REVIEW ARTICLE

Toxicity of Chromium and Cadmium in Plants and Their Remediation: A Comprehensive Review

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Abstract

Minerals in threshold amounts are indispensable for plants. Some of them are non-essential and have heavier atomic masses known as 'Heavy metals' due to high reactivity, they can retard plant growth, the process of aging and the process of energy generation hence retardation in plant growth is the main symptom of heavy metal toxicity. Heavy metal toxicity stimulates the production of reactive oxygen species (ROS), which are generated by diverse environmental distresses like elevated light intensity, temperature, water scarcity, salt stress, nutrient scarcity and attack of disease-causing agents. Plants are usually adapted to contrive against the toxicity of the various heavy metals by activating different concentrations of some enzymatic and non-enzymatic antioxidative compounds. Different traditional methods of palliation include pyrolysis of soil, *in situ* substantiation, landfill, soil washing off and soil solidification. Toxicity from the soil can be reduced by using some plants and microbes by the process of phytoremediation. Among the various heavy metals, the two metals (Cadmium and Chromium) need high concern because a very low amount of these metals are highly toxic for all living beings.

Keywords: Chromium, Cadmium, ROS, Heavy metal toxicity, Incineration, Remediation.

Highlights

- Chromium and cadmium are toxic heavy metals that cause oxidative stress in plants.
- Industrial activities like electroplating and tanning primarily cause Chromium pollution, while cadmium is often released from batteries, fertilizers and industrial wastes.
- Exposure to hexavalent chromium [Cr(VI)] can lead to cancer and other lethal diseases in all living beings.
- Plants can be used to remediate heavy metal toxicity through phytoremediation.
- Plants such as 'Indian mustard' and 'sunflowers' can be used in phytoremediation.
- Phytoremediation is an eco-friendly and cost-effective process, but challenges like slow metal uptake and disposal of contaminated plants are challenging tasks.

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Introduction

Plants require minerals in adequate amounts for their normal life cycle and better reproductive yield; hence, many minerals become more specific or essential for plants (Arnon and Stout, 1939). Many minerals are non-essential and have heavier atomic masses, known as 'Heavy metals,' it retards the growth of plants, aging and processes that generate energy because of their very high reactivity. The density of heavy metals is greater than 5 gm cm^{-3} (Adriano 2001). However, plants require a variety of heavy metals, including cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn). Beyond the permissible level, heavy metals are much noxious for plants, either causing oxidative stress or disrupting the functioning of enzymes.

Free radicals and some enzymes replace necessary metals and nutrients which can cause oxidative stress (Prasad 2008 and Henry 2000) in plants. Moreover, Growth reduction is the main visible sign of toxicity of these heavy metals (Baszynski and Skorzynska Polit, 1997). Baszynski and Maksymiec, in 1996, stated that dicotyledons, like beans and alpha-alpha, were highly tolerant to the toxicity of these metals at the initial growing stage. On the other hand, late-growing plants have been transferred in heavy metal-contaminated soil but they were not as tolerant as early growing plants.

Hence, heavy metal toxicity on the metabolism and physiological functions of plants is very articulate. Some heavy metals are found in different phases such as colloidal suspension, ion form, granular and melt form. Chromium (Cr) and cadmium (Cd) are highly concerned because their minute concentration can influence badly to both plants and animals. Among these heavy metals, cadmium has been recognized as highly hazardous to each living being, including plants and acts biologically in aquatic organisms as well as terrestrial too (Chellaiah, 2018).

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Origin and occurrence of minerals and heavy metals:

Generally, minerals and heavy metals are found in different phases like colloidal, ionic and particulate matter. The ions or unionized organo-metallic chelates are found in a dissolved state. The metal concentration in soil ranges from extremely low to 100000 mg kg-^{1}. According to Blaylock and Huang in 2000, the concentration of these metals varies depending upon the soil type and location. According to Cervantes *et al.*, 2001, among the most abundant elements, Cr is the 7th element found on the planet, which accounts for the formation of 0.1 to 0.3 mg kg^{-1} rocks. In the report of McGrath 1995, around 60 to 70% of global mass production of chromium is used in amalgam. It's 15% in the chemical industry, mainly pigments, leather-tanning, electrodepositing, and wood preservations.

