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Heavy Metal Contamination in Vegetables and Their Amelioration: A Review

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ABSTRACT

Heavy metal (s) contamination of vegetables is an alarming and significant concern due to its potential health risks for consumers. Heavy metal contamination of vegetables has threatened both food security and human health. Contaminants like lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg) and others can be added to vegetable tissues when present in the soil, water, or through other sources. Anthropogenic activities such as mining, industrialization and agricultural practices like pesticide, fungicide, as well as fertilizer use release heavy metals into the soil, water and atmosphere. Vegetables are essential to the human nutrition, which provide vitamins, minerals and fibres and also have beneficial anti-oxidative properties to maintain normal physiological functions. Vegetables absorb heavy metal(s) and store them in their bodies at levels that can lead to health issues. Even at low concentrations, heavy metals can be highly detrimental to the human body due to the lack of an efficient excretion mechanism. The research on review of heavy metal contamination of vegetable crops and their amelioration have been conducted from various secondary sources of published data. Heavy metal polluted soil leads to reduction in growth due to changes in physiological and biochemical activities which affect the growth and yield of vegetable crops. To mitigate heavy metal contamination, various strategies are soil testing, remediation of contaminated sites, improving agricultural practices and monitoring of water sources, *etc*. Remediation techniques for reducing heavy metal contamination in vegetables include immobilization using low-cost absorbents (soil amendments), physical and chemical approaches, phytoremediation/bioremediation, chelating agents, microorganisms, transgenic plants, nanotechnology and grafting, *etc*.

Key words: Amelioration, Contamination, Heavy metal, Toxicity, Vegetables.

Heavy metal relates to any metallic element that has a comparatively high density and is toxic even at low concentrations (Ansari *et al*., 2024). It is a general and collective term that applies to the group of metals and metalloids with atomic density greater than 5 g cm^{-3} or 5 times greater than water (Ansari *et al.,* 2012). Of the naturally occurring nearly 98 elements, 53 are regarded as heavy metals, of which 17 (*i.e*. Ag, As, Cd, Co, Cr, Cu, Fe, Hg, Mo, Mn, Ni, Pb, Sb, U, V, W and Zn) are believed to be important for organisms and/or ecosystems, based on their solubility in environmental devices (Lide, 2005). Among the pollution-producing heavy metals, arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb) are regarded as non-essential elements, with no known physiological functions in plants (Ansari *et al*., 2021). They are extremely toxic to plants and animals, have a long half-life and are persistent in the environment (Ansari *et al*., 2023). In small quantities certain HMs such as copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) are nutritionally essential for plants, animals and human being important cofactors of many enzymes and constituents of cells (Ansari *et al*., 2015a). Heavy metals are existing in soil, rocks, water and air and they play essential roles in geological and geochemical processes. Essential heavy metals include Cu, Zn, Fe, Mn, Mo and Co. Potentially toxic heavy metals involve Pb, Cd, Hg, As, Cr, Ni and Al. (can be toxic in certain forms and concentrations). They are contaminants that are environmentally persistent as well as non-degradable. “Heavy metal contamination results from the excessive accumulation of the toxic heavy metals in soil” due to various activities of human. Agricultural ecosystems are exposed to various sources such as

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industry, reclaimed wastewater, soil amendments and agricultural practices like the application of fertilizer and pesticides (Gupta *et al*., 2010). They are first placed on the surface of soil, then taken in by the plant roots apoplast and subsequently spread and gathered in both the consumable and non-consumable parts, presenting a direct threat to the chain of food (Ahmed *et al.,* 2019; Alsafran *et al*., 2021a). Small quantities of heavy metals can be absorbed through atmospheric deposition (Prasad *et al*., 2021).

