

# Chapter 1

## Heavy Metals in the Environment: The Global Scope



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**Abstract** Heavy metals are ubiquitous and persistent in the ecosystem leading to biomagnification. In this fast urbanization and industrialization period, environmental pollution with heavy metals poses a severe threat to human health, including ecosystem functioning, since anthropogenic releases of heavy metals (HM) into ecosystems and niches are increasing. These pollutants with very low threshold levels are poisonous, carcinogenic, and neurotoxic to human population. Their persistence and nonbiodegradable nature pose a serious concern of bioaccumulation and biomagnification through food chain resulting in deleterious consequences. Various remediation methods aim in reducing those metal concentrations in ecosystems and restore the degraded ecosystem. Remediation using microorganism techniques is a reliable option in remediation. The current chapter highlights various HM entries into the ecosystem and their toxicological consequences in the global ecosystems and summarizes various strategies to mitigate the heavy metal contaminants in various environment. Various policy and regulatory outlines in effective remediation of these toxic metals are briefed as well. The knowledge

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gaps in terms of practical limitations and future perspectives toward remediation and mitigation have been discussed.

**Keywords** Heavy metal · Pollution · Toxicity · Carcinogenic · Biomagnification · Bioremediation · Mitigation · Health impacts

## 1 Introduction

The natural resources of Earth, which aggravate the global issue of environmental contamination (Mitra et al., 2022). Toxic metals are emitted into the ecosystem via mining, metallurgy, exploitation of minerals and fossil fuels, energy production, industry, and transport (Ukaogo et al., 2020). The toxic metals disintegrate into nontoxic forms, so their release into the water is a serious problem (Dixit et al., 2015). Fortunately, noninvasive, natural methods such as phyto- and bioremediation represent increasingly desirable solutions which are both effective and inexpensive (Sharma et al., 2016). Global environmental deterioration has been brought about by augmented industrial development and the overutilization and invasion of nonrenewable resources. The undeviating deposit of contaminants into underground aquifers is the cause of metal contamination of surface and subsurface pollution in environment (Lin et al., 2021). The toxicity and Bioaccumulation t is developing in all life forms are at risk from high quantities of these unbreakable and non-biodegradable metals (Sinduja et al., 2023). Heavy metals can be dangerous and occur in disturbed soils. Under some environmental circumstances, heavy metal accumulation in hazardous amounts might harm the environment (Kowalska et al., 2018). A healthy environment correlates to improved human health. Some dumped materials containing heavy metals in open dumpsites are of concern and represent risks to humans in contact with the soil and plants poisoned by heavy metals resulting from improper waste management (Rani et al., 2024). Waste creation and disposal are the primary reasons of metal pollution. Discarded material is disposed in these dumpsites. There are no waste disposal criteria proposed, resulting in the mixing of waste and the formation of leachate, which is then deposited in soil and groundwater. The disintegration of humic materials in municipal solid waste by microorganisms produces toxic liquids known as leachate, which contain organic matter, macroinorganic components, and heavy metals that pollute eco biomes (Wang & Qiao 2024).

HM are menacing—their presence in the environment, even in trace amounts, is a problem for the environment. Minor fluctuations in heavy metals range above the threshold levels' permitted limit and cause a great concern since they lead to serious environmental and health consequences. The use of municipal waste as fertilizer, contaminated irrigation water, and agricultural practices including applying pesticides and herbicides are examples of anthropogenic sources of heavy metal contamination. Additionally, the anthropogenic source includes trash disposal in farming, mining activities, smoking, transportation emissions, sewage discharge,

and building materials such as paint. Contaminants on farmlands bioaccumulate in the food web, posing significant health risks. Monitoring their concentrations is crucial owing to their harmfulness (particularly Cd and Pb), persistence, and non-biodegradability. Monitoring HM levels is crucial for assessing human exposure and ensuring a sustainable ecosystem, especially when anthropogenic activities rise. Use systematic remediation techniques to remove accumulated metals from ecosystems contaminated by heavy metals.

## 2 Heavy Metal Contamination in Environment

The surroundings in Earth's system with industrialization has rapidly expanded and exacerbated the global environmental heavy metal pollution issue (Huddart & Stott, 2020). Environmental contaminants or pollutants are chemicals that are more common in one area of the environment than in another. Their concentration is five times that of water (Ruba et al., 2021). When the pace of building exceeds the rate of outflow, they become hazardous (Nunes et al., 2021). Since the need for food safety is rising, these contaminations are significant and cause for concern (Zulfiqar et al., 2022).

