Journal of Plant Growth Regulation (2023) 42:3419–3440
https://doi.org/10.1007/s00344-022-10803-1

Principles and Applicability of Integrated Remediation Strategies for Heavy Metal Removal/Recovery from Contaminated Environments

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Received: 17 April 2022 / Accepted: 10 September 2022 / Published online: 21 September 2022

Abstract

Contamination of agricultural soils with heavy metals present lethal consequences in terms of diverse ecological and environmental problems that entail entry of metal in food chain, soil deterioration, plant growth suppression, yield reduction and alteration in microbial community. Metal polluted soils have become a major concern for scientists around the globe. In more recent times, armed with new knowledge and understanding, removal of heavy metals using different applications has emerged as a solution for waste treatment and contaminant remediation in water and soil. However, the description of metal toxicity to the plants and its removal and degradation from the soil is limited. There are a number of reports in the literature where PGP bacterial inoculation and various chelating agents improves metal accumulation and it's detoxification in different plant parts without influencing plant growth. Therefore, there is a need to select some useful chemicals which possess the potential to improve plant growth as well as expedite the phytoremediation of metals. In this review, we have discussed the mechanisms possessed by different chelating agents to promote plant growth and phytoremediation of metals. We anticipate that this analysis of interconnected systems will lead to the discovery of new research fields.

Keywords Heavy metals · In situ · Soil remediation · Synergistic approach · Integrated remediation · Cost-effectiveness

Introduction

Most heavy metals are produced by pollution and their presence causes many ecological, evolutionary, and nutritional problems. Many risks are created due to heavy metal contamination, like soil pollution as well as security of food and its quality (Christophoridis et al. 2020; Zaheer et al. 2022). Heavy metals cause many harmful effects for living things, including plants. They decrease the growth and development of plants even at low concentrations of heavy metals with respect to other metals (Kamran et al. 2019; Kour et al. 2021; Muhammad et al. 2009). Excess amounts of other metals or elements do not damage the tissues/cells of the plant, and their accumulation can even increase the growth of the plant (Ahmad et al. 2022, Ali and Chaudhury 2016). The metals which are lethal or harmful for plants include: lead (Pb), cadmium (Cd), cobalt (Co), iron (Fe), silver (Ag), platinum (Pt), nickel (Ni), chromium (Cr), copper (Cu), and zinc (Zn) (Chen and Lu 2018; Pescatore et al. 2022). Agricultural soil is befouled by many heavy metals, which is a

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Handling Editor: Saddam Hussain.

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major issue. Many anthropogenic activities effect soil and the effectiveness of the plant, like urbanization, smelting, sludge, military operations, mining, dumping, and excess amounts of pesticide and insecticide applications (Chowdhary et al. 2018; Rehman et al. 2020; Saleem et al. 2020e; Shahid et al. 2015). These activities inhibit the growth of the plants and cause many toxic symptoms in the plants due to heavy metal contamination, and these metals destroy human health by entering into the food chain (AFZAL et al. 2021; Gill et al. 2021; Saleem et al. 2020i). However, the metal contaminants are useful in fertilization as well as in pesticides, fungicides, and nematicides for the better production and development of the plant. These applications are a major source for the growth of the plants. Metal deposition in soil is produced due to biomass and an increase in plant growth (Alsafran et al. 2021; Hassan et al. 2021; Sufyan et al. 2021). The chemical composition, plant type and their species, and the pH of heavy metals all impact the phytotoxicity of the heavy metals in the plants (Al Jabri et al. 2022, Saleem et al. 2022d). A large amount of reacting oxygen species and oxidative stress are involved through direct and indirect toxicity of heavy metals and produced in the following ways: (a) reduction of electrons, (b) the irregular management of metabolic pathways, (c) the activities of anti-oxidative enzymes are reduced, and (d) depletion of lower molecular weight compounds (Ali et al. 2013; Farid et al. 2019; Zaheer et al. 2015). Crop yield and productivity can be improved and the health risk decreased acutely by removing the harmful effects of these heavy metals (Ahmad et al. 2022; Ehsan et al. 2014; Najeeb et al. 2009; Rehman et al. 2016).

Heavy metals are natural components of the terrestrial ecosystem. However, their presence in excess is harmful to humans and the environment (Farid et al. 2019; Saleem et al. 2020h). Therefore, remediation is necessary to alleviate the negative effects caused by the heavy metals incorporated to ecosystems (Mahar et al. 2016; Saini et al. 2021). Research has been continuing to develop effective methods of remediation to treat contaminated lands (Madhu and Sadagopan 2020; Saleem et al. 2020d; Tela et al. 2012). Remediation could be done by immobilization, removal, sequestration, active mixing, and phytoextraction (Hashmat et al. 2021; Kamran et al. 2020; Murtaza et al. 2021; Saleem et al. 2020l, 2021; Zaheer et al. 2020b). However, selection and applicability of the remediation methods depend on a number of factors including cost, duration of effectiveness, commercial level availability, general acceptance, applicability to high metal contents, and applicability to mixed metal and organic wastes as well as toxicity, mobility, and volume reduction (Abbar et al. 2017; Aziz et al. 2021; Tariq et al. 2021; Zhang et al. 2013). Heavy metal toxicity can be minimized by reducing their availability using organic and inorganic amendments (Al Jabri et al. 2022; Alam et al. 2022; Lone et al. 2022; Mahar et al. 2016; Saleem et al. 2020a, c, 2022c). Keeping in view the excessive release of heavy metals into environment and its toxic effects especially on plants, in this review, we aimed to discuss heavy metal sources, essentiality, bioaccumulation, homeostasis and possible methods to remediate it from the soil and also the context of their responses toward both heavy metal deficient and toxic soil conditions and to identify remediation measures with future directions for research.

Sources of Heavy Metals in the Soil

Heavy metals are significant environmental pollutants, and their toxicity is a problem of increasing significance for ecological, evolutionary, nutritional, and environmental reasons. The term ‘‘heavy metals’’ refers to any metallic element that has a relatively high density and is toxic or poisonous even at low concentration (Nagajyoti et al. 2010). ‘‘Heavy metals’’ in a general collective term, which applies to the group of metals and metalloids with atomic density greater than 4 g cm^{-3}, or 5 times or more, greater than water (Riaz et al. 2020; Saini et al. 2021). All these factors not only reduce plant growth but also make the environment more vulnerable to the threat of plant population survival. In plants, metal stress disturbs the plant metabolism and decreases plant growth by reducing essential macro and micronutrient uptake (Ubando et al. 2020; Vardhan et al. 2019). In recent years, there has been an increasing ecological and global public health concern associated with environmental contamination by these metals. Also, human exposure has risen dramatically as a result of an exponential increase of their use in several industrial, agricultural, domestic, and technological applications (Cristaldi et al. 2017; Tangahu et al. 2011). Reported sources of heavy metals in the environment include geogenic, industrial, agricultural, pharmaceutical, domestic effluents, and atmospheric sources (Cristaldi et al. 2017; Hasanpour and Hatami 2020). Additionally, sources of heavy metals include mining, industrial production (foundries, smelters, oil refineries, petrochemical plants, pesticide production, chemical industry), untreated sewage sludge and diffuse sources such as metal piping, traffic, and combustion by-products from coal-burning power stations (Laghlimi et al. 2015; Saleem et al. 2020b; Zaheer et al. 2020a). Environmental pollution is very prominent in point source areas such as mining, foundries, and smelters, and other metal-based industrial operations (Nagajyoti et al. 2010; Shahid et al. 2020; Vardhan et al. 2019).

Although heavy metals are naturally occurring elements that are found throughout the earth’s crust, most environmental contamination and human exposure result from anthropogenic activities such as mining and smelting operations, industrial production and use, and domestic and agricultural use of metals and metal-containing compounds (Grčman et al. 2001; Griga et al. 2003; Wan et al. 2016). Environmental contamination can also occur through metal corrosion, atmospheric deposition, soil erosion of metal ions, and leaching of heavy metals, sediment re-suspension and metal evaporation from water resources to soil and ground water (Evangelou et al. 2007; Wuana and Okieimen 2011). Natural phenomena such as weathering and volcanic eruptions have also been reported to significantly contribute to heavy metal pollution (Sun et al. 2014; Zhu et al. 2020). Industrial sources include metal processing in refineries, coal burning in power plants, petroleum combustion, nuclear power stations and high tension lines, plastics, textiles, microelectronics, wood preservation, and paper processing plants (Şenkal et al. 2019; Wan et al. 2016). Heavy metals are also considered as trace elements because of their presence in trace concentrations (ppb range to less than 10 ppm) in various environmental matrices (Soliman and Moustafa 2020; Vardhan et al. 2019). Their bioavailability is influenced by physical factors such as temperature, phase association, adsorption, and sequestration. It is also affected by chemical factors that influence speciation at thermodynamic equilibrium, complexation kinetics, lipid solubility, and octanol/water partition coefficients (Shahzad et al. 2018). Biological factors such as species characteristics, trophic interactions, and biochemical/physiological adaptation, also play an important role (Riaz et al. 2020). Heavy metal-induced toxicity and carcinogenicity involves many mechanistic aspects, some of which are not clearly elucidated or understood. However, each metal is known to have unique features and physic-chemical properties that confer to its specific toxicological mechanisms of action. Sources of different heavy metals in the environment and their toxic effects to the plants are presented in Fig. 1.

