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THE THREAT OF HEAVY METALS IN VEGETABLES: ECOLOGICAL AND HUMAN HEALTH RISKS

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ABSTRACT

Heavy metal contamination of vegetables is an emerging environmental and public health issue. Heavy metals, such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr), are deposited in vegetables due to contaminated soil, industrial wastewater, and heavy metal-contaminated irrigating water. These pollutants not only hinder the crop growth and crop development but also pose grave health risks to humans upon consumption. Long-term nutritional exposure to heavy metals through the consumption of vegetables can lead to serious health effects, some of which include cancer, organ damage, and neurodegenerative diseases. In this review, the sources of heavy metal contamination, the process of uptake in plants, and the environmental risks of the pollutants are discussed. The review also discusses the impacts on human health and suggests probable mitigation strategies such as phytoremediation and efficient agriculture practices. These problems must be corrected by adequate monitoring and regulation for ensuring vegetable safety. Increased knowledge of heavy metal pollution in vegetables is needed for ecosystem health maintenance as well as for public health.

Keywords: Heavy metal contamination, vegetable safety, agricultural pollution, soil contamination, human health risk, environmental toxicity

INTRODUCTION

Heavy metal pollution in agricultural systems has been an essential environmental issue, posing severe risks to food safety, ecosystem health, and human health. Heavy metals, such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr), and copper (Cu), are toxic elements that tend to accumulate in the environment, primarily in soil and water (Liang *et al.,* 2020; Shokrzadeh *et al.,* 2004a; Shokrzadeh *et al.,* 2004b; Kalantari and Ebadi, 2006; Ebadi *et al.,* 2005a; Zare and Ebadi, 2005; Ebadi *et al.,* 2005b). They are characterized by their persistence in the environment since they are non-biodegradable, i.e., they do not degrade or break down with time. As a result, their build-up in farming systems can lead to long-term negative effects on crop yields and food safety (Golia, 2023). Agricultural systems are significant recipients of heavy metal pollution, and the pollutants enter the environment through various anthropogenic activities such as industrial effluent, mining activity, irrigation with raw wastewater, and indiscriminate use of chemical fertilizers and pesticides (Sabeen *et al.,* 2020; Zare *et al.,* 2005; Ali *et al.,* 2013).

The soil may be polluted with heavy metals through atmospheric deposition, indiscriminate disposal of wastes, or the use of polluted inputs like sewage sludge or irrigation water from polluted sources (Zwolak *et al.,* 2019; Ebadi et al., 2017). Vegetables, as one of the principal sources of nutrition for human beings, are extremely susceptible to the uptake of these toxic metals from contaminated soils and therefore can be a route for human exposure to heavy metals (Kalantari *et al.,* 2006; Rattan *et al.,* 2005; Ebadi and Hisoriev, 2017; Ebadi and Hisoriev, 2018a; Ebadi and Hisoriev, 2018b).

The vegetables absorb heavy metals through their roots, and the level of their absorption differs depending on soil type, pH, plant type, and metal content in the soil. Leafy vegetables, root vegetables, and tubers are more susceptible due to their growth habits and higher tendency to absorb pollutants from the soil (Adriano, 2001). For instance, leafy greens like cabbage, lettuce, and spinach tend to accumulate more heavy metals like cadmium and lead, while root vegetables like potatoes and carrots are more prone to arsenic contamination (Ali et al., 2013). Such toxic metals' accumulation in plant edible parts can lead to nutritional quality loss, inhibition of plant growth, and plant death. The health effects of consuming contaminated vegetables are tremendous. Heavy metals accumulated in edible portions of crops can enter the human food chain, where they induce severe health issues. Chronic ingestion of even low levels of heavy metals has been linked to the onset of numerous long-term diseases, including renal failure, liver damage, neurological damage, and cancer (Ebadi *et al.,* 2025, 2025; Kazemeini *et al.,* 2010; Järup, 2003). For example, long-term cadmium exposure through polluted food has been associated with renal tubule dysfunction and osteoporosis (Xiang *et al.,* 2022). Arsenic exposure, for example, has been related to skin, lung, and bladder cancer (Xiang *et al.*, 2022). Heavy metals can also affect human reproductive health and have been found to cause developmental defects, particularly in children (Zwolak *et al.*, 2019; Yolchiyeva *et al.*, 2020).

The increasing concern about heavy metal pollution in vegetables is driven by its food safety and public health significance, particularly in regions of intensive farming and poor environmental governance. In the fast industrializing and urbanizing nations such as China, India, and most nations in Africa, vegetable crops find themselves being cultivated on contaminated soils, which have caused high levels of heavy metals in the food chain (Golia, 2023). Also, countries with lax control of wastewater use in irrigation and poor control of agricultural inputs are most vulnerable to heavy metal contamination. As the global population continues to grow, ensuring that vegetables are safe for consumption and free from harmful pollutants is ever more an urgent task. As such threats continue to be recognized, controlling heavy metal pollution in agriculture should be approached from a many-sided perspective (Khan *et al.*, 2022). Sustainable agricultural approaches, such as the use of soil amendments, employment of cleaner irrigation sources, and use of bio-remediation technologies, are needed to minimize the impact of heavy metals on vegetable crops (Rattan *et al.*, 2005). Moreover, phytoremediation technologies, whereby plants are used to eliminate or immobilize heavy metals from contaminated soils, are becoming increasingly important as a potential solution (Ali *et al.*, 2013). Furthermore, strengthening regulations and adopting more rigorous monitoring protocols on industrial processes, wastewater disposal, and agricultural practices can minimize the environmental load of heavy metals and alleviate the dangers to human health (**Fig. 1**).