Heavy metals like Ni, Pb, Cu, Cd, Cr, Co and Hg are major environmental contaminants that harm plants, decreasing productivity as well as posing risks to agricultural ecosystems. While plants require trace amounts of Fe, Cu, Ni, Mn and Zn, excessive levels of these metals can be harmful. Metals like As, Al, Pb, Cd and Hg are non-essential for normal human function and can rapidly lead to toxicity. Heavy metals in contaminated vegetables may present significant health risks when consumed by humans. The global economy's advancement has led to a gradual increase in both the variety and amount of heavy metals in the soil because of the activities of humans, leading to the degradation of the environment (Sayadi and Rezaei, 2014). Heavy metals are non-biodegradable, possess extended biological 1/2-lives and can accumulate in several human body organs, potentially causing adverse impacts (Jarup, 2003). Vegetables are essential in the human diet, providing vital nutrients in both cooked and raw forms which are required for the survival of humans. They also serve as protective foods by helping to prevent disorders. Vegetables contaminated with heavy metals pose threat to human life and cause serious threats like cancer, cardiovascular diseases, nervous system disorders, neurological impairment as well as bone disorders and several other health disorders (WHO, 1992 and Jarup, 2003). Heavy metal pathways in different ecosystems (terrestrial, aquatic and atmospheric) involve diverse sources, transformations and environmental impacts. In terrestrial ecosystems, heavy metals enter soil systems through industrial emissions, agricultural activities (*e.g*., fertilizers and pesticides) and natural processes like rock weathering. These heavy metals tend to bind with soil particles or organic matter, limiting mobility but allowing bioaccumulation in plants and soil organisms. Long-term bioaccumulation of metals like cd and pb can alter soil fertility and affect microbial ecosystems. Heavy metal pollution in aquatic ecosystems is a major environmental concern worldwide (Abubakar *et al*., 2024). Aquatic life and human consumers are at risk from heavy metals like lead, mercury and cadmium (Sharma *et al*., 2021). In aquatic ecosystems, heavy metal pathway involves direct discharge from industrial and urban runoff, mining activities and atmospheric deposition. The main causes of heavy metal pollution in aquatic habitats are waste disposal, agricultural runoff and industrial effluents. The heavy metals has negative effects on the quality of water as well as the aquatic biota including plankton, fishes and benthos. Bioaccumulation of heavy metals in the aquatic food chain, affect fishes and aquatic organisms, causing serious health impacts in humans who consume contaminated water or aquatic foods. A study conducted by (Sharma *et al*., 2024) reported that heavy metals like Pb, Cd, Hg, Cu and Zn are known to cause toxicity on the growth and development of fish and also reproductive and respiratory systems of fish. In atmospheric pathways, heavy metals are introduced into the atmosphere primarily via industrial emissions, vehicular pollution and volcanic eruptions. Jin *et al.* (2019) and Liu *et al.* (2020) reported that heavy metals are released into the environment as a result of rising human activity, such as industrial advancements and these contaminants build up in the soil, especially in areas that are rapidly industrializing. Heavy metals are discharged into the environment through a variety of man-made practices like irrigation with polluted water, the use of chemical-based fertilizers, dumping of industrial effluents into water bodies, volcanic eruptions, *etc*. (Hembrom *et al*., 2020). Metals from various sources goes into the ground, ground water and eventually taken up by the plants. Vegetables polluted with heavy metals when ingested produces serious consequences on human health. Although trace levels of Cu, Fe, Mn, Ni and Zn are required by plants, but excessive quantities of these metals can be hazardous (Sonone *et al*., 2020). Metals including Al, As, Cd, Pb and Hg are not essential for regular human function and can cause toxicity (Boyd and Rajakaruna, 2013). Heavy metals from contaminated soil and waste, accumulate in the plant's edible parts or on the vegetable's surface. The heavy metals are not essential for plant growth, they are absorbed and accumulated by plants in higher levels causing toxic damage to cells and tissues as a result of the complex interaction of major toxic ions with other essential or non-essential ions (Ahmadpour *et al.,* 2012). Manwani *et al.* (2022) found higher concentrations of heavy metals which includes Mn, Cr, Ni, Fe, Zn, Cu, Pb, Cd and Hg in common vegetables like *Amaranthus tricolour* L.*, Spinacea oleracea, Chennopodium album* L.*, Solanum lycopersicum, Coriandrum sativum* and *Solanum melongena.* Compared to root vegetables, leafy vegetables had higher concentrations of heavy metals. Therefore, compared to root vegetables, eating leafy vegetables could result in greater health risks (Sulatana *et al*., 2022). Essential as well as non-essential heavy metals generally create common toxic effects on plants, like lower accumulation of biomass, necrosis, chlorosis, inhibition of photosynthesis along with growth, altered water balance and assimilation of nutrient, plasma membrane permeability damage, root system damage, senescence, that ultimately cause death of plant (Atanassova and Zapryanova, 2009). Concentrations of heavy metals in vegetables depend on the environmental situations, genotype as well as species, part of plant, cultivation

manner, harvesting approaches, growth stage, processing and cooking, *etc.*

The review was collected during 2017-2018 to assess the heavy metal contamination of vegetable crops and their amelioration methods. The information for the study was gathered from various published literature.

Regulatory safe limit of heavy m etals in plant and soil

The guidelines for a safe limit of the heavy metals for soil and plants (Table 1). According to the Indian Standard given by Awashthi (2000), FAO/WHO(2007) and the European Union Standard (2002).