Oxidation states of the element chromium range from Cr^{2-} to Cr^{6+}; nevertheless, the activity of first, second, fourth and fifth has also been observed to be found in a variety of compounds (Wilkens and Krishnamurthy, 1994). Moreover, Cr (VI) is combined with O_2 as CrO_4^{2-} (Chromate) or $Cr_2O_7^{2-}$ (dichromate) Oxy-anions, which are the most hazardous forms of chromium. The less mobile, less hazardous form of chromium is Cr (III). Becquer *et al.* in 2003, stated that organic matter in terrestrial and aquatic environments is the major matter found bound to Cr(III). According to Rai and his colleagues (1987) $Cr(OH)_3$ has greater solubility than the solid phase of Cr(III) and $Fe(OH)_3$. Consequently, In reaction to aggregation of $Cr(OH)_3$ and $Fe(OH)_3$, whole soluble Chromium Cr (III) remains below acceptable limits for drinking water over the pH range from 4 to 12 (Zayed and Terry 2003; Rai *et al.*, 1989). Equivalently, parental material is the major source of cadmium, in spite of that, human interference has also increased the Cadmium concentration in soil (Pendias and Kebata – Pendias, 2001). Aquatic environments have been influenced by many industrial acts like leather tanning, electroplating, electrodeposition, chrome plating, phosphate fertilizers, pigments and the production of batteries, stabilizers and alloys (Stephens and Calder 2005; Booth 2005) (Fig. 1). Additionally, due to agricultural and industrial processes, a vast area of farmland has also been observed to be polluted through Ar and Cd (McGrath *et al.*, 2001).

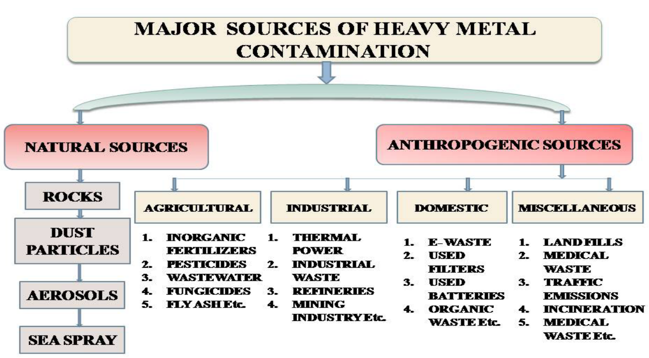

Fig. 1: Schematic presentation of sources of heavy metals.

Effects of heavy metal toxicity on plant's physiology

Various heavy metals disturb plants by affecting their biochemical activities, which further affects their physiological and reproductive capacity. Heavy metals toxicity retards plant growth and plant physiology and also behaves like an enemy to metabolic processes, which causes disturbance of structure of protein which originates from the constitution of bonds between sulfhydryl groups and heavy metals (Hall, 2002), ceases working set of essential biological units, demolishes working of indispensable biological molecules including enzymes and photo-pigment and critically influence plasma membrane righteousness, resultant is biological mechanisms like photosynthesis, enzymatic activities and respiration inhibition in plants (Farid *et al.*, 2013). On the other hand, drooping of matured leaf, yellowing of newly grown leaf, necrosis, wilting, growth hampering, and yield reduction are those symptoms of metal toxicity that which naked eye can see. Additionally, metal stress causes a reduction in the growth of the leaves, modifications in stomata and tolerance. It increases the rolling of leaves, leaf detachment process (abscission) and a complex degree of root suberization.

A rapid increase in the procreation of 'Reactive Oxygen Species' (ROS) has occurred attributable to the heavy metal's elevated concentration. These ROS are O^{2-} (superoxide free radicals), OH^- (free Hydroxyl radicals) and bound radicals like H_2O_2 (Hydrogen peroxide). Hossain and his colleagues in the year 2012, stated that it causes oxidative stress by interfering with counterbalance between antioxidant and pro-oxidants in plant cells. Consequently, many diseases arise, including lipid and protein oxidation, ion leakage, redox imbalance and membrane and cell structure denaturation, all of which end in Programmed Cell Death (Nagajyoti *et al.*, 2010).

The ability of a body of living beings to neglect their toxic effects through the process of neutralization and formation of free radicals using antioxidants follows various pathways (Halliwell and Gutteridge, 2006). Biomolecules such as lipids, carbohydrates, nucleic acids, etc., can be attacked by ROS