The aim of this review is to describe the sources and pathways of vegetable heavy metal contamination, the influences on their absorption and accumulation, and the potential dangers to human health. It will also cover current approaches to reducing vegetable heavy metal pollution, such as soil manipulation, plant breeding for metal tolerance, and phytoremediation. With the knowledge of the mechanisms of vegetable heavy metal contamination and the health risk therein, this review seeks to obtain an understanding of the potential solutions to mitigate these risks and make vegetable crops safe for human consumption.

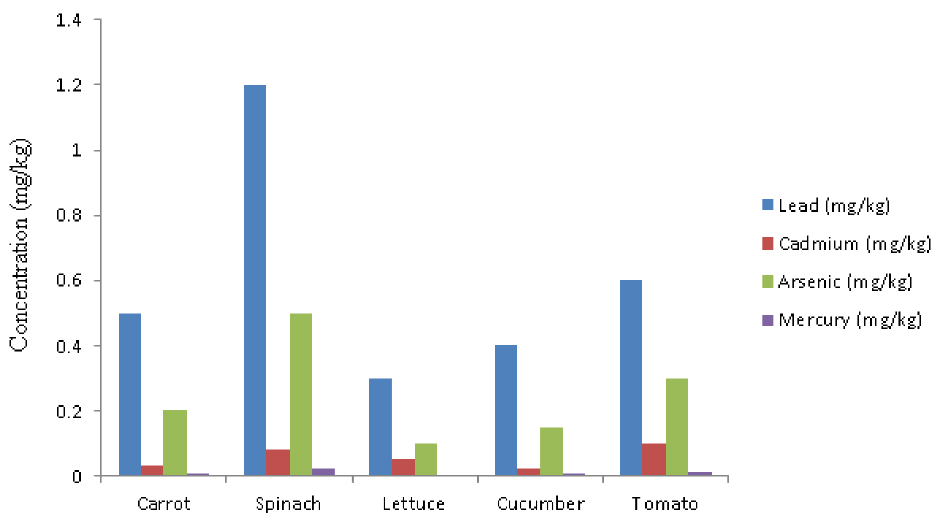

Fig. 1. Distribution of Heavy Metal Concentrations in Vegetable Crops.

CAUSES OF HEAVY METAL POLLUTION

Heavy metal pollution in agricultural environments, and in vegetable crops in particular, can be exacerbated by a variety of anthropogenic activities. Some of the most significant among them are industrial activities, agricultural activities, and urbanization. Each of these sources contributes to the build-up of heavy metals in soil, water, and ultimately in food crops, posing risks to environmental and human health.

- Industrial Activities

Industrial operations are one of the significant sources of heavy metal pollution. Factories involved in mining, metal processing, and manufacturing produce enormous amounts of pollutants, including lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg). The pollutants may be released into the environment through air emissions, wastewater discharge, and solid wastes. Deposition of these metals over the surrounding agricultural lands or water bodies can result in contamination, which can enter the food chain through vegetable crops.

Mining Activities: Mining of metals such as lead, zinc, and copper can deposit heavy metals directly into the surrounding soil and water.

Manufacturing: Facilities for the production of batteries, paints, and electronic equipment are likely to discharge hazardous waste containing heavy metals like mercury, cadmium, and lead.

Power Generation: Coal-fired power plants are also significant contributors of heavy metal pollution, mainly mercury and arsenic.

- Agricultural Practices

Agricultural activities, in particular the excessive use of chemical fertilizers, pesticides, and herbicides, are among the high contributors to heavy metal pollution in soil. Cadmium, arsenic, and copper are some of the heavy metals that are commonly present in fertilizers, and their continuous application over the years can lead to their accumulation in soil. Irrigation with contaminated water, often an outcome of industrial runoff or the application of wastewater, can also increase the concentration of heavy metals in the cultivated land.

Fertilizers and Pesticides: Commercial pesticides and fertilizers contain trace amounts of heavy metals like cadmium, lead, and arsenic, which accumulate in the soil over time.

Irrigation: Irrigation with polluted water, especially where industrial effluents or sewage are not properly treated, leads to toxic metal deposition in agricultural soils (Parveen *et al.,* 2022).

- Urbanization and Waste Disposal

Urbanization leads to greater exhaust emissions, building construction, and improper disposal of industrial and household wastes. All these processes are accountable for inducing heavy metal pollution in soils of urban areas and surrounding farmlands. Lead from vehicle exhausts, copper and zinc from roofs, and other pollutants from poorly managed waste are blamed for environmental contamination (Rasouli *et al.,* 2020).

Vehicle Emissions: Exhaust from vehicles has lead, cadmium, and nickel, which may be deposited on vegetation and soil in urban areas.

Waste Management: Improper disposal of municipal and industrial waste leads to contamination of nearby water bodies and soil. This has high levels of heavy metals from batteries, electronics, and chemicals.