Sources of heavy metals

Geogenic source of heavy metal is a prime source of metal contamination. Anthropogenic activities spread the metal concentrations in different ecosystems. Various sources for contributing to the existence of heavy metals in soil includes sewage irrigation, atmospheric deposition, mining activities, improper industrial waste disposal and the application of fertilizers as well as pesticides. Urban soils and agricultural soils have distinct levels of heavy metal contamination (Babula and Adam, 2008). Urban regions in developing nations such as Pakistan, Bangladesh, Ethiopia, Ghana, South Africa and India have documented elevated levels of heavy metal(s) caused by fast industrial growth, wastewater usage in agriculture and various human-induced actions. Petrochemical activities contribute to soil contamination through spills of oil, disposal of waste, gas flaring and chemical discharge, which can have negative impacts on the ecosystem as well as human health (Sun *et al.*, 2019). Gasoline can lead to higher levels of specific heavy metals like Pb, Cd, Zn, Ni and Cu in soils near roads, which may eventually build up in the vegetables (Kumar *et al.*, 2019). Research has demonstrated that vegetables cultivated close to sites of industrial, sites of mine, highways and solid waste dump sites tend to have heavy metals in greater concentrations than vegetables grown in other locations. Therefore, vegetables cultivated in nearby industrial zones, mining areas, highways and landfills could present substantial health hazards for humans and animals. Heavy metal pollution's primary sources in urban soils consist of emissions from transportation, industrial waste from power plants, combustion of coal, metallurgical industry, automobile repair facilities, household waste, chemical plants, construction materials, weathered particles and atmospheric precipitation. Heavy metal pollution's primary sources in soils of agriculture are urban influence, mineral smelting, waste management, sewage sludge, vehicle emissions, fertilizers and pesticides (Montagne *et al.*, 2007). Different sources of heavy metals (vehicle, mining, garbage, sewage, plastics, Nano-fertilizer, wastewater) are presented in Fig 1, 2, 3, 4 and 5 display the heavy metal levels in agricultural along with urban soils globally.

Physiological processes of vegetable crops influenced by heavy metal toxicity

The physiological processes of vegetables can be significantly influenced by heavy metal toxicity. Based on the effect of heavy metals in the plants, they are categorized as essential and non-essential heavy metals. Some of the heavy metals like (Fe, Cu and Zn) are essential for plants and animals (Wintz *et al.,* 2002). Metals such as Cu, Zn, Fe, Mn, Mo, Ni and Co are essential micronutrients (Reeves and Baker, 2000), whose uptake in excess to the plant requirements result in toxic effects (Monni *et al.,* 2000). They are also called as trace elements due to their presence in trace (10 mg kg^{-1}, or mg L^{-1}) or in ultra-trace (1 g kg^{-1}, or lgL^{-1}) quantities in the environmental matrices.

The essential heavy metals (Cu, Zn, Fe, Mn and Mo) play biochemical and physiological functions in plants and animals. Major functions of essential heavy metals are: They participate in redox reaction and they are an integral part of several enzymes (Gunalan *et al.*, 2019), whereas some of these heavy metals like As, Cd, Hg, Pb and Se do not have any use in the plant system. Even in low concentration it causes toxic effect to plants and it becomes hazardous to all living organisms. Different uses of essential heavy metals in plant system is mentioned below (Table 2).

Heavy metals, when present in excessive concentrations, can negatively impact various aspects of plant physiology, led to decreased growth, yield and total health of plants. Excessive HM concentrations can be toxic

Table 1: Regulatory limits for heavy metals in plants and soils.

Sample	Standard	Cd	Cu	Pb	Zn	Mn	Ni	Cr
Soil (mg/g)	Indian standard (Awashthi, 2000)	3-6	135-270	250-500	300-600	-	75-150	-
	FAO/WHO (2007)	-	-	-	-	-	-	-
	European union standard (EU 2002)	3.0	140	300	300	-	75	150
Plant (mg/g)	Indian standard (Awashthi, 2000)	1.5	30.0	2.5	50.0	-	1.5	20.0"
	"WHO/FAO (2007)	0.2	40.0	-	5.0	60	-	-
	European union standard (EU 2002)	0.2	-	0.30	-	-	-	-

to plants as these metals disturb the physiological processes such as cell elongation, photosynthesis and respiration and inhibit nitrogen metabolism and mineral nutrition (Ansari *et al*., 2009). The impact varies depending on the heavy metal kind, its concentration and the species of plant involved. The impact of heavy metal toxicity on vegetables is a concern not only for plant health but also for food safety. It highlights the importance of monitoring

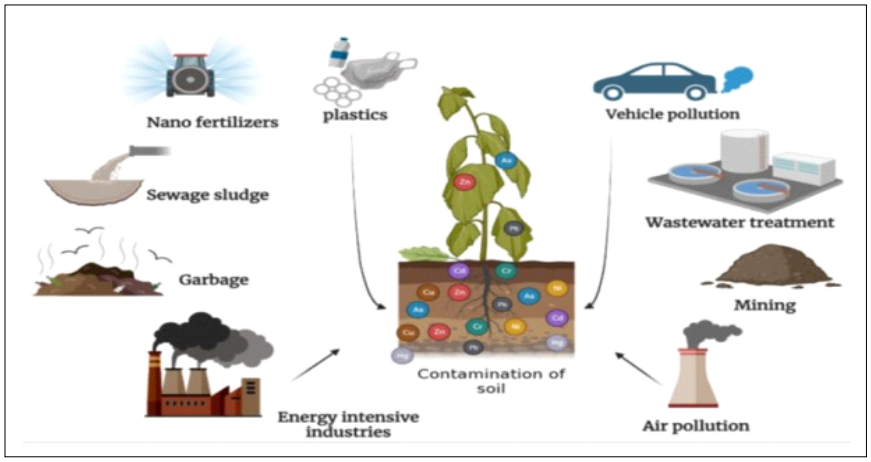


Fig 1: Different sources of HMs (vehicle, mining, garbage, sewage, plastics, nano-fertilizer, wastewater-Angon *et al*., 2024).