## 3 Origins of HM

HM can be found on soil in trace concentrations ( $<1000 \text{ mg kg}^{-1}$ ) due to natural resource breakdown processes; however, they are rarely harmful. Increased levels of heavy metal pollution can result from a variety of biogeochemical process (Teimoory, 2019). Environmental heavy metal accumulation is influenced by the bed rocks, its qualities, and anthropogenic activities such as farming, irrigation, traffic, and industrial production. The amount of HM in land is mostly established from parent material content. The contamination ranges are increased by urbanization-related heavy metal emissions in addition to man-made variables (Mishra et al., 2019). Metal-containing solids include metal mine stakeouts, lead-based paints and gasoline, fertilizer application, animal manures, compost, petrochemicals, pesticides, residues from burning coal, biosolids (sewage sludge) in inadequately protected landfills, and atmospheric deposition (Borah et al., 2020).

## 4 Atmospheric Contamination of HM into Environment

Airborne particulate matter (TMs) eventually deposits through raining and dust and smog leading to HM accumulation with pollutants in eco biomes. Furthermore, the trace metals that are left on the ground may be washed away by rainwater runoff,

which would increase the general level of pollution in the receiving water bodies (Siddiqui & Pandey, 2022). Significant heavy metal discharge occurs in industrial areas where stationary and mobile sources of heavy metal pollutants exceed natural emission limits (Gangwar et al., 2019). Additionally, dust and other airborne particles may be produced by heavy metals in the soil, thus lowering air quality. Long-term inhalation of significant amounts of heavy metal particles may increase the body's burden of these metals and provide a health risk (Bharti & Sharma, 2022).

## 5 Soil Contamination with Heavy Metals

HM has a relation to possible risks and occurrences in polluted soils. Typically, the content of metals in soil varies from less than 1 to 100,000 mg/kg and has not disintegrated and has an extended half-life. This makes them a significant ecological and environmental concern (Asare & Afriyie 2020). Environment, in contact with the metals that have been released from their parent substance. Because they can be easily absorbed by plants through their roots and subsequently distributed throughout their entire body, the soluble versions are more dangerous. The soluble forms are more hazardous because plants can readily absorb them through their roots and then distribute them throughout their entire body. The deposition of metal from vehicles and industry, thriving the movement of toxicity accumulated on the lane and in the proximity of industries, has been proven to significantly contaminate soils (Zwolak et al., 2019). Heavy metals are the most common class of inorganic contaminants, and they have been connected to changes in the biomes (Borah et al., 2020) and when the topsoil is used as a growing medium for plants transmits a variety of pollutants to groundwater, surface water, the atmosphere, and food (Fazeli et al., 2019). Poisonous metals enter plants through the abiotic environment (mostly the soil), but they can enter animals via both the biotic and abiotic environments, either directly or indirectly. These can quickly build up to lethal amounts. When they are eaten through contaminated food and enter the stomach's acidic environment, they convert into their stable oxidation forms and mix with certain proteins and enzymes (Zhang & Wang, 2020).

## 6 Pollution of HM in Aquatic Ecosystem

The tremendous expansion of industries has resulted from wastewater discharge into the ecosystem. Due to the severe worldwide problem of water pollution, this poisoned soil and ultimately led to the accumulation of heavy metals in living organisms, from the level of individual aquifers and wells to the international level (Ali et al., 2021). Heavy metal accumulation brought on by the prolonged application of wastewater to crops and soil can impair soil function, lowering the nutritional value of vegetables (Khalilzadeh et al., 2020).

## 7 Food Chain Contamination of HM

HM are released from physical, chemical, and biological processes and human activity (Table 1.1). Studies show that they spread throughout the food web after being absorbed by crops and released into the environment. Both people and animals consume a lot of hyperaccumulated plants. When it comes to Pb, plants absorb the heavy metal from air dust, whereas sewage water can contain As and Hg. As they ascend the food chain, certain heavy metals tend to concentrate on top consumers (Sonone et al., 2020).

## 8 Present Scenario of Heavy Metal Pollution

HM pollution contaminated in ecosystem is a widespread alarm (Rashid et al., 2023). Aside from geogenic and climatic conditions, the prime causes of contamination currently are rapid development and widened manufacturing technology applications. Most likely as a result of the previously described problems, there may not be enough knowledge about how detrimental these compounds are to agricultural and human health (Hasnine et al., 2017; Ahmed et al., 2019). Burning fossil fuels in vehicles emits pollutants that contain heavy metals. These pollutants can contaminate soils through dry or wet deposition (Soleimani et al., 2018). Urban soils are commonly contaminated with HM including Pb, Zn, Cr, Ni, and Cd. These inorganic pollutants are extensively investigated due to their potential to cause harmful health impacts. In contrast to organic molecules, they are persistent in the environment and present long-term toxicity hazards to humans, animals, and vegetation (Yadav et al., 2019; Yuan et al., 2021). High levels of heavy metals, especially lead (Pb), due to the use of leaded gasoline (Guagliardi et al., 2015).