4. Other Sources

Other sources include natural processes like volcanic eruptions, which can release heavy metals into the atmosphere and eventually into water bodies and soils. Anthropogenic sources, nevertheless, are the predominant sources of heavy metal contamination of agricultural systems (**Table 1**).

Table 1. Sources, Mechanisms, and Impact of Heavy Metal Pollution in Agricultural Systems.

Source	Heavy Metals Involved	Mechanism of Pollution	Impact on Agriculture	References
Industrial Activities	Lead (Pb), Cadmium (Cd), Chromium (Cr), Mercury (Hg)	Emissions from manufacturing, mining, power plants, and metal refineries.	Soil and water contamination, affecting vegetable growth and quality.	Ali *et al.,* 2013; Xiang *et al.,* 2022
Agricultural Practices	Cadmium (Cd), Arsenic (As), Copper (Cu), Zinc (Zn)	Use of contaminated fertilizers, pesticides, and irrigation with polluted water.	Soil degradation, reduced crop yield, heavy metal uptake by vegetables.	Rattan *et al.,* 2005; Zwolak *et al.,* 2019; Samieifard *et al.,* 2021
Urbanization	Lead (Pb), Copper (Cu), Zinc (Zn), Nickel (Ni)	Vehicle emissions, waste disposal, and construction activities.	Pollution of soil, water, and crops in urban and peri-urban areas.	Xiang *et al.,* 2022
Natural Processes	Lead (Pb), Mercury (Hg), Zinc (Zn), Copper (Cu)	Volcanic activity and geological formations that release metals into the environment.	Limited impact compared to anthropogenic sources, localized.	Rattan *et al.,* 2005

IMPACT ON VEGETABLES

Agricultural soil heavy metal pollution is a significant threat to vegetable crops, affecting plant growth, nutrient uptake, and overall crop yield. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) accumulate in soil through industrial wastewater, mining, sewage sludge use, and excessive application of chemical fertilizers and pesticides. After entering the soil, these metals are absorbed by plant roots, inducing phytotoxicity that disrupts physiological and biochemical processes (Ebadi *et al.*, 2020; Shaukat *et al.*, 2002).

Vegetable lead contamination is primarily caused by vehicle exhaust, industrial activities, and lead pesticide application. Pb exposure causes growth inhibition, chlorosis, and reduction in the efficiency of photosynthesis. Pb also accumulates in edible parts of plants, posing serious health risks to consumers (Nas and Ali, 2018). Similarly, cadmium is a non-essential metal that readily enters plants through soil-root interactions, replacing essential metals such as calcium and zinc. Cd toxicity leads to stunted growth of roots and shoots, oxidative stress, and low productivity of crops (Haider *et al.*, 2021). Arsenic and mercury contamination are fueling the problem. Arsenic stress in vegetables induces failure in seed germination, low biomass, and disruption in enzymatic function necessary for plant growth. Mercury, being a very toxic metal, inhibits chlorophyll synthesis, protein metabolism, and inflicts structural damage to plant cells, leading to reduced crop production (Ghuge *et al.*, 2023). These toxic effects not only deteriorate vegetable quality but also endanger food safety and human health through bioaccumulation (Macki Aleagha and Ebadi, 2011) along the food chain (**Fig. 2-3** & **Table 2**).

Table 2. Effects of Heavy Metals on Vegetable Growth, Nutrient Uptake, and Crop Yields.

Heavy Metal	Source of Contamination	Effects on Vegetables	Impact on Nutrient Uptake	References
Lead (Pb)	Vehicular emissions, industrial discharge, lead-based pesticides	Growth inhibition, leaf chlorosis, reduced photosynthesis	Blocks calcium and iron uptake, leading to nutrient deficiencies	Nas and Ali, 2018
Cadmium (Cd)	Phosphate fertilizers, sewage sludge, industrial waste	Stunted root/shoot growth, oxidative stress, lower productivity	Replaces zinc and calcium, disrupting plant metabolism	Haider *et al.*, 2021
Arsenic (As)	Groundwater contamination, pesticide residues, mining waste	Poor germination, reduced biomass, enzyme inhibition	Impairs phosphorus uptake and disrupts metabolic pathways	Ghuge *et al.*, 2023
Mercury (Hg)	Industrial effluents, coal combustion, fungicides	Chlorophyll inhibition, protein metabolism disruption, cell damage	Affects nitrogen and sulfur metabolism, reducing crop quality	Franić and Galić, 2019

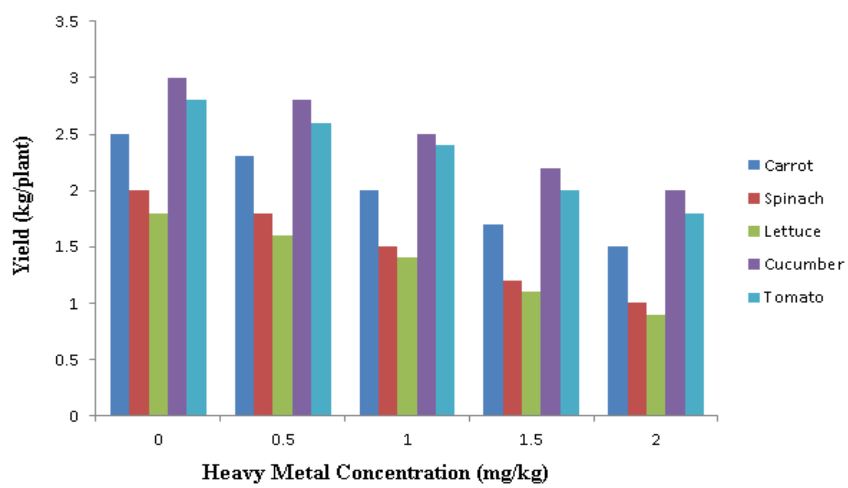

Fig. 2. Effect of Heavy Metal Contamination on Plant Growth and Yield.