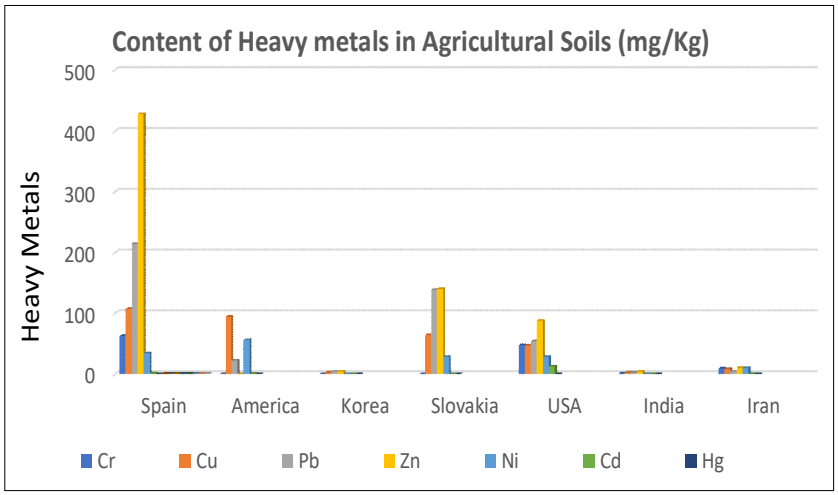


Fig 2: Heavy metals (mg/kg) in agricultural soils of different regions worldwide.

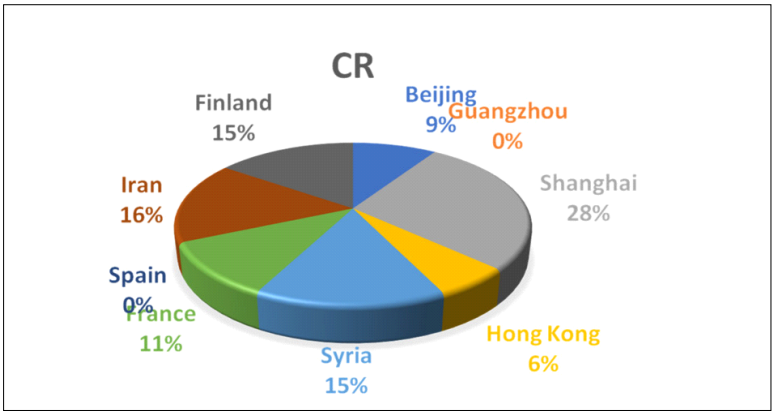


Fig 3: Content of chromium in urban soils of different regions around the world.

and managing heavy metal contamination in the soils of agriculture to ensure the production of safe and nutritious food crops. Sustainable agricultural practices, soil amendments and phytoremediation strategies are among the approaches used to mitigate the adverse effects of the

Table 2: Uses of essential heavy metals in plant system.

Metals	Functions
Cu	Photosynthesis-Electron donor in photosystem-I.
Zn	Many enzymes contain Zn-carbonic anhydrase, RNA polymerase and also to maintain the integrity of ribosome.
Mn	Acts as catalyst-involves in oxidation of carbohydrate.
Mo	Metabolism of N and S-Nitrate reduction and biological N fixation.
Ni	Component of urease enzyme.
Co	Useful in expansion of leaf disc, Constituent of vitamin B12 and Propionate.

(Mahmood and Islam, 2006).

toxicity of heavy metals in vegetable crops. Additional research into plant tolerance mechanisms and the identification of metal-tolerant plant species can contribute to the development of phytoremediation strategies for contaminated environments. Key physiological processes in vegetables (Fig 6) that can be influenced by heavy metal toxicity include.

Water uptake and transport

Heavy metals could affect root morphology as well as function, leading to impaired water uptake and reduced nutrient transport. This can result in water stress and nutrient deficiencies in vegetables.

Nutrient uptake and assimilation

Certain heavy metals, like Cd and Pb, can compete with important nutrients which is Zn, Fe and Ca for the uptake by plant roots. This competition can disrupt nutrient assimilation and result in nutrient imbalances.

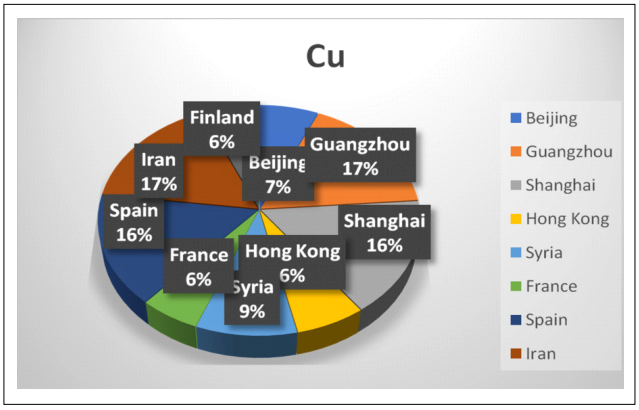


Fig 4: Content of copper in urban soils of different regions around the world.