In biological systems, heavy metals have been reported to affect cellular organelles and components such as cell membrane, mitochondrial, lysosome, endoplasmic reticulum, nuclei, and some enzymes involved in metabolism, detoxification, and damage repair (Rana et al. 2020; Saleem et al. 2020f). A reliable strategy and stable treatment systems are urgently needed to address the issue of increasing heavy metals contaminated by domestic and industrial processes due to the expanding human population. Indeed, many countries do not have adequate water resources to sustain their agricultural needs. To ensure agricultural productivity, inadequately treated with metal polluted sources are extensively applied to food crops; however, the quality and safety of food crops grown in soils irrigated with poorly treated reclaimed water cannot be guaranteed (Vardhan et al. 2019; Wang et al. 2020).

Fertilizers as a Source of Heavy Metals

Soil contamination with heavy metals is becoming a worldwide threat due to its adverse impacts on environmental safety (Saleem et al. 2020g; Zhang et al. 2013). Anthropogenic activities especially application of agrochemicals are the major sources of heavy metals accumulation in soil (Antonkiewicz et al. 2018; Ashraf et al. 2017; Tombarkiewicz et al. 2022; Yang et al. 2018). The inorganic and organic fertilizers (Fertilizer is a substance

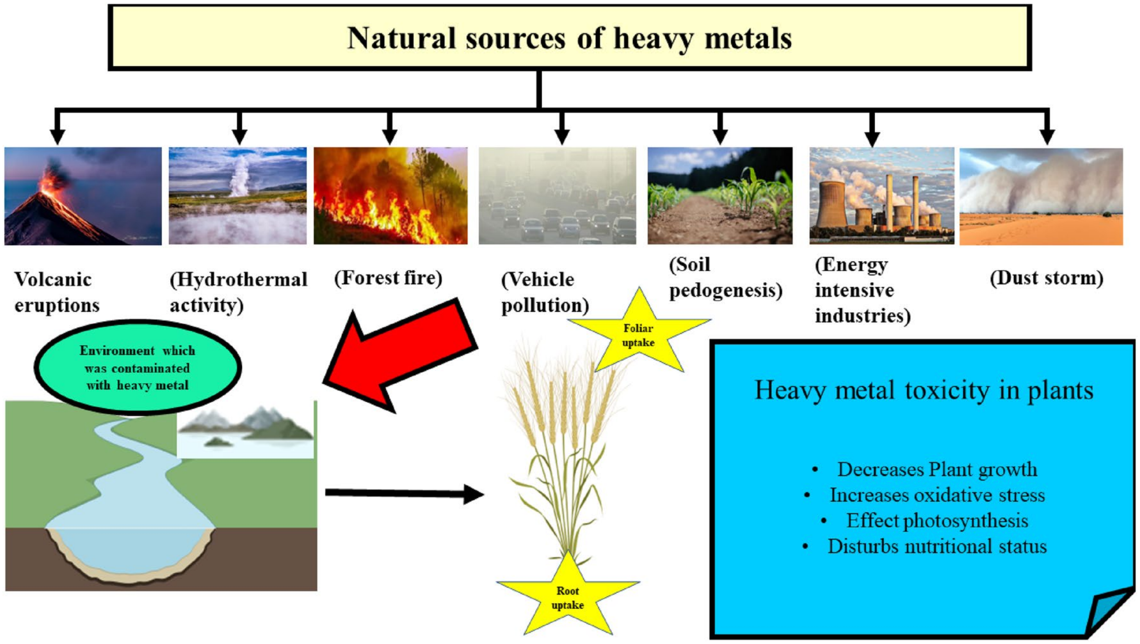


Fig. 1 Natural and anthropogenic sources of heavy metal contamination in food crops and imposing a toxic effect to the plants

added to soil to improve plants growth and yield) are the most important sources of heavy metals to agricultural soil include liming, sewage sludge, irrigation waters, and pesticides, sources of heavy metals in the agricultural soils (Kour et al. 2021; Wan et al. 2016). Others, particularly fungicides, inorganic fertilizers, and phosphate fertilizers have variable levels of Cd, Cr, Ni, Pb, and Zn depending on their sources. Soil is one of the key resources that are being polluted with excess of Cu and is derived from parental rocks and anthropogenic activities. The potential industrial and agricultural sources for Cu includes batteries, pigments and paints, alloys, fuel, catalysts, fertilizers, and pesticides (Rehman et al. 2019b; Saleem et al. 2019, 2020j). Cd is of particular concern in plants since it accumulates in leaves at very high levels, which may be consumed by animals or human being. Cd enrichment also occurs due to the application of sewage sludge, manure, and limes (Afzal et al. 2020; Alatawi et al. 2022a; Heile et al. 2021; Imran et al. 2020, 2021; Javed et al. 2020; Saleem et al. 2022b). Because some of the compounds used to provide these elements contain tiny quantities of heavy metals (such as Cd and Pb) as impurities i.e., their concentration in the soil rises dramatically with repeated fertilizer applications (Yang et al. 2018). Fertilizers provide a variety of essential nutrients to plants to promote growth and productivity while also increasing soil organic matter. Anaerobic digestion (AD) produces organic or biofertilizers, which are in the form of ammonium fertilizers (sulfate and nitrate) following the fermentation process (Zhang et al. 2013). Chemically manufactured/synthetic fertilizers, often known as inorganic fertilizers, blend inorganic and chemical ingredients (Yang et al. 2011).

Higher quantities of As, Cd, and Pb were found in various phosphate and micronutrient fertilizers and other materials (e.g., nitrogen, potash, gypsum) (Ahmad et al. 2022). A few waste-derived fertilizer products have also been discovered to contain high levels of dioxins (measured in parts per trillion) in their composition (Abubakari et al. 2017). Phosphorus is widely used in fertilizer production; nevertheless, its widespread use contributes significantly to the accumulation of heavy metals in soil (Alam et al. 2022; Alatawi et al. 2022b; Sarwar et al. 2022; Ullah et al. 2022). It has been demonstrated that water-insoluble phosphorus fertilizers cause the formation of Phosphate rocks, which play a key role in the immobilization of metals in soils via metal phosphate precipitation (Saleem et al. 2022a). Long-term misuse of fertilizers, which results in a heavy metal deposition in agricultural soils, impacts soil fertility, plant development, and production while also boosting fertility (Griga et al. 2003). The most frequent forms of inorganic fertilizers include phosphate fertilizers, liming materials, and bio-fertilizers, which lead to the buildup of heavy metals in soils, which are subsequently ingested by plants (Shahzad et al. 2018).

The Use of Pesticides as a Source of Heavy Metals

Pesticides are used worldwide in agriculture, industry, public health, and for domestic applications: as a consequence, a great part of the population may be exposed to these compounds. In spite of this extensive use, knowledge on the health risks associated with prolonged exposure is rather poor, and major uncertainties still exist (Antle and Pingali 1994; Husak 2015). Epidemiological observations in man have so far produced little conclusive information, mainly because of weaknesses in exposure assessment (Chhipa 2017). Several common pesticides that were historically widely used in agriculture and horticulture contains high concentration of metals in it (Tariq et al. 2007). For example, nearly 10% of the insecticides and fungicides permitted in the United Kingdom in the recent past were based on compounds containing Cd, Cr, Ni, Pb, and Zn depending on their sources. Although the levels of heavy metals in agricultural soil are very small, but repeated use of phosphate fertilizer and the long persistence, time for metals, there may be dangerously high accumulation of some metals (Raj et al. 2021). For example, Cu-containing fungicidal sprays like Bordeaux combination ($CuSO_4$) and Cu-oxychloride are employed to limit fungus infection which inhibit the plant growth (Hussain et al. 2022; Rehman et al. 2019b). Contamination might be an issue, especially if the sites are refurbished for other agricultural or non-agricultural activities. According to (Zubrod et al. 2019), the world population increases to approximately 97 million people each year. Around 50,000 plant pathogen species, 9000 insect and mite species, and 8000 weed species cause agricultural loss worldwide, with most of the damage happening in the United States (Ali et al. 2022b). Plant infections are estimated to have caused a 13% loss in agricultural production, insect pests a 14% loss in crop production, and weeds a 13% loss in crop production. According to prediction research, pesticides are estimated to safeguard approximately one-third of agricultural products worldwide (Benelli et al. 2018). Pesticides are toxic compounds or mixtures of harmful substances that are naturally occurring or chemically produced. These are frequently used in the agricultural area to control weeds (herbicides), fungi (fungicides), bacteria (bactericides), and insect infestations (insecticides) that are hazardous to the crops and the environment (Naha et al. 2020). These can also be employed against some disease carriers and pests (e.g., ticks, rodents, mosquitoes, and lice), which can be used throughout the ecosystem to combat disease (Kamal et al. 2022). Agricultural regions utilize many pesticides, accounting for over 85% of worldwide pesticide production. In wet areas (carpets, freezers, cabinets), these can also help reduce and prevent insect infestation breakouts, fungus, and germs (Hayles et al. 2017).

