high Cd, suppressed at 129 low. 130 Conclusion: This review focused on the hazardous effects of heavy metals three key 131 ecosystem components: soil, plants, and humans. The dangers of heavy metals especially 132 Cadmium were thoroughly highlighted. In addition, their effects on human health were 133 observed and several research studied related to restrict nitrogen metabolism, increasing and 134 lowering the activity of particular enzymes due to toxicity.The presence of Cd in agricultural 135 soil not only impacts plant physiology and crop productivity but also poses significant risks to 136 human health through bioaccumulation in edible plants. Understanding the mechanisms of Cd 137 uptake, accumulation, and phytotoxicity is essential for developing effective strategies for 138 phytoremediation, soil management, and pollution control. Further interdisciplinary research 139 is vital for mitigating heavy metal pollution and ensuring ecological and agricultural 140 sustainability.There is an urgent need for long-term monitoring of soil and food 141 crops,development of Cd-resistant crop varieties,use of biofertilizers,development of low-Cd142 accumulating crop genotypes, application of biochar and organic amendments to immobilize 143 Cd.Integrated monitoring systems for agroecosystems and Policies limiting Cd emissions and 144

promoting sustainable agriculture and mycorrhizal inoculants and strict enforcement of 145 effluent discharge standards. 146 147 148 149 150 151 152 References: 153 1. Adil, M. F., Sehar, S., Han, Z., Lwalaba, J. L. W., Jilani, G., Zeng, F., Chen, Z. H., & 154 Shamsi, I. H. (2020). Zinc alleviates cadmium toxicity by modulating photosynthesis, ROS 155 homeostasis, and cation flux kinetics in rice. Environmental Pollution, 265, 114979. 156 2. Afzal,J.,Hu,C.,Imtiaz,M.,Elyamine,A.M.,Rana,M.S.,Imran,M.,&Farag,M. A.(2019). 157 Cadmiumtolerance inricecultivarsassociatedwithantioxidant enzymes activities and Fe/Zn 158 concentrations. 2 International Journal of Environmental Scienceand Technology, 16(8), 4241159 4252. 160 3. Ahmad, A., Yasin, N. A., Khan, W. U., Akram, W., Wang, R., Shah, A. A., Akbar, M., 161 Ali, A., & Wu, T. (2021a). Silicon assisted ameliorative effects of iron nanoparticles against 162 cadmium stress: Attaining new equilibrium among physiochemical parameters, antioxidative 163 machinery, and osmoregulators of Phaseolus lunatus. Plant Physiology and Biochemistry, 164 166, 874–886. 165 4. Ahmed, T., Noman, M., Ijaz, M., Ali, S., Rizwan, M., Ijaz, U., Hameed, A., Ahmad, U., Wang, Y., Sun, G., & Li, B. (2021b). Current trends and future prospective in nanoremediation of heavy metals contaminated soils: A way forward towards sustainable agriculture. Ecotoxicology and Environmental Safety, 227, 112888.

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