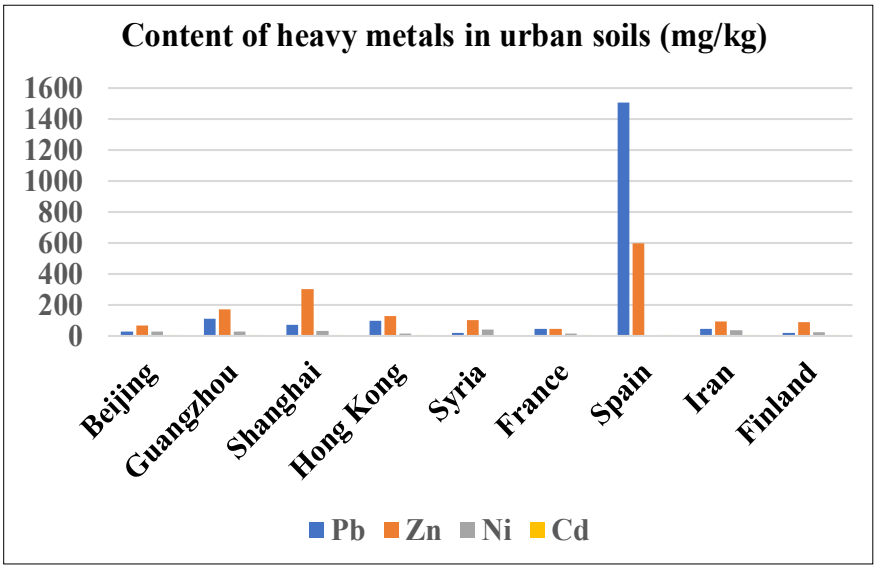


Fig 5: Content of lead, zinc, nickle and cadmium (mg/kg) in urban soils of different regions worldwide.

Photosynthesis

Heavy metals, especially cd and pb, interfere with chlorophyll synthesis and cause chlorosis (yellowing) by disrupting chlorophyll synthesis, accelerating its degradation. This leads to chlorosis, reduced photosynthetic efficiency and a decline in overall plant productivity.

Respiration

Heavy metals can affect mitochondrial function, disrupting cellular respiration. This leads to a decrease in energy production, negatively impacting growth and metabolism in vegetables.

Oxidative stress

Heavy metals induce the ROS (Reactive Oxygen Species) generation within plant cells. ROS could cause oxidative damage to components of cells, involving proteins, lipids,and DNA leading to cellular dysfunction as well as programmed cell death.

Enzyme inhibition

Heavy metals act as enzyme inhibitors, affecting the crucial enzyme activity involved in several metabolic procedures. Enzyme inhibition can disrupt key biochemical pathways, hindering normal plant growth and development.

Cellular structure and Integrity

Heavy metals can alter cell wall structure and composition in vegetables. This disruption affects cell integrity, leading to increased permeability and vulnerability to environmental stress.

Root morphology and growth

Heavy metal toxicity can inhibit root elongation and alter root architecture in vegetables. This negatively impacts the plant's capability to explore the soil for nutrients and water and causes stunted growth.

Translocation of metals

Some heavy metals can be translocated from roots to above-ground plant parts, including edible portions like leaves, fruits, as well as tubers. This poses a risk to human health when contaminated vegetables are consumed.

Genetic and molecular responses

Vegetables respond to heavy metal stress by activating stress-responsive genes. These genes are involved in detoxification processes, metal transport and antioxidant defense mechanisms.

Different sources of heavy metals contamination

Atmosphere to soil

Heavy metals in the atmosphere primarily originate from the dust as well as gas emissions generated by the production of energy, automotive transport, paint factories, sulfuric acid factories, metallurgical processes and construction materials production. With the exception of Hg, heavy metals are primarily released into the atmosphere as aerosols and then settle onto the soil via the natural process of sedimentation along with the precipitation.

Sewage to soils pathway

Wastewater could be categorized into various types such as sanitary sewage, urban mining mixed sewage, industrial mining wastewater and chemical wastewater. Sewage water irrigation introduces heavy metals into the soil, where they become immobilized through various mechanisms. It leads to the continuous addition of heavy metals (Cd, Hg, Cr, Pb, *etc*.) in soil annually. Sewage irrigation can lead to heavy metal contamination.