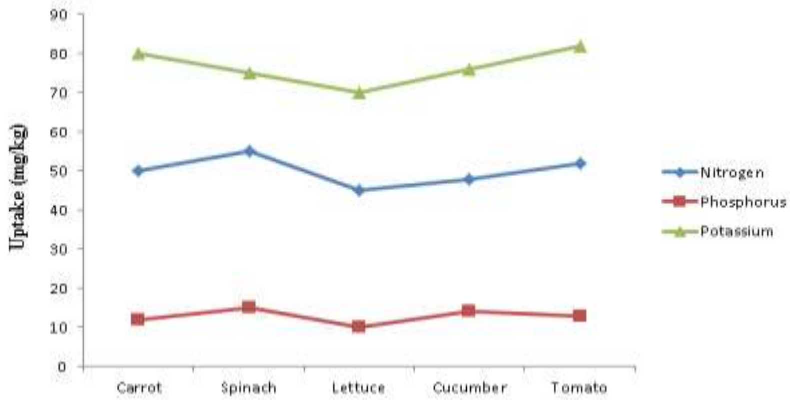

Fig. 3. Influence of Heavy Metals on Nutrient Uptake in Vegetables.

Not only do such heavy metal pollutants reduce the yield of crops but also alter the nutritional content of vegetables, rendering them poisonous for human consumption. Proper monitoring and environmentally friendly farming practices are thus essential to avert the potential damage of vegetable pollution with heavy metals.

HEALTH AND ENVIRONMENTAL IMPACTS OF HEAVY METAL CONTAMINATION

Vegetable crop contamination with heavy metals poses a significant risk to both environmental ecosystems and human health. After deposition of the toxic metals in agricultural soils, they last for extremely long times since they are non-degradable, and consequently, it leads to long-term contamination of food crops and groundwater resources. The deposition of heavy metals in vegetables enables them to penetrate the food chain, resulting in bioaccumulation and biomagnification, with devastating effects on biodiversity and ecosystem stability (Nwankwo *et al.,* 2020; Hembrom *et al.,* 2020).

- Ecological Consequences

Heavy metal pollution destroys soil microbial community, and soil fertility and nutrient cycling process is altered. Cadmium (Cd) and lead (Pb) at high concentrations inhibit soil microbial enzymatic activity, resulting in a reduction in populations of beneficial microbes that are essential for decomposition of organic matter and nitrogen fixation. Moreover, excessive arsenic (As) and mercury (Hg) contamination affects aquatic environments, as water from the contaminated soils flows into water bodies, rendering fish and other aquatic organisms poisonous (Meryem *et al.,* 2022). This disruption leads to reduced biodiversity and natural ecosystem impairment (Raissy *et al.,* 2010; Rahimi *et al.,* 2010; Kandeler *et al.,* 1996).

Table 3. Environmental and Human Health Risks of Heavy Metal Contamination in Vegetables.

Heavy Metal	Environmental Impact	Health Risks	References
Lead (Pb)	Soil microbial toxicity, reduced soil fertility, contamination of water bodies	Neurotoxicity, developmental delays, cardiovascular diseases	Hembrom *et al.*, 2020
Cadmium (Cd)	Disrupts nitrogen fixation, bioaccumulates in plants and water sources	Kidney damage, osteoporosis, respiratory issues	Kandeler *et al.*, 1996
Arsenic (As)	Alters microbial composition in soil, contaminates drinking water	Carcinogenic, skin lesions, liver damage	Munir *et al.*, 2021
Mercury (Hg)	Affects aquatic ecosystems, toxic to fish and invertebrates	Neurodevelopmental disorders, immune system dysfunction	Uddin *et al.*, 2023

- Human Health Risks

Consumption of vegetables contaminated with heavy metals has been linked with a range of health conditions (Afshari *et al*., 2010). Neurotoxicity due to lead (Pb) exposure is most severe during developmental stages in children. Chronic consumption of cadmium (Cd) can lead to renal toxicity and osteoporosis, while arsenic (As) is a known carcinogen that leads to skin, lung, and bladder cancer. Mercury (Hg) exposure, through contaminated food intake, affects the nervous system and can cause infant developmental disorders (Munir *et al.*, 2021) based on **Table 3**.

MANAGEMENT AND MITIGATION APPROACHES FOR VEGETABLE HEAVY METAL POLLUTION

The contamination of vegetables with heavy metals poses a severe risk to environmental health and food safety. Effective management and mitigation strategies are necessary to minimize heavy metal accumulation in agricultural soils and plant uptake (Kiyani *et al*., 2021). Various approaches, including soil remediation methods, phytoremediation, and organic farming practices, can be employed to alleviate the impacts of heavy metal pollution in vegetable production systems (**Fig. 4** & **Table 4**).