Biosolids and Manures as a Source of Heavy Metals

The application of biosolids to agricultural soils can be a beneficial agricultural practice as it provides essential nutrients and organic matter that can help to improve soil properties (Mohajerani and Karabatak 2020). Biosolids can provide a waste management route for sewage sludge; however, biosolids are also considered a sink for industrial and domestic chemicals that become sequestered in solids during wastewater treatment (Spinosa and Vesilind 2001). The presence of detectable concentrations of dioxins and pharmaceuticals in biosolids has been well documented (Clarke and Cummins 2015), and has led to concerns that land applications may result in the accumulation of dioxins and a series of emerging pollutants in soil with subsequent translocation through the human food chain (Girovich 1996). While the environmental occurrence of these contaminants is usually low (mg kg^{-1} down to sub ng kg^{-1}), toxicologists, epidemiologists, and risk assessment experts advise that there may still be significant and widespread adverse environmental and human health consequences (e.g., cancer risk and adverse reproductive development) at the detected levels (Mohajerani and Karabatak 2020). Heavy metals such as As, Pb, Cu, Hg, Cd, Se, Ni, and Mo accumulate in biosolids (composts, livestock manures, and municipal sewage sludge) when they are applied to the soil (Basta et al. 2001). Animal wastes generated in agriculture, such as chicken, pig, and cattle manure, are commonly put on crops and pastures as solids or slurries, depending on the kind of animal waste. Even though most manures are good fertilizers, Cu and Zn are added to feeds in the pig and poultry industries as growth promoters. As a result of their presence in poultry, health products can potentially contaminate the soil with heavy metals (Machete and Chabo 2020). The manures produced by animals fed on such diets have significant As, Cu, and Zn quantities. If this method is used regularly on restricted land areas, it can significantly accumulate these metals Biosolids are solid finished products formed from wastewater treatment and subsequent treatment of the resulting sludge to limit the risk of pollution to humans and the environment (López-Rayo et al. 2016). Biosolids (BS), on the other hand, contain HMs such as Ni, Cu, Pb, Cd, and Zn which are not required for plant growth (De Bhowmick and Sarmah 2022). A significant difficulty is the generation of vast quantities of biosolids formed during wastewater treatment operations. Biosolids have traditionally been dealt with by using typical biosolids disposal procedures such as ocean dumping, landfilling, and incineration (Bucknall 2020). Due to more onerous environmental restrictions and the high economic expenses associated with these disposal methods, these choices are becoming less practical. Recently, researchers have looked into the possibility of using biosolids for positive reasons in various applications (Drechsel et al. 2022). Land application of biosolids has been proposed as a sustainable approach for resource recovery because of their high concentrations of organic matter and nutrients. The amendment of soils with biosolids has emerged as the most common method of utilizing biosolids. Most biosolids are applied as a soil amendment to agricultural land and pastures (Widyastuti et al. 2021; Wu et al. 2021; Yang et al. 2012; Zamora-Ledezma et al. 2021). It is also possible to use biosolids for home purposes by adding them to potting mix and other soil additives. However, the amount of biosolids used for domestic reasons is far less than that used for agricultural purposes (Roopnarain et al. 2022).

Wastewater and Metal Mining as a Source of Heavy Metal

Triggered by exorbitantly increasing population rapid industrialization and urbanization posed the menace of air water and soil pollution which is a potential threat to mankind. Among industries tanneries played a leading role in polluting the soil and water bodies. The wastewater discharged from the tanning industry contains numerous pollutants including heavy metals (Hashem et al. 2020; Kamran et al. 2019; Maqbool et al. 2018). Globally, wastewater irrigates around 20 million hectares of arable land. More than half of the vegetables supplied to urban areas in Asian and African cities are grown with the help of wastewater irrigation (Chowdhary et al. 2018). Environmental advantages and dangers are often overlooked by farmers, who are more concerned with boosting their yields and profits than anything else (Hao et al. 2019). As a result, even though wastewater effluents typically contain modest levels of heavy metal contamination, repeated irrigation with wastewater effluents may cause heavy metal deposition in the soil. There is a legacy of metal pollution in soil throughout many countries due to the mining and processing of metal ores and the existence of industrial activities. Heavy metal concentrations rise due to mining tailings discharges (Particles that have settled to the bottom of the flotation cell are heavier and larger) into nearby wetlands and other natural depressions. Due to extensive Pb and Zn ore mining and smelting, human and environmental health and well-being are at risk (Sandeep et al. 2019). Many restoration approaches used on these sites are time-consuming, expensive, and ineffective in restoring soil productivity. Human exposure to HMs in the environment depends on their bioavailability in soil. Consumption of plant material grown in (the food chain) or oral bioavailability (contaminated soil ingestion) are two techniques of food chain absorption. In addition to textiles and tanning and petrochemicals, insecticides and pharmaceutical manufacturing facilities all produce materials with highly changeable compositions, such as those resulting from spilled oil or petroleum-based products. Textiles, tanning, petrochemicals, insecticides, and pharmaceuticals are only a few examples. Many of these wastes are put on land, but they offer little benefit to farming or forestry. In addition, many of them contain heavy metals (Pb, Cr, and Zn) or dangerous organic compounds; hence thus are rarely used on the ground. Some are deficient in plant nutrients or lack soil-conditioning qualities (Fig. 2) (Jayakumar et al. 2021; Khanna et al. 2021; Kumar et al. 2021, 2022).

Toxic Effect of Metals on the Plants

Fe, Zn, Mn, Cu, Ni, Co, and Mo are all transition-metal elements that are vital to plant nutrition (which is required for nitrogen fixation in legumes). Metallic heavyweights include non-essential cadmium, lead, and mercury (Flora et al. 2008; Mehta et al. 2021).When present in high concentrations in agricultural plants' tissues, all metals are toxic to the plants. Deficiencies of important heavy-metal elements are more widespread in agriculture than their toxicity, which is surprising considering their importance in food production (Daulta et al. 2022). This is even though Mn and Fe poisoning can impair crop yields on acidic soils and soils that have been waterlogged or otherwise flooded. As a result of weathering or human activity, some heavy metals can accumulate in soils, resulting in toxicities that can harm humans (Sandeep et al. 2019). Although the molecular biology of heavy metal uptake and transport in plants has been thoroughly characterized, researchers still strive to determine how plant cells and tissues maintain heavy metal homeostasis.

Furthermore, excessive levels of heavy metals have been shown to trigger cellular reactions in laboratory animals. The production of antioxidant molecules and enzymes is among the many responses caused by reactive oxygen species (Gavrilescu 2022). By preventing the entry of heavy metals into roots and their migration to xylem; and by chelating heavy metals that enter the cytoplasm and sequestering them in non-vital compartments such as the apoplast and vacuole, plants may tolerate high concentrations of heavy metals in their environment (Khan et al. 2021). In addition, knowing how specific plant species might accumulate excessive levels of heavy metals will also help us learn how plants can avoid and tolerate heavy metals in their tissues, as shown in Fig. 3 (Raza et al. 2021).

Toxic Effect of Zn

Zn is a plant micronutrient which is involved in many physiological functions its inadequate supply will reduce crop yields. Zn deficiency is the most wide spread micronutrient deficiency problem, almost all crops and calcareous, sandy soils, peat soils, and soils with high phosphorus and silicon are expected to be deficient (Shi et al. 2015; Zvezdanović et al. 2007). Zn deficiencies can affect plant by stunting its growth, decreasing number of tillers, chlorosis, and smaller leaves, increasing crop maturity period, spikelet sterility, and inferior quality of harvested products (Liu et al. 2007; Umair Hassan et al. 2020). Beside its role in crop production Zn plays a part in the basic roles of cellular functions in all living organisms and is involved in improving the