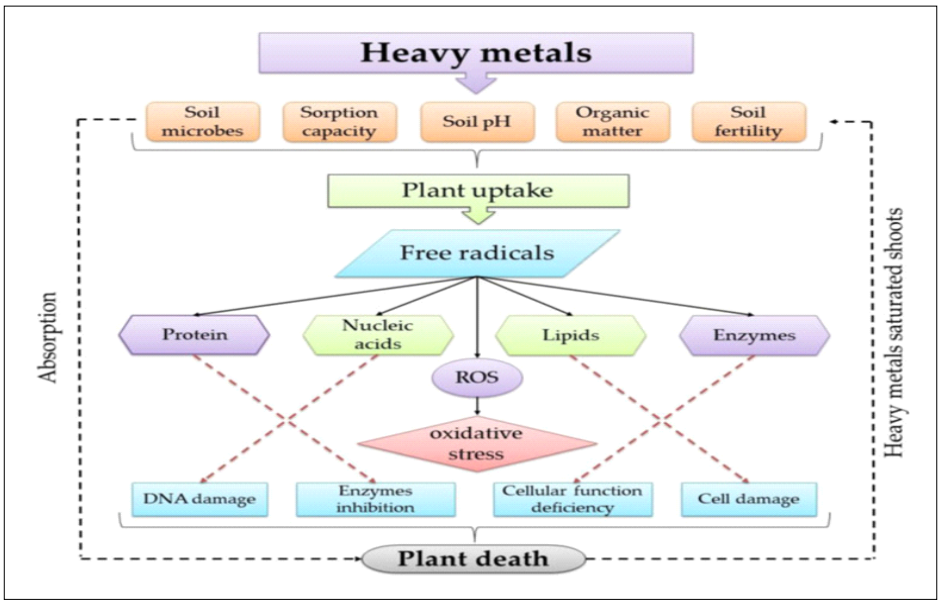


Fig 6: Mechanism of action and pathway of heavy metals toxicity in soil and plant (Alengebawy *et al.*, 2021).

Solid wastes to soils pathway

Mining as well as industrial solid waste have intricate compositions and pose the most severe contamination issues. When waste is accumulated, heavy metals can easily leach out because of the presence of the sun-light, rainwater and washing. They can spread to the surrounding soils as well as water and solid wastes can easily increase the scope of contamination with the assistance of wind along with the water.

Agricultural supplies to soils

Fertilizers, mulch and pesticides are crucial agricultural inputs for the production of agriculture according to Zhang *et al.* (2011). Heavy metals are the predominant pollutants found in the fertilizers. Potash and Nitrogen fertilizers have low heavy metal content levels, whereas phosphoric fertilizers classically contain major amounts of toxic heavy metals. Content of heavy metal in the fertilizers typically follows this order: phosphoric fertilizer > compound fertilizer > potash fertilizer > nitrogen fertilizer (Boyd, 2010). Cadmium is a significant heavy metal pollutant in soil that contaminates soil through the use of phosphoric fertilizers. Numerous researches have demonstrated that the continuous application of high levels of the compound as well as phosphate fertilizers leads to a consistent increase in the available cadmium content in soils, resulting in a corresponding increase in cadmium absorption by plants. Recently, mulch has been increasingly utilized in the commercial cultivation of horticultural crops on a large scale, leading to soil contamination known as white pollution due to the presence of heat stabilizers containing Cd and Pb added during mulch production. This leads to heavy metal pollution increased levels in the soil (Satarug *et al.*, 2003).

Methods for amelioration or remediation of heavy metals

The United States Environmental Protection Agency (UPEA) classifies heavy metals as important pollutants. Over 70,000 chemicals are currently in use worldwide. Pb, Hg, As and Cd are ranked 1st, 2nd, 3rd and 6th correspondingly in the US Agency for Toxic Substances and Disease Registry (ATSDR) list, that categorizes hazards at toxic sites of waste based on their occurrence as well as toxicity severity. Heavy metal pollution is becoming a significant concern at regional, local and global levels. Heavy metals in higher concentrations in aquatic and terrestrial ecosystems can function as ecological toxins. Currently, human activities contribute more metals to the environment than natural sources.

According to data from the Central Pollution Control Board (CPCB) in 2011, Maharashtra Andhra Pradesh and Gujarat account for hazardous waste 80%, involving heavy metals, in India (Marg, 2011). Roadways and automobiles are significant contributors to the environmental load of heavy metals due to the presence like Pb, Cd and As in particulate matter emitted from traffic. Utilizing sewage sludge in the fields of agricultural led to heavy metals build-up in the soil, affecting plant growth. Groundwater can be polluted by the leachate direct infiltration from solid waste land disposal, liquid leachate from the mine tailings, sewage and sewage sludge, liquid waste deep-well disposal and other sources. Heavy metal can have a serious impact on human health when it enters the body through ingestion, skin contact, diet, inhalation, or oral intake.

Remediation of heavy metal toxicity in soils, water and ecosystem is crucial to protecting both human health and ecosystems. Various management practices are being implemented to reduce the toxicity of metal by decreasing the amount of the metal accessible to the plants. Biology-based technologies, such as hyper metal accumulator plants that occur naturally or are created through transgenic methods, have gained significant interest in addressing heavy metal contamination. Nanoparticles are currently being researched for metal remediation because of their outstanding adsorption and unique electrical properties, mechanical properties, higher chemical stability and larger specific area of the surface. Several strategies for remediation can be employed (Fig 7) each with advantages and disadvantages.