Table 4. Management and Mitigation Strategies for Heavy Metal Contamination in Vegetables.

Strategy	Description	Effectiveness	References
Soil Amendments	Use of biochar, compost, and lime to immobilize heavy metals	High	Sarma, 2011
Chemical Remediation	Application of chelators to extract metals from soil	Moderate	Di Palma *et al.*, 2015
Electrokinetic Remediation	Use of electric fields to remove metals from soil	High but costly	Sruthy and Jayalekshmi, 2014
Phytoextraction	Hyperaccumulator plants absorb metals from soil	High	Raza *et al.*, 2020
Phytostabilization	Plants stabilize metals, preventing mobility	Moderate	Sarma, 2011
Microbial Inoculants	Use of mycorrhizal fungi and bacteria to reduce metal uptake	Moderate	Qin *et al.*, 2024
Clean Irrigation Water	Use of filtration systems to remove contaminants from water sources	High	Kirchmann and Thorvaldsson, 2000

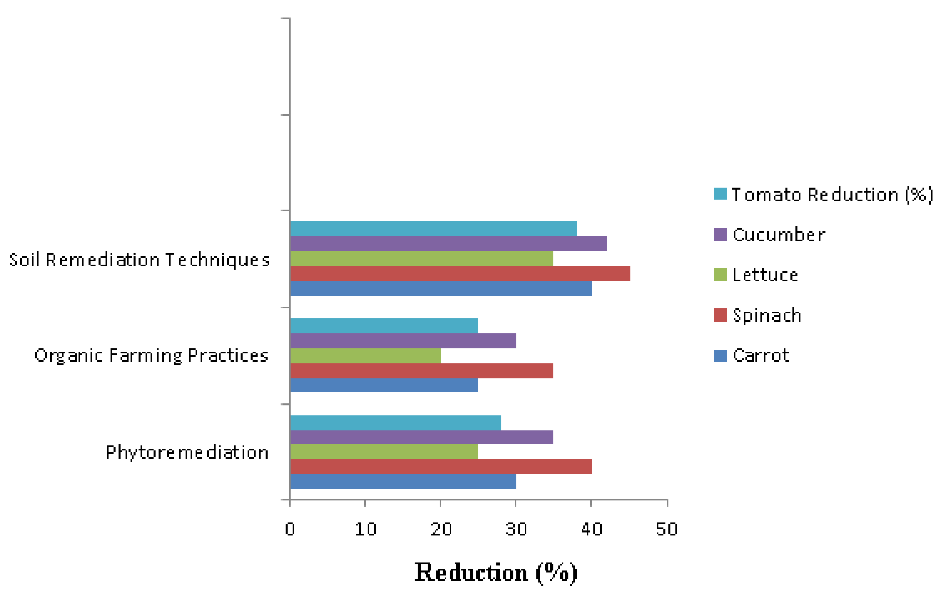

Fig. 4. Remediation Strategies for Heavy Metal Contamination in Vegetables.

- Soil Remediation Techniques

Soil remediation plays an important role in the mitigation of heavy metal pollution. Different methods are employed to immobilize or leach heavy metals from contaminated soils:

Soil Amendments: The addition of organic matter like biochar, compost, and manure improves soil health and reduces the bioavailability of heavy metals. Additives like lime and phosphate fertilizers also immobilize metals, preventing plant uptake (Sarma, 2011).

Chemical Remediation: Heavy metals are chelated by chelating agents, such as ethylenediaminetetraacetic acid (EDTA) and diethylenetriaminepentaacetic acid (DTPA), and removed from the soil. However, if used excessively, the chelators induce secondary pollution when not well regulated (Di Palma *et al.,* 2015).

Electrokinetic Remediation: It uses an electric field for the extraction of heavy metals from contaminated soil. It is particularly effective in fine-textured soil but requires the expenditure of large amounts of energy (Sruthy and Jayalekshmi, 2014; Qayyum *et al.,* 2020).

- Phytoremediation: A Green Option

Phytoremediation is an environmental-friendly, inexpensive process that uses plants to accumulate, remove, or detoxify heavy metals from contaminated soils. There are multiple approaches that belong to phytoremediation

Phytoextraction: Hyperaccumulator crops such as *Brassica juncea* (Indian mustard) and *Helianthus annuus* (sunflower) can absorb heavy metals and store them in their tissues, which are then harvested for disposal (Raza *et al.,* 2020; Awan et al., 2020; Xu *et al.,* 2021).

Phytostabilization: Some plants such as *Vetiveria zizanioides* (vetiver grass) can stabilize heavy metals in soil, rendering them less mobile and less susceptible to leaching into groundwater (Sarma, 2011).

Rhizofiltration: It involves the utilization of plant root systems to extract heavy metals from contaminated water sources and decrease their concentration before irrigation (Haroon *et al.,* 2022; Di Palma *et al.,* 2015).

- Organic Farming Practices

Organic farming practices include emphasis on the use of natural inputs and soil health management to minimize heavy metal contamination. These practices include:

Crop Rotation and Intercropping: Vegetable crops can be alternated with non-cultivated plants that uptake heavy metals to reduce levels of contamination over time (Kirchmann and Thorvaldsson, 2000).