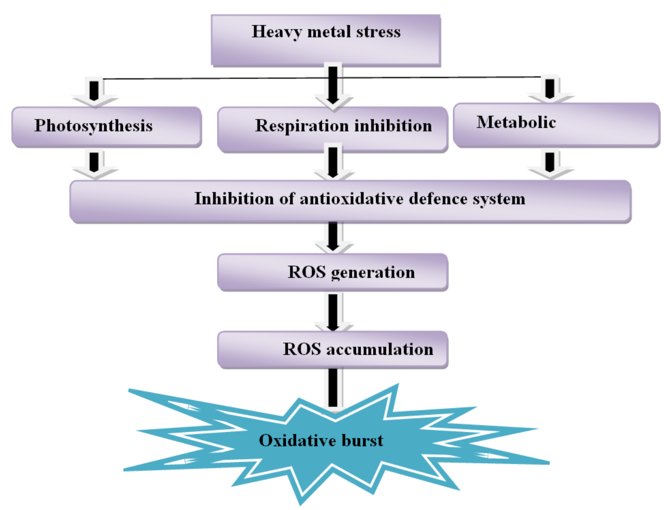

Fig. 2: Heavy metals stress and their effects on physiological activities and the phenomenon of "Oxidative Burst," resulting in damage to the plant body and poor reproductive yield.

species that have high oxidizing activities and are usually generated under stress (Wojtaszek, 1997). Various kinds of environmental stresses like high light, temperature fluctuation, water stress, salt stress, different metals, nutrient scarcity and attack by disease-causing agents are the cause of production of ROS species. Lushchak (2021) stated that reactive oxygen species that are free radicals considered to originate from oxygen are very sensitive molecules and ions that have rapidly been increased, known as "Oxidative burst." It occurs by an antioxidant depletion or when cells come under heavy exposure to reactive oxygen species ($^1O_2$, O_2•-, H_2O_2, OH^- etc).

A major abiotic issue increasing contamination in soil, air and water is "metal stress," which drops down the agricultural crop productivity. An immoderate amount of these heavy elements can give rise to an "oxidative burst," which proves toxic for the plants (Figure 2). There are many enzymatic and non-enzymatic scavengers, like catalase, superoxide dismutase (SOD), ascorbic acid (AsA), reduced glutathione (GSH) and others, which overcomes heavy metal hassle by lowering effects of the reactive oxygen species (ROS).

Effects on seed germination

In a consequence of changing environmental conditions, seed germination and growth of early seedlings is very sensitive (Seregin and Ivanov, 2001). Peralta and his colleagues in the year 2001, stated that the rate of seed germination and seedlings are frequently used to gauge heavy metal hassle. Compared with control, Mahmood and his colleagues in the year 2007 found that high amounts (01, 05 and 10 µM) of heavy elements (Copper, Zinc and Magnesium) inhibited seed germination and initial growth of paddy, wheat and barley saplings. Seed pullulation is the first physiological activity altered by these hazardous metals and seeds, germinating into a medium that contains a bit of a metal element (i.e., Cd), showing its level of tolerance against that metal element reported by Peralta *et al*., 2001. Reduction in the growth of seeds has been recorded 25% in *Echinochloa colona* under the treatment of 200 µM Chromium concentrations (Rout *et al*., 2000). Also *Phaseolus vulgaris* L. germination reduction has been recorded up to 48% on the treatment of high-concentration (500 ppm) of Chromium (VI) in soil medium (Taylor and Parr, 1982).

According to Jain *et al.,* (2000), at the treatment of 20 and 80 ppm of Chromium Sugarcane bud germination has been reduced up to 32 to 57%, respectively. Further, in 2001 Peralta *et al*. stated that germination of Lucerne (*Medicago sativa*) has also been decreased to 23% at 40 ppm chromium (VI) application. Zeid, in the year 2001, concluded that the reason behind this either can be a suppressive influence of Cr on the Amylase or, enhancement in Protease activity, or sugar transport to the axes of the embryo.

Effects of heavy metals on roots and shoots:

When comparing the aggregation of metals in roots and shoots, it was reported that roots acquire more metals than shoots since they are the first organs of plants to come into touch with heavy metals present in soil and water (Rout *et al*., 2001). To do it, the first observable toxicity shown by heavy metals is the suppression of root elongation or a reduction in cell elongation (Fiskesjo 1997).

Effects on plant growth:

Heavy metal toxicity negatively influences plant's overall growth (Rout *et al*., 1997). The control of fewer nutrients, lower root growth and water transfer to plant aerial portions may all contribute to slowed plant growth. Chromium transport to the plant's aerial portions could have the quickest impact on the cell's physiological mechanism of shoots, which can lead to constriction in plant aerial growth (Shanker *et al*., 2005).