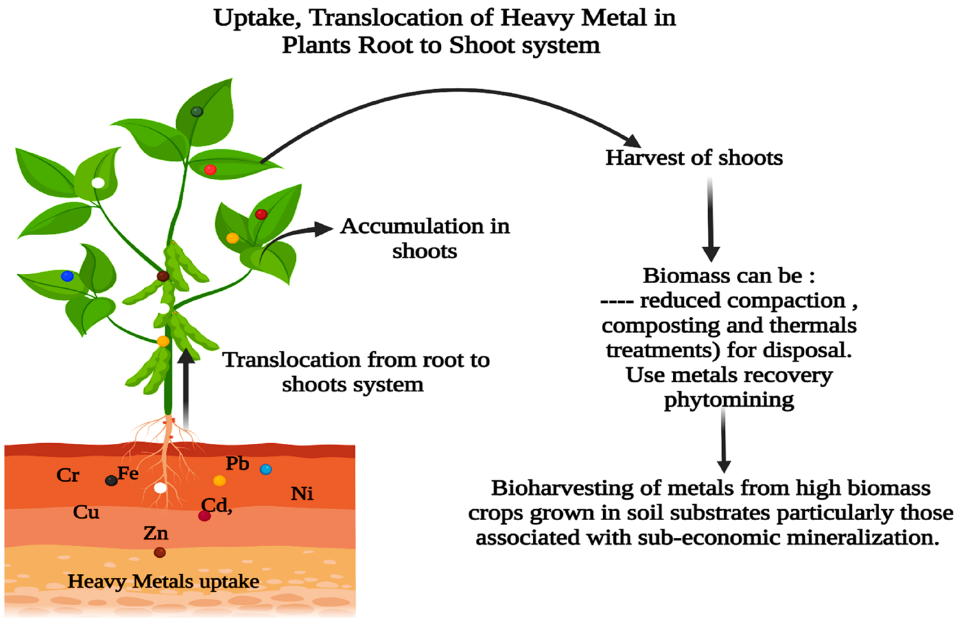


Fig. 2 Schematic representation of phytoextraction of metals from root to shoot system and accumulations in shoots

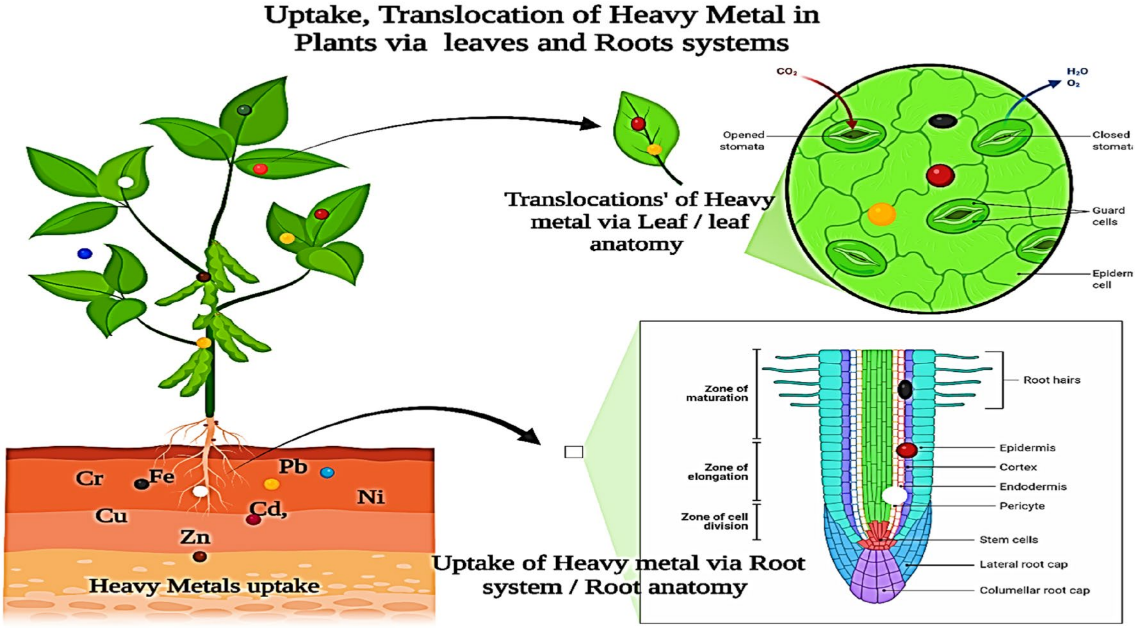


Fig. 3 Schematic diagram shows the uptake, translocation, and sequestration of heavy metals in plants

human immune system (Tang et al. 2020; Tanveer et al. 2022; Zhang et al. 2021). The threshold of Zn toxicity varies among plant species, time of exposure to Zn stress and composition of the nutrient growth medium. Plant growth inhibition extends in *T. aestivum* after addition of $ZnSO_4$ (Ahmad et al. 2022; Sarwar et al. 2014), whereas *Pisum sativum* became inhibited after Zn application (Mukherjee et al. 2014). Photosynthesis is strongly affected in plants exposed to heavy metals excess. High Zn concentrations in plants can cause phytotoxicity. The yield may be reduced when plant leaf Zn concentrations reaches about 300–1000 μg Zn g^{-1} (Ullah et al. 2020). The best way to identify Zn deficiency in crops is the determination of Zn concentrations in tissues, however, the results should be interpreted in full recognition of the interaction of Zn with other nutrients because the deficiency of one nutrient may result in excess accumulation of other nutrients by a plant (Rajput et al. 2018; Rizwan et al. 2019; Zhang et al. 2021).

Toxic Effect of Cd

Cd is a highly toxic metal that affects terrestrial and aquatic organisms, including humans. Due to agricultural and industrial growth, Cd concentrations in agricultural soils have increased (Priyadarshanee et al. 2022a, b). A diverse spectrum of human endeavors and environmental contaminants contribute to the introduction of Cd into ecosystems (Iftikhar et al. 2022). For animals and people alike, the high mobility of cesium in polluted soils poses a significant threat to health (Paul and Saha 2022). Cyanide toxicity affects many human organs, but the kidneys are particularly vulnerable, where it can induce renal tubular damage, kidney stones, and pulmonary emphysema (Gupta 2019). As a result of its identical charge, same ionic radius, and chemical activity, Cd substitutes for calcium in minerals (Kong et al. 2021). Cd toxicity in plants manifests as chlorosis and growth stunting. Higher toxicity slows down plant growth, resulting in plant necrosis (Pramanick et al. 2022). Poisoning plants with cadmium prevents carbon fixation and lowers chlorophyll concentrations and photosynthetic activity, negatively affecting plants (Sperdouli et al. 2022). Soil Cd reduces physiological activity such as stomatal conductance, leaf water content, and transpiration, resulting in plants' osmotic stress and physiological impairment (Javad et al. 2022). Plant membranes are damaged, and cell macromolecules and organelles die due to a buildup of reactive oxygen species (ROS) caused by cadmium poisoning (Sun et al. 2022). Many studies have been conducted on the impact of Cd toxicity on crop yield, ROS generation, the formation of lipid peroxidation, and the many remediation techniques available (Haider et al. 2022). As illustrated in Fig. 4, only a little research on the effects of Cd on plants and Cd remediation approaches to avoid Cd mobilization in the rhizosphere have been conducted (Ai et al. 2020).

Toxic Effects of Cr

Cr is the seventeenth most abundant element on the planet (Matrosova et al. 2021). Plating, alloying, animal hide tanning, water corrosion prevention, textile colors, pigments,

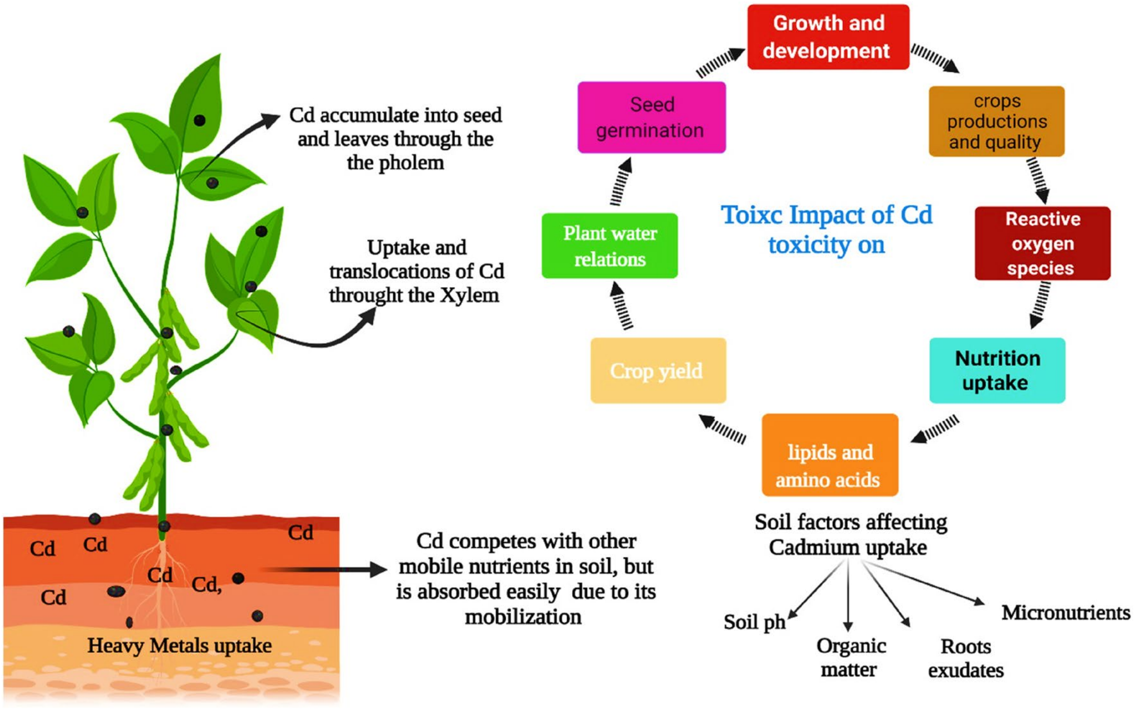
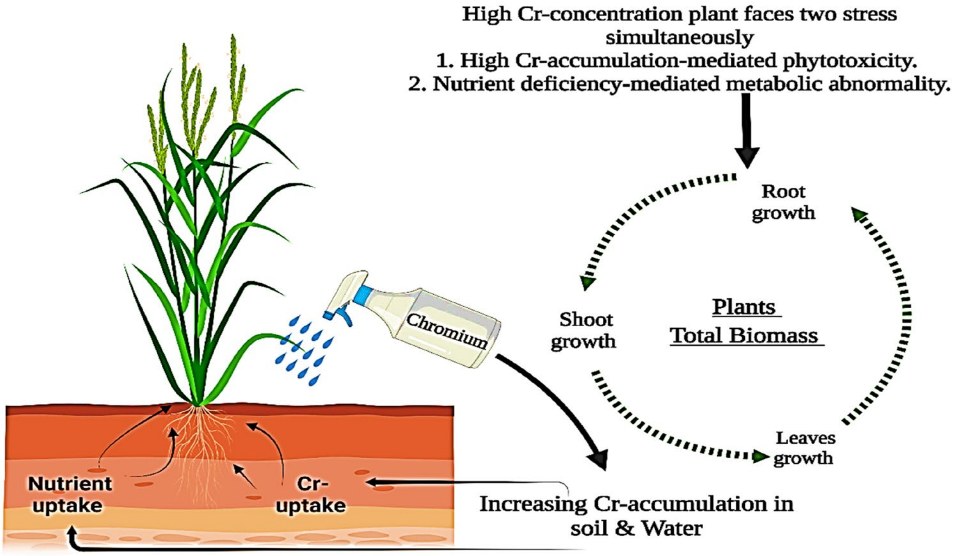