Use of Microbial Inoculants: Plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, which are beneficial microorganisms, can enhance plant resistance against heavy metal stress and reduce metal uptake (Shah *et al.,* 2022; Qin *et al.,* 2024).

Avoidance of Contaminated Irrigation Water: The use of clean water sources and installing filtration systems can ensure that agricultural soils are no longer contaminated (Sruthy and Jayalekshmi, 2014; Zeb *et al.,* 2022).

CONCLUSION

Heavy metal contamination of vegetables is a serious public and environmental health concern, majority resulting from industrial processes, agricultural use, and urbanization. These toxic elements are deposited in the soil, incorporated into the food chain, and pose severe risks to consumers including neurological impairment, organ damage, and carcinogenic effects. The impact on vegetable crops is also a concern since heavy metals disrupt plant metabolism, retard growth, and inhibit uptake of nutrients, subsequently reducing agricultural productivity and food security. To counteract these risks, a combination of management practices is needed. Remediation strategies of soils, including amendments and chemical treatments, can immobilize or leach heavy metals out of contaminated soils. Phytoremediation by hyperaccumulator plants provides an economic and eco-friendly means of metal extraction and stabilization. Organic agricultural practices, such as crop rotation, microbial inoculants, and clean irrigation systems, also reduce heavy metal uptake and maintain soil health. Even with these advances, challenges still exist in applying remediation technologies at large scales, and further research is necessary to improve efficiency, cost-effectiveness, and sustainability.

Future studies need to focus on integrating the most advanced biotechnological techniques, such as genetically engineered crops and microbial-mediated remediation, to enhance metal tolerance and detoxification activity. In the meantime, strict regulatory frameworks and monitoring networks need to be put in place to control heavy metal-polluted sources of pollution as well as ensure food safety. Through a multidisciplinary approach, it is possible to avoid heavy metal contamination in vegetables, provide public health protection, and promote sustainable agricultural management for long-term environmental sustainability.

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REFERENCES

Adriano, D.C. (2001). *Trace Elements in the Terrestrial Environment*. Springer, New York.

Afshari, H., A.G. Ebadi, H. Abbaspour and M. Shokrzadeh (2010). Detection of some heavy metals in two most consumed vegetables (*Spinacia oleracea* L. and *Raphanus sativus* L.) from different Sari market places. *American-Eurasian Journal of Agricultural & Environmental Sciences,* 8(5): 615-616.

Ali, H., E. Khan and M.A. Sajad (2013). Phytoremediation of heavy metals—Concepts and applications. *Chemosphere,* 91(7): 869-881.

Awan, B., M. Sabeen, S. Shaheen, Q. Mahmood, A. Ebadi and M. Toughani (2020) Phytoremediation of zinc contaminated water by marigold (*Tagetes Minuta* L). *Central Asian Journal of Environmental Science and Technology Innovation,* 1(3): 150-158.

Di Palma, L., E. Petrucci and B. Pietrangeli. (2015). Environmental effects of using chelating agents in polluted sediment remediation. *Bulletin of Environmental Contamination and Toxicology,* 94: 340–344.

Ebadi, A.G. and H. Hisoriev (2017). Metal pollution status of Tajan River – Northern Iran. *Toxicological & Environmental Chemistry,* 99: 9-10, 1358-1367.

Ebadi, A.G. and H. Hisoriev (2018a). *Cladophora glomerata* L. as indicator of chemical pollution in coastal areas of Farahabad Region, Iran. *Revista Publicando,* 5(14): 183-191.

Ebadi, A.G. and H. Hisoriev (2018b). Physicochemical characterization of sediments from Tajan River Basin in the Northern Iran. *Toxicological & Environmental Chemistry,* 100(5-7): 540-549.

Ebadi, A.G., H. Hisoriev and K. Aliev (2017). Measurement of some chemical and biochemical parameters in Cladophora glomerata L. from Farahabad Region of Iran. *Bulgarian Chemical Communication,* 49: 540-544.

Ebadi, A.G., M. Shokrzadeh and M. Norouzi (2005a). Survey and measurement of some heavy metals in two great rivers (Mazandaran – Iran). In: *Ecological Chemistry*, 3rd ed., Chişinău, Republic of Moldova, 20–21 May 2005. Tipografia Academiei de Ştiinţe a Moldovei, p. 56.

Ebadi A.G., M. Toughani, A. Najafi and M. Babaee (2020) A brief overview on current environmental issues in Iran. *Central Asian Journal of Environmental Science and Technology Innovation,* 1(1): 1-11.

Ebadi, A.G., S. Zare, M. Mahdavi and M. Babaee (2005b). Study and measurement of Pb, Cd, Cr and Zn in green leaf of tea cultivated in Gillan Province of Iran. *Pakistan Journal of Nutrition,* 4(4): 270–272.

Ebadi, A.G., F. Boufahja, S.A. Basim and Z. Selamoglu (2025). Fish as bioindicators: Monitoring environmental mercury pollution with aquatic food webs – A mini review. *International Journal of Environmental Science and Green Technology,* 1(1): 56–65.

Franić, M. and V. Galić. (2019). As, Cd, Cr, Cu, Hg: Physiological implications and toxicity in plants. *Plant Metallomics and Functional Omics: A System-Wide Perspective,* pp. 209–251.