Effects on leaf:

According to Shanker *et al*., (2005), healthy growth of leaf, area development and total number of leaf all contributed to crop output. However, heavy metals like cadmium and chromium have a remarkable effect on the morphology of plants, including yellowing, drying and necrotic symptoms on younger leaves. The senescence and drooping of the leaves of *Datura innoxia* plants are hazardous indications of a chromium-contaminated environment, according to Vernay *et al*., in 2008. None of these symptoms, however, have manifested in media containing too much chromium (III). Chromium (VI) levels of 200 ppm have had a significant destructive effect on the leaf area and total fresh and dry biomass production of *Albizzia lebbek* seedlings (Sharma, 1995). These scientists have employed high Chromium (VI) concentrations in the leaf development features as biological indicators of heavy element contamination and in the identification of unsusceptible species.

Effects on plant's dry biomass:

Plant biomass serves as a measure of agricultural procreation in terms of dry biomass. According to Bishnoi and his colleagues (1993), the photosynthetic process, which is regarded as 80 to 90% of a plant's total dry matter, is the foundation for the production of organic molecules. On the one hand, the production of biomass in the *Bacopa monnieri* plant is decreased by heavy metals like Cr and C) (Tokalioglu and Kartal, 2006). On the other hand, fragmentation increases in *Azolla* species due to varying content of chromium. When compared with the normal plants, the plants treated with high Chromium concentrations showed necrosis and overall biomass decreased.

Water relations

Water affects all growth processes in all living beings, especially plants and plays a major role in plant growth regulation (Kramer and Boyer, 1995). Soil polluted with heavy metals has poor physiological properties and shallow root system and plants grown in that soil usually go through water scarcity. A major trait in remediation by plants of soil polluted through heavy metals could be considered as a selection of drought-tolerant species. Heavy metal toxicity can cause many disorders, which lead to a reduction in the number and size of leaves, decreased water loss, stomata size, disturbance in xylem vessels, increased leaf rolling and abscission, high roots suberization and enhanced stomata resistance (Barcelo and Poschenrieder, 1990), (Table-1). Heavy metals are thought to be able to affect root hydraulic conductivity through a variety of mechanisms that act on the apoplastic or symplastic pathway. As a result, even at low concentrations in the growing medium, a decreased cell

Table 1: Effects of heavy metals toxicity on various plants species

Heavy metals	*Plants*	*Adverse effects*	*References*
Arsenic (As)	Paddy	Reduces seed germination, sapling height, area of leaves and dry matter	Marin and Pezeshki, (1993)
	Tomato	Decrease in fruit and fresh leaves	Barrachina *et al.*, (1995)
	Canola	elongation retardation, yellowing and drooping	Cox *et al.*, (1996)
	Chickpea	Overall growth retardation	Tu *et al.*, (2004); Shrivastava *et al.*, (2005); Tu and Ma, (2003)
	Maize	Translocation to shoot inhibition and disruption of photosynthesis apparatus	Baker and Rosenqvist, (2004)
Cadmium (Cd)	*Silene vulgaris*	Retards reductase activity of nitrate, transport mechanisms reduction and photosynthetic activity	Mathys *et al.*, (1975)
	Oil seed rape	Reduce aerial growth and total biomass production	Li *et al.*, (2009)
	Garlic	Shoot length reduction	Jiang *et al.*, (2007)
	Maize	Growth retardation	
Lead (Pb)	Rice	Affects roots more than shoots, seed vigour, chlorophyll (chl.), nitrogen (N) and protein, total biomass	Kibria *et al.*, (2010)
Chromium (Cr)	Tomato	Decrease plant nutrients	Shanker *et al.*, (2003)
	Onion	Germination inhibition and reduce plant biomass production	Zhao *et al.*, (2020)
Zinc (Zn)	Ryegrass	Reduction of epigeal growth and inhibition of hypogeal growth	Bonnet and Veisseire, (2000)
	Gaur	Reduces germination and chlorophyll content, Carotenoids content, sugar, amino acids and extension in cluster beans	Manivasagaperumal *et al.*, (2011)
Mercury (Hg)	Rice	Growth reduction and also reduces tiller and panicle formation and yield reduction too	Kibria, (2009)
	Tomato	Germination and flowering reduction, biomass reduction and chlorosis	Shanker *et al.*, (2011)
Cobalt (Co)	Radish	Reduce total volume of leaf surface area, epigeal and hypogeal and chlorophyll content	Jaya kumar *et al.*, (2008)

expansion can take place without compromising the integrity of the cell.

Withdrawal of heavy elements by plants

Heavy metal's concentration in the atmosphere has been increasing day by day (Govindasamy *et al*., 2011). A 700 km^2 area in the Netherlands known as the 'Combine region' was poisoned due to the build-up of cadmium, lead and zinc (Meers *et al*., 2010). About 46,700 hectare area of China has been destroyed annually due to the activities of mining. There is no vegetation on that land due to serious contamination and degradation of soil as well as off site contamination (Xia 2011). To minimize the effect of these metals, it's very important to reclamate heavy metals used to found in contaminated areas of land; however, there are few obstacles, such as expense and difficult technical requirements (Barcelo *et al*., 2003).