Fig. 4 The absorption, transport, accumulation, and toxicity of cadmium (Cd) in plant species are discussed. Soil pH, micro-and macronutrients, and organic matter in soil are significant variables influencing plants' Cd uptake

ceramic glaze, refractory brick, and pressure-treated wood are examples of Cr's industrial applications (Dongre 2021). This broad anthropogenic usage of Cr has resulted in environmental contamination, which has grown in recent years and now poses an increasing hazard (Hojjati-Najafabadi et al. 2022). Cr (0), trivalent Cr (III), and hexavalent Cr (VI) are the most stable and frequent chromium species; however, additional oxidation states exist as well. Steel and other alloys can be made from Cr (0), a metallic form of Cr generated in industry and has a high fusing point. Cr can reach natural streams by weathering Cr-containing rocks, industrial activities, and soil leaching (Aharchaou et al. 2022). Cr can be reduced, oxidized, sorption, desorption, dissolution, and precipitation in the aquatic environment. Cr (III) aqueous solubility is affected by the pH of the water (Ibrahim et al. 2019). Cr III can be exposed

Fig. 5 Effect of higher Cr-accumulation and Nutrient deficiency on plant's growths and development



to higher concentration and lower nutritional concentration. Which effect plant totals biomass, roots growth, shoot growth, and metabolic activities, as shown in Fig. 5.

Cr (III) tends to precipitate at neutral to basic pH while solubilizing at acidic ph. Divalent cations can precipitate even though Cr (VI) chromate and dichromate are extremely soluble at any pH (Prasad et al. 2021; Sandeep et al. 2019). The Cr concentration of underlying soil rocks and sediments fluctuates as the natural composition of the rocks and sediments changes (Hussain et al. 2021; Javed et al. 2021; Ma et al. 2022a, b, Saleem et al. 2022d). Soil chromium levels can be increased by disposing chromium-bearing liquids and solid wastes, such as chromium byproducts, ferrochromium slag, or chromium plating baths. Cr (III) and Cr(II) are commonly found in soil (VI) (Prasad et al. 2021). As of this writing, the mechanism underlying plant uptake of Cr is yet unknown. Instead of being necessary, Cr is a non-essential element whose absorption relies on Cr speciation and lacks a specialized mechanism (Sterckeman and Thomine 2020). Because Cr (III) uptake by plants is a passive process, they do not have to put any effort. It is hypothesized that carriers utilize Cr (VI) absorption to carry essential components such as sulfate (Khan et al. 2021).

Toxic Effects of As

As is one of the toxic environmental pollutants which has recently attracted attention because of its chronic and epidemic effects on human health through widespread water and crop contamination due to the natural release of this toxic element from aquifer rocks in many countries (Farooq et al. 2015; Uddin Nizam et al. 2016). As is a highly toxic and carcinogenic element (Siddiqui et al. 2020b) and the most widespread sources of arsenic in soil and water are natural sources, such as volcanic activities, weathering, and erosion of minerals and rocks, and geothermal waters (Islam et al. 2013; Saleem et al. 2022a). In addition, use of pesticides, fertilizers, industrial wastes, agricultural chemicals, and Cu chromate-arsenate (CCA) wood preservative are the major anthropogenic sources of arsenic contamination in soil and water (Tanveer et al. 2022). There exist abundant evidences that As negatively interferes with several biochemical and physiological processes inside plant causing reduced plant growth and yield (Farooq et al. 2015; Kalve et al. 2011). Inside the plant cell, heavy metals including arsenic induce oxidative stress by enhanced production of reactive oxygen species (ROS), which may cause cell death via oxidative processes such as protein oxidation, enzyme inhibition, DNA and RNA damage, and lipid peroxidation (Gomes et al. 2014; Merrington 2018; Shahid et al. 2017). The sites contaminated with As need immediate attention due to the associated severe health risks. As has significant effects on different activities, considerable changes were noted in both shoot and roots systems, as shown in Fig. 6.

Toxic Effect of Hg

As a heavy metal in the periodic table's transition element series, mercury is a toxic substance. Because it may be found in three forms (elemental, organic, and inorganic), each with a distinct toxicity profile, it is notable (Barik et al. 2021). When mercuric Hg is methylated by soil and water microorganisms, methylmercury is the most common organic form of Hg in the environment (Barkay and Gu 2021). In addition to altering biological tissues, mercury is a prevalent environmental pollutant linked to numerous health problems (Maghsoudi et al. 2021). Multiple chemical forms of Hg are present in the environment, exposing people and animals. It

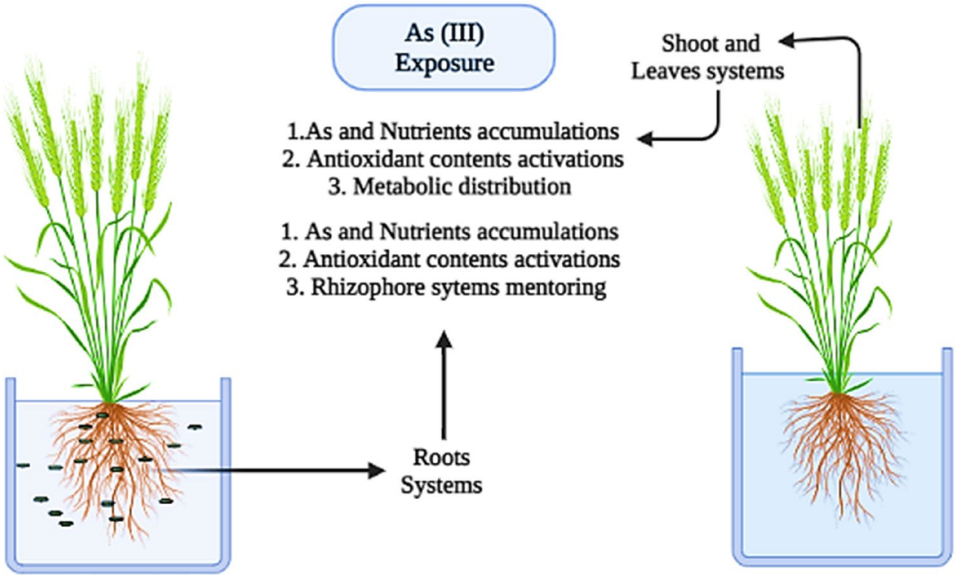


Fig. 6 As (III) effect on the shoot and roots systems, metabolic distribution, antioxidants contents, and activities

is made up of mercuric (Hg^{+1}), inorganic mercurous (Hg^{+1}), and organic mercury compounds (Hg^{+2}). Humans, plants, and animals all come into contact with mercury since it is so common in the environment (Priyadarshanee et al. 2022a, b). Hg is used in various industrial processes, including the production of caustic soda and nuclear reactors, antifungal agents for wood processing, a solvent for reactive and valuable metals, and a preservative for medicinal products (Cai et al. 2019; Haider et al. 2022).