Engineering remediation

Engineering remediation involves the application of physical and chemical techniques to manage heavy metal pollution in soils.

Physical remediation

Physical remediation involves mechanical separation and electrokinetic separation. Mechanical separation offers the benefit of a substantial volume decrease in the contaminated soil.

Replacement of soil removal, contaminated soil and soil isolation

Replacement of contamination by adding a substantial quantity of uncontaminated soil to create a covering layer over the contaminated soil. Soil removal entails extracting "contaminated soil and replacing it with clean soil, particularly crucial for heavily contaminated soil in small areas. Soil isolation involves separating contaminated soil from the uncontaminated soil", but additional engineering measures are required to fully remediate it (Zheng *et al.*, 2002). These approaches are only suitable for small soil areas due to the significant manpower and material resources required.

Electrokinetic remediation

Soil electro-kinetic remediation is a cost-efficient technology. This method is advantageous because it can be used with various metals and is a novel remediation technology that involves applying voltage at the two sides

of an electrolytic tank containing contaminated soil to create an electric field gradient (Tahmasbian and Nasrazadani, 2012). To lessen contamination, the pollutant in the soil is moved by electric seepage, electro-migration, or electrophoresis to the processing chamber, that is located at the 2 polar sides of the electrolytic cells. It is ideal for impermeable soil, as it is easy to install and operate, cost-effective and does not disrupt the natural environment, making it effective for environmental remediation and ecotype protection (Luo *et al.,* 2004).

Chemical remediation

Chemical remediation methods like soil washing and soil flushing can eliminate inorganic contaminants like heavy metals and toxic anions. Soil washing is an efficient technique for cleaning heavily contaminated soils, while soil flushing is a less invasive method.

Soil leaching

This method cleanses heavy metal-contaminated soil using particular reagents to remove the heavy metal complex along with soluble irons attached to solid phase particles. The heavy metals eliminate from the soil which have been recycled from the extracting solution.

Adsorption

Heavy metal ions could be immobilized as well as adsorbed by minerals of clay like zeolite and bentonite and also materials like steel and furnace slag

Soil amendments remediation

Soil amendments include the addition of lime (Guo *et al.*, 2006), the addition of biological products and it consists of the addition of bark sawdust, the addition of chelating agents (Ethylene Diamine Tetra Acetic Acid; EDTA) Sukumara *et al.* (2012), cattle manure addition, the addition of rice hull (Nagh and Hanafiah, 2008).

i) Addition of lime - Decrease the mobility of Cu, Cd, Pb,Ni, Zn.
ii) Addition of chelating agents - Decrease the mobility of Cu and Pb.
iii) Addition of bark saw dust - Decrease the mobility of Pb, Cd, Cu, Hg.
iv) Addition of cattle manure - Reduce the mobility of Cd.
v) Addition of rice hull - Decrease the mobility of Cd, Cr and Pb.

Biological method of remediation/Bio-remediation

Phytoremediation

Phytoremediation involves using living green plants to absorb contaminants, clean them and reduce or eliminate their risk. These plants possess a specific hyper-accumulation capacity for soil contaminants, primarily accumulating in the root and above-ground parts. Harvest, cure and burn plants to eliminate heavy metals from contaminated soil once the plants are grown or reach a specific level of heavy metal enrichment. Over 400 species of these plants have been discovered worldwide, with the majority falling under the Cruciferae family, such as the Alyssums, Thlaspi and genus Brassica. Phytostabilization, phytovolatilization and phytoextraction are the three primary types of phytoremediation.

- Phytostabilization involves plants fixing heavy metals by adsorption, precipitation and root reduction, there by decreasing their migration and bioavailability. This process helps stop heavy metals from entering the groundwater and food chain.
- Phytoextraction involves using plants and their roots to stop the movement of contaminants through processes like wind erosion, water erosion, leaching and soil dispersion (Jiang *et al.*, 2010).
- Plants absorb and release contaminants, mainly organic compounds, through photo-volatilization, uptake and transpiration (Rahim *et al.*, 2013).

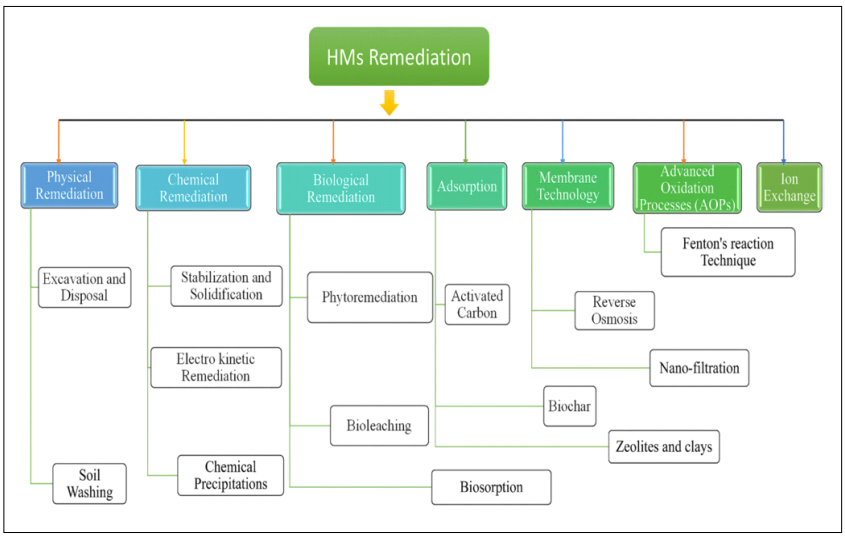


Fig 7: Remediation classifications of heavy metal contamination (Angon *et al.*, 2024).