Therefore, many chemical, physical and biological methods are required to achieve the aim of heavy metal reclamation from soil. Different conventional methods like *in-situ* vitrification, incineration of soil, landfill, solidification and washing off soil have been used since ancient times (Wuana *et al.,* 2011; Sheoran *et al*., 2011). Chemical and physical methods have some limitations like high expenditure, more manpower, disruption of soil micro-flora, an also variation in soil properties. Chemical remediation ways cause the formation of secondary pollutants. Therefore, reclamation of soil contaminants should be done in that way, which is not very costly and easy to perform and there should be no harm to the natural resources or nature.

Phytoremediation process:

Phytoremediation comprises two words: 'Phyto' means 'plant' and 'medium' means' removal of evil' comes from Greek and Latin, respectively. Plants use different mechanisms to reclamate the contaminants from soil. Over the past two decades of research and study, phytoremediation has emerged as a cutting-edge technology. It was first proposed by Chaney (1984) and is now widely acknowledged as a good option by a group of scientists. Phytoremediation is the method for the alleviation of heavy element toxicity from soils without spending too much money and also easy to perform comparatively to other methods (Arbisu and Alkorta, 2003).

Phytoremediation is a biochemical activity by which the flora and microorganisms of soil, related to those plants are used for the detoxification of soil from contaminants (Greipsson 2011). By using this technique, many contaminants such as organic contaminants such as (pesticides, polynuclear, biphenyls and hydrocarbons) and heavy metals could be reduced. This is known to eliminate the toxicity of heavy metals from soil using plant and green substitute solutions (Vithanage *et al*., 2012; Kalve *et al*., 2011). Elimination of contamination from soil medium by the Phytoremediation process keeps the soil and topsoil fertility the same. It never harms the soil fertility (Mench *et al*., 2009). (Fig. 3).

Van Aken, in the year 2009, stated that Phytoremediation methods can be started even at a low cost comparatively and is 5% cheaper than other methods (Prasad, 2003). Vegetation grown in contaminated soil also helps in alleviation of heavy metals and it reduces soil erosion (Pathak *et al*., 1998). Plants that have higher biomass, like Jatropha, willow, poplar and other fast-growing plants, are used for energy generation and act like Phytosanitary (Abhilash *et al*., 2012). Today, plant-based management has been widely accepted as "green clean" as an alternative process by using chemical based procedures (Pilon Smits 2005).

Phytoremediation techniques:

Various methods (steps) are being used to reclaim heavy metal toxicity from polluted soil-

Phytoextraction

This process usually comprises the collection and retention of impurities above ground in plant tissues, such as root and shoots. A sustainable remediation method, phytoextraction extracts heavy metals from contaminated soils by using plants as a tool. Its expanding potential is highlighted by recent studies, especially with plants that exhibit strong cadmium translocation and accumulation capacities, such as *Elsholtzia splendens* and *Sedum plumbizincicola*. In contaminated soils, these plants work well, especially when supplemented with soil additives such as chelating agents to boost bioavailability (Ali *et al*., 2013). Plant species, soil types and degree of contamination are major factors that influence Phytoextraction. To improve the procedure, innovations like genetic engineering and biochar are being studied. Large tracts of contaminated land can be remedied economically and environmentally by phytoextraction, especially in developing nations where soil contamination is a major problem (Wei *et al*., 2023; Zhang *et al*., 2023).

Phytofilteration

Plants and other rhizospheric organisms are used to alleviate pollutants from water in a competitive and sustainable approach. Through their root systems, plants absorb cadmium, which either binds to pectin or other components of their cell walls or is sequestered intracellularly by chelating molecules. Because of their high tolerance and quick growth rates, aquatic plants like *Lemna minor* (duckweed) and *Eichhornia crassipes* (water hyacinth) are especially good at removing cadmium. According to studies, plants exposed to cadmium experience oxidative stress, which causes an increase in the activity of antioxidant enzymes to lessen toxicity (Alsafran *et al*., 2022; Zayed *et al*., 2023). Moreover, two main forms of chromium are Cr (III), which is less poisonous and mobile and Cr (VI), which is extremely soluble and toxic. *Typha latifolia* (cattail) reduces Cr (VI) to Cr (III) by enzymatic action. Furthermore, Chromium bioavailability in the water column is decreased by its adsorption onto the root surface and subsequent transfer into plant biomass (Ahmed *et al*., 2023).