Toxic Effects of Pb

Pb is naturally occurring, and human activities such as burning fossil fuels, mining, and manufacturing contribute to releasing excessive amounts of metal into the environment. There are several industrial, agricultural, and residential uses for Pb (Sharma and Sharma 2022). Pb -acid batteries, ammunition, metal products (such as solder and pipes), and X-ray shielding devices are now all made using it. An estimated 1.52 million metric tons of lead were consumed (Anderson 2012). Over the last several years, the usage of lead in paints, ceramic tiles, caulking, and pipe solder has declined dramatically. A quarter of the 16.4 million households in the United States with more than one kid under six still have high levels of Pb-contaminated deteriorating paint, dust, or bare soil (Sandil and Kumar 2022). Despite this development resulting from children playing in bare, contaminated dirt, lead in dust and soil re-contaminates cleansed residences (Naqhiyah Farhan 2018); and boosts blood Pb levels in those youngsters. The most prevalent source of lead poisoning in children is dust and chips from deteriorating lead paint on interior surfaces (Hauptman et al. 2017). Children who live in homes where Pb paint is deteriorating have been shown to have blood lead levels of 20 g dL^{-1} or higher (Marino 2003). Pb's toxicological effects are likely to affect one or more of a plant's physiologically active tissues engaged in the growth, maintenance, and photosynthesis (Jaishankar et al. 2014). There has not been any indication that Se is necessary for plants. Seed germination and growth can be compromised in plants with an excess of Se. The physiological significance of se in plants, despite several investigations, remains a mystery (Pour and Makkawi 2021). The physiological reactions of plants to Se and their capacity to accumulate Se in tissue were highly variable (Kumbhakar et al. 2022).

Approaches for Remediation of Heavy Metals

HMs remediation from contaminated soil, water, or sediment has been the subject of numerous treatment procedures, including physical, chemical, and biological. For example, thermal treatment, adsorption, and chlorination are examples of adsorption and chlorination operations (Singh et al. 2021). As described earlier in this article, most of the steps mentioned above are only suggested as a single remediation method. However, despite their success, these methods have some downsides, including inefficiency and high costs (Sreejith et al. 2022). Several benefits can be gained by repurposing these problems as integrated processes, including increased efficiency, reduced cost and time, increased flexibility, less environmental impact, and the potential for large-scale treatment options (Feng et al. 2018). Because of these considerations, many researchers worldwide have found that combining or integrating treatment options is more beneficial (Selvi et al. 2019). An in-depth understanding of the objectives of both processes is necessary for the integration process. For large-scale applications, it is essential to combine two approaches to be tested and compared to their solo equivalents in terms of cost and efficiency (Wibowo et al. 2021). It has been shown that integrated strategies for heavy metal removal from various environments are becoming more popular (Azimi et al. 2017).

Chemical-Biological Remediation Approach

Chemical–biological integrated treatment method is claimed to be a cost-effective and eco-friendly solution to remove heavy metals from wastewater. According to several researchers worldwide, adopting this treatment rather than individual chemical or biological therapies is good and has shown significant advantages in HMs elimination (Greenwell et al. 2016; Pradhan et al. 2017). A combination of both therapies' advantages and disadvantages is recommended. One of the most popular repair procedures is chemical remediation because of its ease of use and rapid results. However, metal precipitates and toxic by-products have significantly impeded this method (Crini and Lichtfouse 2019).

In contrast, biological treatment is increasingly popular due to its little impact on the environment and high return on investment. The downsides include a long acclimation period, alterations in the isolate's biodegradability, and sludge production (Marzuki et al. 2021). However, these limitations can be circumvented by combining both approaches and thoroughly knowing the workings of each method. Because of its efficiency and cost viability, some experts believe that this integrated system often includes biological therapy followed by chemical treatment and the other way around (Kaasa et al. 2018). An environmentally acceptable choice of non-toxic chemicals would unquestionably enhance the efficacy of this procedure, even though academics have already adopted it (Khanna et al. 2021).

Phytobial Remediation Approach

Plants can be used to remove heavy metals from soil and water, which is both cost-effective and environmentally friendly. In phytobial remediation, both plants and bacteria clean up soil and water. The literature says that plants and microbes are used to break down heavy metals in phytobial-based remediation (Khanna et al. 2021; Kumar et al. 2022). Figure 7 shows how metals can get into cells like metal bio-precipitation, metal bioaccumulation, metal binding on the cell surface, metal biotransformation, and metal methylation bioaccumulation. Operations such as solubilization, reduction, biosorption, and siderophores are ways that metals can be removed from the body. Heavy metals can also be removed from the body through DNA-mediated interactions (Ahemad 2015). Integrating the right bacteria that can make a lot of plant growth-promoting substances (PGPS) can help these mechanisms work better (Banov et al. 2020). People use organic acids, siderophores, biosurfactants, and other chemicals to make metals easier for us to use (Roy et al. 2015).

Phytobial remediation is widely recognized as the cleanest and most cost-effective option compared to other invasive technologies. Large areas of polluted groundwater, soil, and sediment can also be treated. It is also an in situ treatment option that has been shown to aid in topsoil preservation by minimizing heavy metal dispersion in the soil. Despite these advantages, this method is restricted to shallow aquifers and soils due to plant root length restrictions, the risk of heavy metals entering the food chain, regular monitoring (due to little rainfall), the long duration (which can last several seasons), safety lack, complicated metal recovery procedures, proper disposal method, and a high recycle economy. A study by (Roy et al. 2015) proposed many solutions to address these issues, including the use of deep-rooted plants, the development of herbivore-distracting transgenic plants, the development of appropriate evaluation methods, and the integration of other methods such as bioremediation, EK, and bioaugmentation, among others. The various microorganisms involved in phytobial cleanup are explained in depth here (Chaudhari 2021).

Phytobial Remediation Using Free Living Organism

Phytoremediation is helped by the movement, immobilization, and volatilization of free-living microorganisms, which allow the process (Waigi et al. 2017). Redox transformation, volatilization, chelation, and leaching are ways metals may be transferred. As is eliminated using bacteria such as Sulfur *spirillum barnesii*, Geobacter, and *Bacillus selenatarsenatis*.

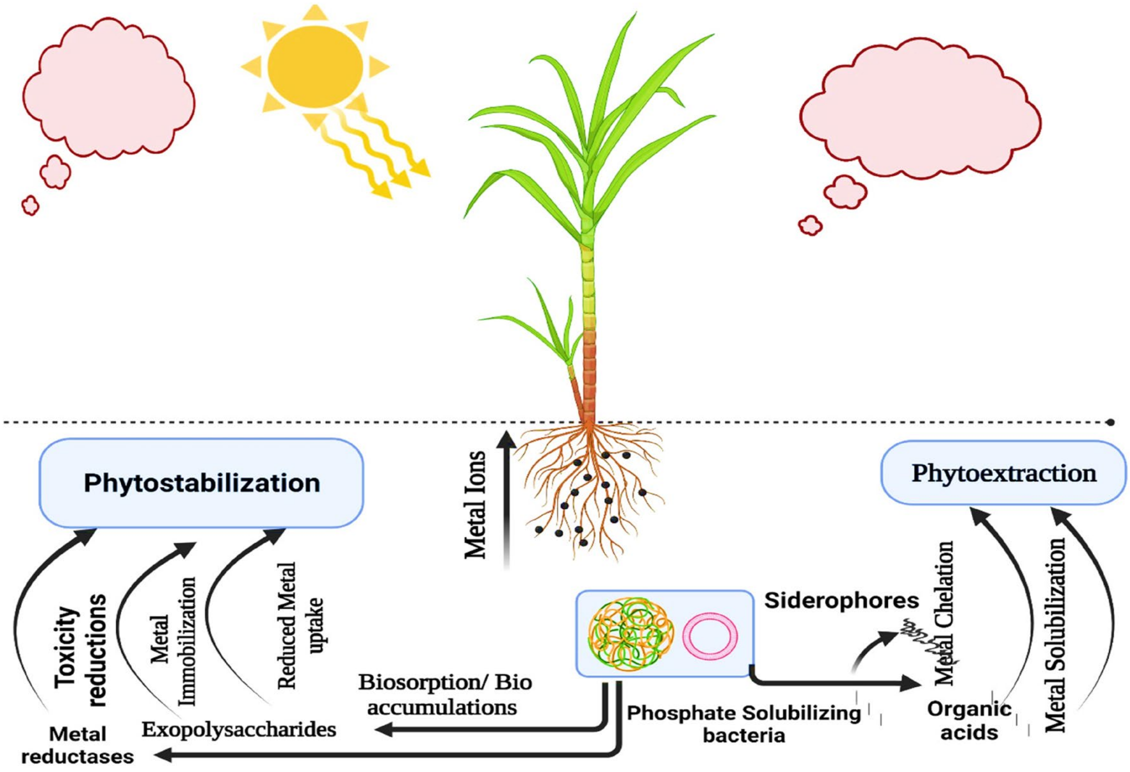


Fig. 7 Various microbial interactions with heavy metals

A new hybrid method uses anaerobic bioleaching and electro kinetics (Lee et al. 2009). Heavy metals build up in the plant's harvested tissue, which can be thrown away—adding microorganisms that move around to contaminated water speeds up the buildup of heavy metals (Quarshie et al. 2021). The immobilization process changes the physical and chemical properties of the pollutant so that it cannot move. The metals are oxidized by the enzymes found in bacteria, making them more challenging to move and less harmful. To remove heavy metals from the soil, bacteria such as Sporosarcina ginsengisoli, Candida glabrata, Bacillus cereus, and Aspergillus Niger were utilized in an immobilization approach (Jiang et al. 2022). It used the process of biomethylation to remove HMs from the environment. There were a lot of bacteria, fungi, and algae used in the biotransformation process (Ai et al. 2020).