Ghuge, S.A., G.C. Nikalje, U.S. Kadam, P. Suprasanna and J.C. Hong (2023). Comprehensive mechanisms of heavy metal toxicity in plants, detoxification, and remediation. *Journal of Hazardous Materials,* 450: 131039.

Golia, E.E. (2023). The impact of heavy metal contamination on soil quality and plant nutrition. *Sustainable Chemistry and Pharmacy,* 33: 101046.

Haider, F.U., C. Liqun, J.A. Coulter, S.A. Cheema, J. Wu, R. Zhang, M. Wenjun and M. Farooq (2021). Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicology and Environmental Safety,* 211: 111887.

Haroon, B., M. Irshad, A.G. Ebadi and P. An. (2022). Soil metal contamination and its mitigation. *Sustainable Plant Nutrition Under Contaminated Environments,* Springer International Publishing, pp. 17–40.

Hembrom, S., B. Singh, S.K. Gupta and A.K. Nema (2020). A comprehensive evaluation of heavy metal contamination in foodstuff and associated human health risk: A global perspective. *Contemporary Environmental Issues and Challenges in the Era of Climate Change,* 33–63.

Järup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin,* 68(1): 167-182.

Kalantari, M.R. and A.G. Ebadi (2006). Measurement of some heavy metals in sediments from two great rivers (Tajan and Neka) of Iran. *Journal of Applied Sciences,* 6: 1071–1073.

Kalantari, M.R., M. Shokrzadeh, A.G. Ebadi, C. Mohammadizadeh, M.I. Choudhary and Atta-ur-Rahman (2006). Soil pollution by heavy metals and remediation (Mazandaran–Iran). *Journal of Applied Sciences*, 6(9): 2110–2116.

Kandeler, F., C. Kampichler and O. Horak (1996). Influence of heavy metals on the functional diversity of soil microbial communities. *Biology and Fertility of Soils*, 23: 299–306.

Kazemeini, H.R., E. Rahimi, A.A. Kharrattaherdel, N. Nozarpour and A.G. Ebadi (2010). Cadmium concentration in muscle, liver and kidney of sheep slaughtered in Falavarjan abattoir, Iran. *Toxicology and Industrial Health*, 26(5): 259–263.

Khan, R., A. Noorpoor and A.G. Ebadi. (2022). Effects of air contamination on agriculture. *Sustainable Plant Nutrition under Contaminated Environments*, Springer International Publishing, pp. 1–16.

Kirchmann, H., G. Thorvaldsson (2000). Challenging targets for future agriculture. *European Journal of Agronomy*, 12(3–4): 145–161.

Kiyani, V., S. Kiyani and N. Behdarvand (2021). Environmental risk assessments of CuCl2 and AgSo4 toxicity in Gambusia holbrooki based on ISO 31000. *Central Asian Journal of Environmental Science and Technology Innovation*, 2(5): 206-214.

Liang, H., Z.I. Khan, K. Ahmad, A. Nisar, Q. Mahmood, A.G. Ebadi and M. Toughani (2020). Assessment of zinc and nickel profile of vegetables grown in soil irrigated with sewage water. *Revista de Chimie*, 71(4): 500–511.

Macki Aleagha, M. and G. Ebadi (2011). Study of heavy metals bioaccumulation in the process of vermicomposting. *African Journal of Biotechnology*, 10(36): 6997-7001.

Meryem, S.S., A. Pervez and A.G. Ebadi. (2022). Role of quorum sensing in nutrient acquisition and synergistic plant-microbe association. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 287–308.

Munir, N., M. Jahangeer, A. Bouyahya, N. El Omari, R. Ghchime, A. Balahbib, S. Aboulaghras, Z. Mahmood, M. Akram, S.M. Ali Shah and I.N. Mikolaychik (2021). Heavy metal contamination of natural foods is a serious health issue: A review. *Sustainability*, 14(1): 161.

Nas, F.S., M. Ali (2018). The effect of lead on plants in terms of growing and biochemical parameters: a review. *MOJ Ecology and Environmental Sciences*, 3(4): 265–268.

Nwankwo, C.N., A.E. Gobo, C. Israel-Cookey and S.A. Abere (2020) Effects of hazardous waste discharge from the activities of oil and gas companies in Nigeria. *Central Asian Journal of Environmental Science and Technology Innovation*, 1(2): 119-129

Parveen, A., M.A. Ashraf, I. Hussain, S. Perveen, R. Rasheed, A.G. Ebadi and S. Thind. (2022). Potential of inorganic fertilizers for sustainable development in agriculture. *Sustainable Plant Nutrition Under Contaminated Environments*, Springer International Publishing, pp. 41–55.

Qayyum, S., I. Khan, K. Meng, Y. Zhao and C. Peng (2020) A review on remediation technologies for heavy metals contaminated soil. *Central Asian Journal of Environmental Science and Technology Innovation*, 1(1): 21-29.

Qin, H., Z. Wang, W. Sha, S. Song, F. Qin and W. Zhang. (2024). Role of plant-growth-promoting rhizobacteria in plant machinery for soil heavy metal detoxification. *Microorganisms*, 12(4): 700.

Rahimi, E., M. Hajisalehi, H.R. Kazemeini, A. Chakeri, A. Khodabakhsh, M. Derakhshesh, M. Mirdamadi, A.G. Ebadi, A. Rezvani and F.M. Kashkahi (2010). Analysis and determination of mercury, cadmium and lead in canned tuna fish marketed in Iran. *African Journal of Biotechnology*, 9(31): 4938–4941.