Phytostabilization

Contaminants, including metals, are absorbed and precipitated by plants and they cease their motility and restrict them from migrating to water (groundwater), and air and entering into the food chain of an ecosystem. A phytoremediation method called Phytostabilization uses plants to immobilize environmental contaminants, especially heavy metals like chromium (Cr) and cadmium (Cd). In contrast to other techniques, such as phytoextraction, which eliminates pollutants from the soil, Phytostabilization aims to reduce the pollutant's mobility and bioavailability, frequently by binding or precipitating metals in the soil. Metals can be absorbed by plant roots, which reduces their bioavailability. Metal ions attach to organic molecules and soil particles in the rhizosphere or on the surfaces of roots, where this adsorption frequently takes place (Huang *et al*., 2024). Metals can precipitate in less mobile, less poisonous forms when certain plants change the pH and redox potential of the soil (Rao *et al*., 2024). For instance, plant root activity can convert chromium (Cr), particularly in its poisonous hexavalent form (Cr(VI)), to the less mobile trivalent form (Cr(III)), greatly minimizing its environmental impact (Shahid *et al*., 2017). The structure of plant roots stabilizes the soil and stops water and wind from eroding or leaching metal-laden particles (Bardos *et al*., 2021).

Phytovolatilization

In essence, it is the process of accumulating contaminants by roots and, converting them into gaseous form and then releasing them into the environment and evapotranspiration is the engine behind it. Cadmium usually builds up in the roots of plants and is carried to the shoots, where it may be volatilized. Although the process is not as strong as it is for metals like mercury, recent research has indicated that certain plants may be able to volatilize cadmium. Cadmium volatilization in plants is comparatively modest, however, some species, including *Salix* (willows), have demonstrated the ability to increase this heavy metal's volatilization when cultivated in contaminated soils (Liu *et al*., 2022).

Compared to other metals, the volatilization of chromium and, particularly Cr(VI), has received less attention. However, Khan *et al*., (2023) stated that certain plants may volatilize chromium under particular circumstances, particularly when exposed to microbial interactions that promote the conversion of Cr(III) into gaseous forms. It has been demonstrated that plants like *Brassica juncea* (Indian mustard) and *Triticum aestivum* L. (wheat) reduced the toxicity of chromium and may even volatilize it as Cr(VI) is transformed into its gaseous forms (Wang *et al*., 2022). The field of phytovolatilization of cadmium and chromium is still in its infancy, but there is increasing interest in learning how plants might reduce heavy metal contamination by volatilizing hazardous components, even if the process is not as commonly observed for these metals as it is for mercury. The effectiveness of phytovolatilization, like other phytoremediation methods, is contingent on a number of variables, including plant species, soil composition and the existence of particular microbial communities that might promote the volatilization of toxic metals. Additionally, recent research suggests that microbial support and genetic engineering may be used to improve phytovolatilization. The efficiency of phytovolatilization in metal-contaminated soils can be increased by adding specific microbial strains to the rhizosphere, which can help convert heavy metals into volatile forms (Ghosh *et al*., 2023).

Phytodegradation

Organic contaminants are broken down directly by enzymes released from the roots or by metabolic processes occurring within plant tissues. Certain types of plants can lessen the toxicity of cadmium through biochemical processes, even though they do not immediately break it down into less harmful forms like they do organic contaminants. For instance, it is known that *Salix* (willows) and *Brassica juncea* L. (Indian mustard) can withstand elevated cadmium levels by either storing it in their roots or changing it into less bioavailable forms (Zhao *et al.*, 2021). By reducing the mobility and bioavailability of cadmium by enzymatic reactions, such as the conversion of Cd(II) to less soluble forms, the plant can effectively restrict its toxicity in the environment. These mechanisms could be considered a type of phytodegradation (Mokhayeri *et al.*, 2023).

Certain plants may increase microbial activity in the rhizosphere, which further breaks down or sequesters cadmium through microbial interactions, in addition to decreasing its bio-availability (Bai *et al.*, 2023). The "degradation" of cadmium in a more general sense can be facilitated by the microbial communities in the root zone, which can be crucial in changing it into less hazardous or immobilized forms. It has been demonstrated that plants such as *Helianthus annuus* (sunflower) and *Triticum aestivum* L. (wheat) may convert Cr(VI) to Cr(III) in their roots, greatly reducing the risk of chromium toxicity (Raza *et al.*, 2022). In certain instances, plants also store Cr(III) in their roots, which stops it from entering the food chain and lessens its overall effect on the ecosystem (Jiang *et al.*, 2022). Given its capacity to change the metal into a less hazardous state, this reduction and sequestration process is seen as an efficient way to mitigate chromium contamination in soils and is an example of phytodegradation.