Endophyte and Rhizo Microbe Remediation

Endophytes are bacteria or fungi that live inside plants. They spend at least part of their life cycle without hurting the plant. They can be found in practically every plant, and some of them have the power to promote plant growth. A few fungal endophytes produce secondary metabolites. Heavy metal tolerance in Methylo bacteria strains from the Pteris vittata plant has been identified. However, further research is needed to fully understand the unstudied endo Phyto biome possibilities. The root zone of a plant is referred to as the rhizosphere. Some bacteria in this region have a symbiotic connection with the plant by secretions, lysates mucigel, secreting exudates, and mucilage to help plant development. Microbe-secreted siderophores, for example, will aid in metal chelation and solubilization (Selvi et al. 2019). Rhizoremediation uses these secretions to stimulate plant growth, immobilize heavy metals, and prevent metal buildup. Different metals can bind to siderophores with other ligand-binding groups. Pseudomonas azotosomes siderophores have been shown the arsenic to mobilize and remove. The higher pH in the rhizosphere zone assists in the mobilization and absorption of heavy metals because root bacteria are aerobic. The cation and anion uptake ratio is connected to the increased pH in the rhizosphere. According to researchers, the plant-microbial partnership secretes biosurfactants that aid with metal immobilization by raising the pH of the rhizosphere (Ali et al. 2022a, b; Manghwar et al. 2021).

Fungal and Algal Phytoremediation

Mycorrhizal fungi are associated with many plants, increasing the root surface area and aiding in water and nutrient uptake. Several recent studies have shown that mycorrhizal fungus can help plants better absorb and store heavy metals. A few researchers have found that mycorrhizal fungi present in Plantago lanceolata L promote As buildup, although other researchers have not confirmed this. Algae are considered an essential component of the aquatic system that contributes significantly to the biogeochemical cycle. Their outstanding absorption and sequestration potential has piqued the interest of researchers all over the world. It also has a high tolerance for heavy metals, the ability to remove them selectively, grows both autotrophically and heterotrophically, synthesizes metallothionein and phytochelatin, and the ability to cause genetic changes. Some micro- and macroalgae such as Enteromorpha sp., Ulva sp., Cladophora sp., Chaetomorpha sp., and Fucus serratus have all been reported to collect substantial levels of heavy metals.

Enhanced Phytoremediation Approaches

Significant technology must be employed to remove or reduce heavy metals to tolerable levels. Although it may be accomplished by various integrated strategies, including recombinant genetic engineering of bacteria and plants, heavy metal removal applications have shown recombinant genetic engineering to be worthwhile (Wu et al. 2021). Gene-modified microorganisms perform better than their wild counterparts, with enormous restorative potential. Genetic engineering can also activate phytoremediation and boost heavy metal accumulation and uptake. The "ars" operon in the "arsR" gene encodes a regulatory protein that helps detect arsenic pollution. A recombinant E. coli strain with the "ars" gene was produced by (Kaur and Garg 2014), which accumulated 60 times as much arsenic as the control strain. "Ars" recombinant strains are best appropriate for in situ bioremediation in a real-world context (Saravi and Dehpour 2016). When Enterobacter cloacae CAL2 was added to the canola plants, heavy metal accumulation was four times higher than in control cells. Transgenic plants were introduced to boost the plant's capacity for heavy metal removal from the soil (Fahrenfeld et al. 2019).

Hyperaccumulators for Remediation of Heavy Metals

HM ions are actively removed from plants by excluders, which make up the majority of plant species capable of living in soils high in dangerous trace elements (Sun et al. 2022; Tang et al. 2021, 2022). An HM ion is only toxic to the roots of an excluder plant, while the aerial parts are mainly unaffected by the toxin. When exposed to large concentrations of HM, hyperaccumulators, on the other hand, may store the toxin above ground without showing any symptoms of phytotoxicity (Iftikhar et al. 2022). *Sebartia acuminata* (Sapotaceae), a New Caledonian Ni-accumulating tree, was the first to be referred to as a hyperaccumulator because of its 26 per cent dry weight nickel concentration in its latex. The translocation factor (TF) and bioaccumulation factor (BCF) are also important in screening hyperaccumulators for phytoremediation of heavy metals. Screening of hyperaccumulators depend on BCF and TF values (both of them are greater than 1) for evaluation and selection of plants for phytoremediation (Parveen et al. 2020; Saleem et al. 2020j). The TF is the capacity of plants to transfer metals from roots to shoots and BCF express the ability of plants to accumulate metals from soils to tissues (Deng et al. 2021; Saleem et al. 2020k, 2021). Another requirement for criteria of plants whether it is Cu hyperaccumulator species or not is Cu accumulation in shoots. Cu accumulation in shoots should be greater than 1000 mg kg^{-1} dry weight when grown on metals rich soils (Javed et al. 2020; Rehman et al. 2019a). Caryophylacales and other hyperaccumulator-rich groupings include Asteroideae, Euphorbiaceae, Rubiaceae, Fabaceae, Scrophulariaceae, Myrtaceae, Proteaceae, and Caryophyllaceae, and other hyperaccumulator-rich groups. Hyperaccumulator species appear to predominate in some plant genera; for example, 48 of 170 species in the genus Alyssum were found to hyper accumulate Ni in a thorough survey. Metal specificity and accumulation may vary between populations, discovering that hyperaccumulation ability differs among species. Hyperaccumulators differ from non-hyperaccumulators in various essential physiological processes of HM detoxification, according to (Sajid et al. 2018), who researched the Zn, Cd, and Ni model hyperaccumulator alpine pennycress (Noccaea caerulescens, originally Thlaspi caerulescens). As a result of these changes in the root cell plasma membrane, root vacuole sequestration of Hm ions increased xylem transport of Hm to shoots. It increased Hm influx into the plasma membrane of leaf cells and (v) sequestration in the leaf vacuole. The plant can absorb more Hm ions. According to (Sun et al. 2022), the plant's improved active metal transport rather than enhanced intracellular ligands play the most important role in hyperaccumulation (such as glutathione, photoheating, or metallothionein). When compared to the non-accumulating sister species Arabidopsis lyrate and the closely related reference model Arabidopsis thaliana, a Zn and Cd hyperaccumulator, Arabidopsis helleri, showed an abundance of HMA4 gene copies and corresponding transcripts, as well as other transition metal homeostasis and biotic factors (Banov et al. 2020).

Chelating Agents

Even though chelation is based on fundamental coordination chemistry, creating a perfect chelator and chelation treatment that fully removes a toxic metal from a desired site in the body necessitates a thorough drug design strategy (Cappai 2020). Chelating agents are organic or inorganic substances that may bind metal ions and create chelates, complex ring-like structures that bind metal ions. In bidentate chelates, the "ligand" binding atoms form two covalent links, one covalent and one co-ordinate linkage, or two co-ordinate couplings. S, N, and O atoms are commonly used as ligand atoms in chemical groups such as –SH, –S–S, –NH2, =NH, –OH, –OPO3H, or > C=O. The metal ion and the two-ligand atoms linked to the metal create ring structures in bidentate or multidentate ligands (Fig. 8). Several donors use bidentate ligands. Inorganic chelate ligands, for example, create a five-membered ring with metal ions. Other chelating ligands, such as EDTA 4, a hexadentate ligand, are also conceivable. However, the proton retains its positive charge because no electrons are lost or gained (Holbein et al. 2021).

These complexes' pharmacokinetics and their toxicological behavior are determined by this feature, which is referred to as the 'net ionic charge' of the complex. It is measured in nanograms. Complexes of this nature can be produced in the biological environment by metal cations such as Na^{+}, Mg^{+}, Cu^{+}, Cu^{2+}, and Zn^{2+} and transition metals such as Mn, Fe, and Co. Metal cations such as Na^{+}, Mg^{+}, Cu^{+}, Cu^{2+}, and Zn^{2+} are all found in the biological environment (Blackman et al. 2019). However, the chelating agent and the chelated metal's properties are the most important factors determining their stability. Using equilibrium equations that depend on the atomic structure of chelated metal atoms, one can get quantitative information about the strength constant in compounds. The chelating agent can remove the metal with a lower equilibrium constant from the equation because of its higher stability stable (Treviño et al. 2019).