Raissy, M., E. Rahimi, M. Ansari and A.G. Ebadi (2010). Determination of mercury and arsenic levels in fish caught in the Beheshtabad River, Chaharmahal and Bakhtiari Province, Iran. *Toxicological & Environmental Chemistry*, 92(9): 1627-1631.

Rasouli, A., A. Bafkar and Z. Chaghakaboodi (2020). Kinetic and equilibrium studies of adsorptive removal of sodium-ion onto wheat straw and rice husk wastes. *Central Asian Journal of Environmental Science and Technology Innovation*, 1(6): 310-329.

Rattan, R.K., S.P. Datta, P.K. Chhonkar, K. Suribabu and A.K. Singh. (2005). Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. *Agriculture, Ecosystems & Environment*, 109(3–4): 310–322.

Raza, A., M. Habib, S.N. Kakavand, Z. Zahid, N. Zahra, R. Sharif, M. Hasanuzzaman (2020). Phytoremediation of cadmium: physiological, biochemical, and molecular mechanisms. *Biology*, 9(7): 177.

Sabeen, M., Q. Mahmood, A.G. Ebadi, Z.A. Bhatti, M. Irshad, A. Kakar, M. Bilal, H.M. Arshad and N. Shahid. (2020). Health risk assessment consequent to wastewater irrigation in Pakistan. *Soil & Environment*, 39(1).

Samieifard, R., A. Landi and N. Pourreza (2021). Adsorption of Cd, Co, and Zn from multi-ionic solutions onto Iranian sepiolite isotherms. *Central Asian Journal of Environmental Science and Technology Innovation,* 2(3): 102-118.

Sarma, H. (2011). Metal hyperaccumulation in plants: a review focusing on phytoremediation technology. *Journal of Environmental Science and Technology,* 4(2): 118–138.

Shaukat, S.S., I.A. Siddiqui, G.H. Khan and M. J. Zaki (2002). Nematicidal and allelopathic potential of *Argemone mexicana*, a tropical weed. *Plant and Soil*, 245: 239-247.

Shah, A.M.U.H., A. Ditta, A. Parveen, S. Thind and A.G. Ebadi. (2022). Transcription factors that scavenge reactive oxygen species in rhizobacteria. *Sustainable Plant Nutrition Under Contaminated Environments,* Springer International Publishing, pp. 235–256.

Shokrzadeh, M., A.G. Ebadi, M. Azadbakht and R. Heidari (2004a). Measurement of lead, cadmium and chromium in five species of most consumed fish in Caspian Sea. *International Journal of Biology and Biotechnology*, 1(4): 673–675.

Shokrzadeh, M., A.G. Ebadi, M. Azadbakht, R. Heidari and S. Zaree (2004b). Qualitative analysis of lead, cadmium, chromium and zinc in vegetables (*Spinacia oleracea* L. and *Raphanus sativus* L.). *International Journal of Biology and Biotechnology*, 1(4): 677–679.

Sruthy, O.A. and S. Jayalekshmi (2014). Electrokinetic remediation of heavy metal contaminated soil. *International Journal of Structural and Civil Engineering Research*, 3: 103–111.

Uddin, S., S. Khanom and M.R. Islam. (2023). Mercury contamination in food—an overview. *Mercury Toxicity: Challenges and Solutions,* pp. 33–70.

Xiang, M., J. Ma, J. Cheng, K. Lei, F. Li, Z. Shi and Y. Li (2022). Collaborative evaluation of heavy metal pollution of soil-crop system in the southeast of Yangtze River Delta, China. *Ecological Indicators,* 143: 109412.

Xu, W., D. Guo, A.G. Ebadi, M. Toughani and E. Vessally. (2021). Transition-metal catalyzed carboxylation of organoboron compounds with CO_2. *Journal of CO_2 Utilization,* 45: 101403.

Yolchiyeva, F., S. Hacjiyeva, A.A. Huseyinli and A. Hasanova (2020) A. Ecological problems of water resources in Azerbaijan and their impact on human health. *Central Asian Journal of Environmental Science and Technology Innovation,* 1(2): 71-76.

Zare, S. and A.G. Ebadi (2005). Measurement of heavy metals in fish from the Tajan River. *Pakistan Journal of Biological Sciences*, 8(10): 1460–1462.

Zare, S., A.G. Ebadi and M. Babaee (2005). Measurement and survey of organochlorine pesticides (OCPs) level in milk samples of agricultural workers (Mazandaran–Iran). *International Journal of Biology and Biotechnology*, 2(4): 967–970.

Zeb, B.S., M.T. Hayat, T. Zeb, F.Y. Khan, H.Z. Abbasi, I. Nawaz and A.G. Ebadi. (2022). Uptake of organic pollutants and the effects on plants. *Sustainable Plant Nutrition under Contaminated Environments,* Springer International Publishing, pp. 209–234.

Zwolak, A., M. Sarzyńska, E. Szpyrka and K. Stawarczyk (2019). Sources of soil pollution by heavy metals and their accumulation in vegetables: A review. *Water, Air, & Soil Pollution,* 230: 1–9.

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