Rhizodegradation

Phyto-stimulating, rhizospheric biodegradation, or plant-based reclamation or degradation, is a process of improving the biodegradation of a contaminant using plants to increase the bioactivity of the rhizosphere, thereby stimulating the microbial populations in the vicinity of heavy metals. Exudates from plant roots, such as organic acids, sugars and amino acids, are released into the soil. These exudates have the ability to activate microbial populations that can break down organic contaminants in the rhizosphere, the area of soil that surrounds plant roots. By changing the chemical structure of pollutants, certain exudates also directly aid in their degradation (Ghosh *et al.*, 2022). For Rhizodegradation to occur, the rhizosphere microbes are essential. They can metabolize the pollutants, converting them into less hazardous molecules or fully mineralizing them into non-toxic by-products like carbon dioxide, water and inorganic minerals. They are drawn to the root exudates. Actinomycetes, fungi and bacteria are examples of these microorganisms (Singh *et al.*, 2022).

Enhancing microbial processes that can either immobilize or decrease the mobility of the metal in the soil is known as Rhizodegradation of cadmium. Some plants, including Indian mustard (*Brassica juncea*), can increase rhizosphere microbial activity, which encourages cadmium to change into less harmful forms (Zhao *et al.*, 2021). Cadmium can interact with microorganisms that break down organic contaminants in the rhizosphere, decreasing its bioavailability and decreasing the likelihood that it will leak into groundwater (Bai *et al.*, 2023). Rhizodegradation can be thought of as the conversion of Cr(VI) to Cr(III) in the rhizosphere. While this process is not degradation in the strict sense, the transformation of chromium from a toxic, mobile form to a less toxic, immobile form reduces its environmental impact. Plants like *Helianthus annuus* L. and *Triticum aestivum* L. can enhance the microbial processes in the rhizosphere that reduce Cr(VI) to Cr(III), thus mitigating the contaminant's mobility and toxicity (Raza *et al.*, 2022).

Phytodesalination

Sodium hyperaccretion halophyte is the biological method of recovering salt soil. It is primarily based on the fact that these species have the ability to secrete sodium ions into their shoots

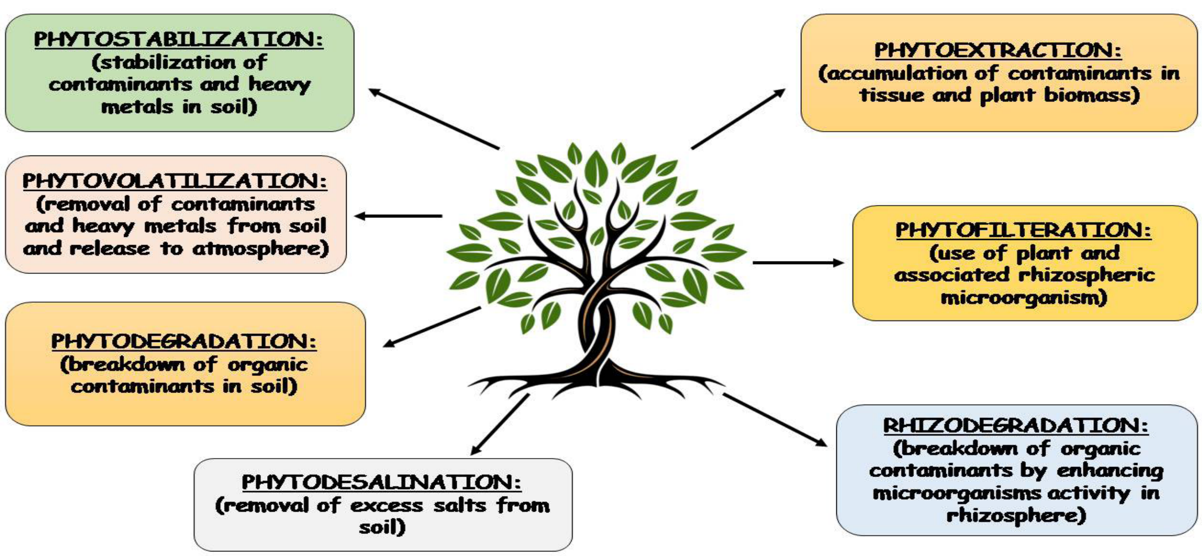

Fig. 3: Various phytoremediation techniques

through the formation of salt glands, similar to Rhizophora. Because of their capacity to absorb, store, or expel salts, the plants-especially halophytes, are suited for settings where excessive salinity levels are an issue. By efficiently storing salts in their tissues, halophytes like *Salicornia* and *Atriplex* species reduce the amount of salt present in the nearby soil or water. Additionally, several plants have specific glands on their leaves that can release extra salt straight into the atmosphere. Restoring agricultural potential and biodiversity in saline regions is made possible by this excretion mechanism, which lowers the overall salt content of the environment (Hasegawa *et al*., 2000; Greenway and Munns, 2015).