The number of ring formations is another issue to consider regarding heterocyclic rings. Despite Pb's more excellent stability consistent, Ca^{2+} is readily available. It preferentially binds to Na$_2$EDTA because of the number

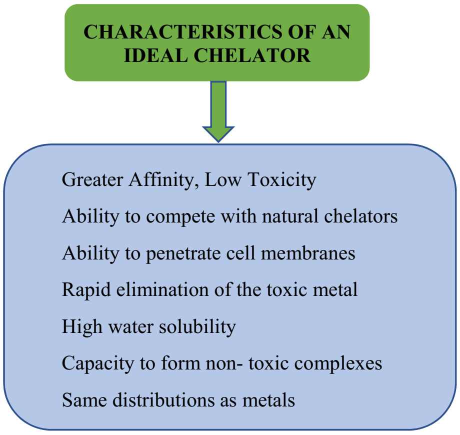


Fig. 8 Ideal chelating agent characteristics for better heavy metal chelation

of heterocyclic rings produced and the relative concentrations of the two EDTA salts in the bodily fluid (Machete and Chabo 2020; Treviño et al. 2019). Furthermore, even if an ideal chelator possesses all the required characteristics, the results are unpredictable. Toxic factors or endogenous compounds like hemoglobin, cytochromes, and other chelating agents may prevent a chemical entity from being an ideal chelator in vivo, despite its ability to chelate metals in vitro (Hajeb et al. 2014). It is also essential to consider the pH of the solution when it comes to complexes. This is because metals prefer to form hydroxides at high pH, making them more difficult for chelating agents to access (Gao et al. 2022, Zhang and Zhou 2019). As a result of these conditions, this feature becomes critical. Cleavage of metal ions and their complexes can be most effectively performed when these properties are combined with those of the metal complex itself (Schattschneider et al. 2019). A more stable complex will be formed most of the time (but not always) when a chelating agent occupies a more significant percentage of a metal ion's coordination sites. When it comes to the absorption, distribution, and ability to find and bind to metal ions, chelators' net ionic charge dictates their absorption, distribution, and ability to get to the metal ion (Selvi et al. 2019). First, transport toxic metal ions across physiological barriers to areas where they are concentrated; then form stable complexes with these ions, which are non-toxic and aid in their excretion. Finally, chelation complexes are formed that are non-toxic and aid in their excretion from the site of deposition (Sperdouli et al. 2022).

Common Chelating Agents: Pharmacology and Toxicology

An ideal chelator must be highly bio transformable, maintain chelating activity at bodily fluid pH, be soluble in water, reach metal storage sites, and form metal complexes that are less dangerous than the free metal ion.

During World War II, dimercaprol (also known as British Anti-Lewisite or BAL) was created as a test antidote to the arsenic-based poison gas Lewisite (BAL). As a result of their work painting the hulls of ships following World War II, many navy personnel suffered lead poisoning (Tang et al. 2021, 2022). This was the first time EDTA had been used medically to chelate lead. BAL has dominated physician prescriptions for general metal intoxication for decades because of its excellent ability to treat human arsenic and mercury poisoning. This dithiol is structurally similar to BAL but has fewer harmful effects than BAL had in the 1960s (Flora et al. 2008, Flora and Pachauri 2010). In the former Soviet Union, scientists created novel dithiol sodium 2,3-dimercaptopropane 1-sulfonate (DMPS) as a mercury chelating agent. Chelation therapy has been used to reduce the body's hazardous metal levels for patients with severe symptoms and high biological indicators. Chelating medicines can influence metal toxicity by mobilizing the poisonous metal, primarily eliminated in the urine. Metal poisoning can be reduced by chelating drugs that form a stable complex with the metal ion, thus protecting biological targets from the metal's harmful effects. Deferoxamine (DFOA), which includes complexes covering Fe3surface + 's entirely, prevents iron from catalyzing free radical reactions(Gerhardsson 2022). However, the metal exposed by the chelator may become more toxic in other situations due to the biological context of handling it (Fig. 9). To put it simply, unlike EDTA, which cannot completely cover the surface of Fe^{3+}, it produces an open complex (basket complex) that enhances Fe3potential + 's to

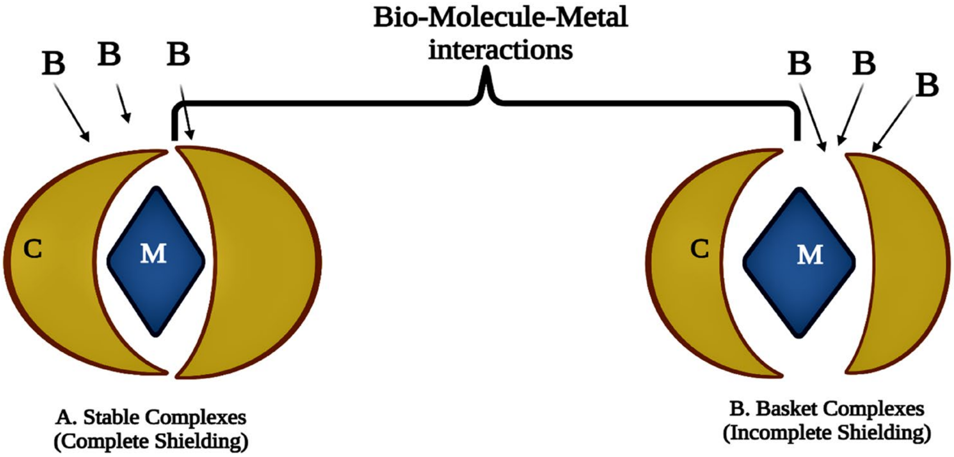


Fig. 9 Metal chelating agent structures in two distinct complexes. Both **A** Stable and **B** Basket complexes have a positive effect on the interaction of the metal with bio-molecules. Use of the abbreviation "B" for biomolecules, "C" for chelator, and "M" for metal

create oxidative stress, which is suitable for the treatment of oxidative stress. Various chelating chemical structures are shown in Fig. 9.

Conclusion and Future Prospective

Heavy metals discharged into the environment due to numerous human activities have caused variable levels of soil contamination across the world. As a result, careful and stringent monitoring of these operations is recommended as a viable solution to heavy metal contamination. However, a detailed understanding of the origin and sources of different heavy metals, the potential risks to the environment and individuals, and their chemistry is mandatory to determine an effective remedial technique. Other remediation techniques, including thermal processes, physical, biological, chemical, and electrical, with advantages or disadvantages to rectify the soil contamination by immobilizing, containing, and extracting the heavy metal contaminants were discussed in additional research. Heavy metal resources (Mining, pesticides, fertilizers, herbicides, and irrigation of agriculture fields with industrial and sewage water, Biosolids, manures, pesticides), phytotoxicity of some contaminants (such as Pb, As, Hg, Zn, and Cd), removal/recovery from the contaminated environment using different remediation approaches such as the integrated option summarized in this literature review. Single remediation techniques, despite their effectiveness, have some significant disadvantages, such as high costs and inefficiency. The advantages of integrated approaches are less cost and time, a high level of flexibility, lower environmental effect, and the large-scale treatment possibility and high efficiency. Due to these mentioned factors, numerous studies have discovered combining or integrating treatment approaches (Chemical-Biological, Electro-Kinetic Microbial, Electrokinetic-Phytoremediation, and Phytobial Remediation) are more helpful and beneficial. Cost and efficiency are the determinative factors for large-scale applications of the integration process in the severely polluted site. Biotechnological techniques are overgrowing in remediation, and the recombinant genetic engineering of bacteria and plants is one of the promising biotechniques that can enhance the Phytoremediation Approaches. As a result, due to the high demand for integrated processes, future remediation should be able to estimate the ecological impact, depth understanding of the objectives, and be more innovative. As a remediation technique, chelate extraction, chemical soil washings, and phytobial remediation require more study assessments due to their economic feasibility, extensive use, and efficacy. Future research should include creating new remediation technologies and developing the assessment methodologies for determining remediation efficacy. Governments' strict definition and implementation of new standards are also vital to environmental protection and undoubtedly significantly reduce dangerous heavy metal levels in the environment.

An in-depth understanding of the objectives of both processes is necessary for the integration process. For large-scale applications, it is essential to combine two approaches so that they can be tested and compared to their solo equivalents in terms. It has been shown that integrated strategies for heavy metal removal from various environments are becoming more popular. More analysis of the method is required to doubt the in-place operational parameters.

Acknowledgements This work was supported by the Qatar University vegetable factory project QUEX-CAS-MJF-VF-18/19.

Author Contributions MHS, KU, and MA conceived and designed the article and HAJ critically revised the manuscript and approved the final version. MHS and KU, MA wrote the manuscript. MR and HAJ critically edited and revised the manuscript.

Funding Open Access funding provided by the Qatar National Library.

Declarations

Conflict of interest There is no competing interest in the publication of this manuscript.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Written consent was sought from each author to publish the manuscript.

Data Availability Data and material is available for research purpose and for reference.

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