Microbial remediation

Microbial remediation involves utilizing specific microorganisms to facilitate the precipitation, oxidation-reduction, absorption and intracellular addition of heavy metals in soil. Microorganisms can eliminate metal contaminants through sorption and/or transformation processes. Microorganisms are unable to break down and eliminate heavy metals, but they can influence the movement and alteration of the metals by changing their physical and chemical properties. Siegel *et al.* (1986) discovered that fungi have the ability to organic acids, secrete amino acids and other metabolites for dissolving heavy metals along with minerals that contain heavy metals. Fred *et al.* (2001) found that the fungus *Gomus intraradices* could enhance sunflower's tolerance to and absorption of chromium. Developing microorganisms with the ability to break down heavy metals using biotechnological methods such as genetics and genetic engineering is a current priority in this field.

Microbial leaching is an efficient method for extracting valuable metals from low-quality ores and mineral concentrates. Microbial leaching can be used for industrial raw material supply and has potential applications in repairing mining sites, treating mineral industrial waste, detoxifying sewage sludge and remediating soils and sediments contaminated with heavy metals (Bosecker, 2001).

Animal remediation

Removal of heavy metals from the soil using soil-dwelling animals. Some soil-dwelling animals, such as maggots and earthworms, have the ability to absorb heavy metals from the soil. Wang *et al.* (2007) demonstrated that Culow concentrations in the soil can enhance the Cu absorption by ryegrass through the activities along with earth worms secretion.

Biotechnological remediation

Through the utilization of genetic tools. Transgenic plants extracted 6% of zinc and 25% of cadmium from the soil metal, as reported by Kupper and Kochian (2010). Tobacco callus exhibited increased resistance to the methyl mercury (CH_3Hg^+) and added higher levels of mercury from a medium containing CH_3Hg^+, as reported by Nagata *et al.* (2010). Transgenic plants could enhance the broader and more secure implementation of phytoremediation.

Nanotechnology approach to remediation

Nanotechnology involves utilizing particles ranging from 1 to 100 nm in size to influence the movement, harmfulness and/or accessibility of pollutants in their original surroundings. Nano-ZVI, emulsified zerovalent nanoparticles and bimetallic nanoparticles help decrease metal contamination in soil and groundwater and highly effective in metal removal (Xiong *et al.*, 2009; Joshi and Agarwal, 2010).

Plant hormone for remediation

Plant hormones like abscisic acid (ABA), brassino steroids (BRs) and auxins (indole-3-acetic acid, IAA) were discovered to play crucial roles in stress regulation. Auxins were found to alleviate the severity of different stresses like salinity and drought. Farooq *et al.* (2009) studied heat as well as heavy metal stress, while *Dimpka et al.* (2008) focused on heavy metal stress. ABA also induces plant reactions to unfavorable environmental conditions (Kellos *et al.*, 2008).

Grafting method of

The technique of grafting involves joining two or more live plant segments so that they can form vascular connections and grow like a single plant. Grafting was previously utilized in the fruiting vegetable crops to reduce the soil pathogens impact, but its applications have expanded significantly over time to include a wider range of vegetable species and cultivars.

Advantage of grafting

- Yield increase.
- Rootstock effect on fruit quality.
- Restrict heavy metal uptake.
- Resistance/tolerance to soil-borne diseases.
- Improved plant growth.
- Enhanced nutrient and water uptake.

Grafting fruit vegetables onto suitable rootstocks can help reduce or eliminate yield limitations caused by nutrient and heavy metal toxicities. Grafting of fruit vegetables is an alternative means to combat soil-borne pathogens (Savvas, 2010). Fruit vegetables, like pepper (*Capsicum annuum* L.), eggplant (*S. melongena* L.) and tomato (*Solanum lycopersicum* L.) have relatively lower rates of heavy metal translocation to the fruit, according to Angelova *et al.* (2009).

CONCLUSION

Heavy metal contamination of vegetables is a significant environmental and public health concern. It is essential to monitor as well as control the heavy metal levels in the soil, plant as well as in the environment in order to stop environmental degradation and protect the ecosystem as well as human health. The amount of metal contamination could be decreased by the use of a number of remediation technologies. In developed and especially emerging nations where the heavy metal contamination is a major issue due to population growth and human interreference, alternative and environmentally friendly remediation technologies must be encouraged.

Conflict of interest

All authors declared that there is no conflict of interest.

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