Plants absorb saline water through their roots and as water vapor is expelled into the atmosphere through their leaves, the salts stay in their tissues. The salinity of the surrounding environment is progressively decreased by this process (Santos *et al*., 2014). The main use of Phytodesalination is to reclaim soil impacted by salinization major issue in arid and semi-arid regions. Additionally, it can be used to treat saline wastewater, particularly in regions where increased salinity has been brought on by agricultural or industrial runoff. In this sense, constructed wetlands containing salt-tolerant plants have demonstrated success; the plants lower the salinity of water by absorbing salt from it, making it safer to discharge or reuse (López *et al*., 2020). Moreover, Phytodesalination may be used to restore coastal ecosystems (Vasudevan and Srinivasan, 2018).

Large-scale Phytodesalination is facing numerous obstacles. Plants frequently absorb salty water but accumulate salt slowly and they may not be able to withstand very high salinities. Different plants have different degrees of tolerance to salt, so selecting the right species is also essential. To find the best plants for certain saline settings, a great deal of research is required because of the restrictions on species adaptability (Hasegawa *et al*., 2000; Santos *et al*., 2014). Notwithstanding these difficulties, Phytodesalination is still a viable and affordable substitute for conventional desalination techniques like reverse osmosis. Phytodesalination has great potential to lessen the adverse impacts of salinity on the environment and agriculture with more study and improvement of plant species and methods.

Conclusion

In conclusion, various heavy elements such as zinc (Zn), copper (Cu), and magnesium (Mg) play a crucial role in the proper functioning of plants, both biologically and physiologically. These elements are essential for processes like amino acid, protein, and nucleic acid biosynthesis, as well as the synthesis of other secondary metabolites. However, certain heavy metals become toxic when their concentrations exceed permissible limits. The extent of toxicity depends on the type of metal and the plant species, as the tolerance levels vary from plant to plant and metal to metal. Some plants exhibit minimal harm even at high concentrations, while others show adverse effects at relatively low levels.

Excessive exposure to heavy metals disrupts fundamental plant mechanisms, including carbon dioxide fixation and the electron transport chain (ETS), leading to impaired growth and the production of harmful free radicals known as reactive oxygen species (ROS). The visible symptoms of heavy metal stress include stunting, wilting, chlorosis, and reduced biomass. Additional effects include a decline in stomatal size, leaf rolling, and increased root suberization.

To cope with stress, plants activate complex defense mechanisms involving the perception and transmission of stress signals, followed by metabolic adjustments. Enzymatic and non-enzymatic proteins, such as catalase, peroxidase, ascorbate peroxidase (APx), and superoxide dismutase (SOD), play a vital role in mitigating heavy metal stress by neutralizing ROS. Heavy metal contamination is a significant abiotic stressor, contributing to environmental pollution and reducing crop biomass. Excessive accumulation of these elements can result in oxidative bursts, which are toxic to plants.

Traditional methods for mitigating heavy metal contamination in soils and polluted areas include techniques such as soil pyrolysis, in situ stabilization, landfilling, soil washing, and soil solidification. Looking ahead, phytoremediation offers a promising and cost-effective solution for reducing heavy metal toxicity in the soil. This approach leverages hyperaccumulator plants and microorganisms to detoxify contaminated environments. Phytoremediation, combined with traditional knowledge of heavy metal removal, is not only eco-friendly but also sustainable for long-term environmental restoration.

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Contribution of Authors

The corresponding author is working in the area of Plant Nutrition and Stress Physiology of Plants, with an experience of about 16 years and published many research and review articles which are oriented towards plant nutrition and plant stress. Miss Swati Singh, Miss Afreen Naaz and Mr. Rahul Verma are pursuing their Ph.D. degree under the guidance of the corresponding author from the Department of Botany, University of Lucknow, Lucknow, (U.P.), India and their areas of thrust are also related to the plant nutrition and plant stress physiology.

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