**Table 1.1** Entry of heavy metal through food chain into the environment

As	As <sup>+3</sup>	Arsenate attaches itself to reduced nitrogen or amino groups, whereas As adheres to plant phytochelatin and S-based proteins	Ali et al. (2021)
Cd	Cd <sup>+2</sup>	Cadmium is carried in the form of Cd amino chains known as Cd metallothionein that accumulates in the organs of the human body	Peana et al. (2022)
Cr	Cr <sup>+6</sup>	Reduced and complexed organic acids and other root exudates make Cr more soluble and mobile in the root xylem tissues, which makes it easier to remove from the soil	Ao et al. (2022)
Pb	Pb <sup>+2</sup>	Pb attaches to ion-exchangeable spots in the cell walls after navigating the root cell membranes and joining the food chain	Athukorala (2021)
Ni	Ni salts	By absorbing dust and salts from the soil, water is transferred to plants, and bioaccumulation allows them to enter the food chain	Nnaji et al. (2023)
Hg	Methyl mercury	Hg attaches itself to root tissue, decreasing transit within the plant and human body bioaccumulation	Baig et al. (2020)

Five million places worldwide have elevated soil concentrations that are over the set regulatory thresholds (Li et al., 2019). The rate exceeds the limit by 16%, exceeding the threshold by as much as 7.0%, 2.7%, 1.6%, 1.5%, and 1.1% correspondingly (Zhao et al., 2022). The global emission of Cd in 2009 amounted to 743.77 tons, as reported by (Bermudez et al., 2012). According to Cheng et al. (2014), 40,000 tons of chromium and 800,000 tons of lead are discharged globally during its course of the last 50 years. The majority of these metallic elements have already been deposited in the soil. Nevertheless, prolonged toxicity is detrimental, such as the development of lung cancer and bone fractures (Rai et al., 2019). Table 1.2 provides a listing of concentration of HM found in soils across the globe.

One of the biggest challenges facing humanity in the twenty-first century is the quick advancement that has taken place in recent decades due to increased awareness and attention to soil quality (Liu et al., 2016). In China, the heavy metal contamination of agricultural soil has emerged as an alarming problem. China is currently dealing with challenges related to polluted sites, unlike the USA and Europe, which have extensive expertise in managing such sites (Li et al., 2016). There are various types of contaminated areas in China, but mining districts and polluting companies are two of the most prevalent types (Yan et al., 2022).

Beltran-Peña et al. (2020) suggested to boost global agricultural production by 2050 in order to meet the projected demands. There are various types of contaminated areas in China, but mining districts and polluting companies are two of the most prevalent types. This is particularly concerning in the most vulnerable regions on the planet, as it increases the menace of worsening food crisis (Kopittke et al., 2019). Human exposure can occur through a variety of routes, including as eating contaminated food, breathing in particles, eating them, and absorbing them through the skin (Anaman et al., 2022). There are over ten million polluted sites that have been identified globally, and more than 50% of these sites have been confirmed to have metal toxicity (Khalid et al., 2017). The higher concentrations of toxic elements (TEs) in heavily industrialized and densely populated cities are mostly attributed to emissions from power plants, industrial activities, and the pollution generated by heavy traffic.

The pollution index indicates that the majority of the soils are experiencing varying degrees of pollution, ranging from slight to severe, and are approaching the danger threshold. The soil contamination alert levels were determined in Thailand, Nigeria, and Mongolia using the Nemerow Pollution Index values of 0.7, 0.9, and 1, respectively. The USA has detected soils that are highly polluted with a Nemerow Pollution Index value of 36. The pollution index values analyzed indicate harmfulness of toxicity range (Weissmannová et al., 2015). The geo-accumulation index ( $I_{geo}$ ) and enrichment factor (EF) are utilized for assessing soil contamination in various regions and verifying the amounts of toxic metal pollution in soil (Rinklebe et al., 2019).

**Table 1.2** Global heavy metal concentrations (mg/kg) from different regions

Regions	HM	Adsorption rate (mg/kg)	Permissible limit (maximum)	Number of times exceeding permissible limit	Reference
Greece	Chromium	418	100	4.2	Panagopoulos et al. (2015)
Sri Lanka		14,880	100	148.8	Herath et al. (2015)
Albania		3117	100	31.2	Shtiza et al. (2005)
Germany		224	100	2.2	Shaheen et al. (2014)
China	Cadmium	14	3	4.7	Shi et al. (2015)
Italy		42	3	14.0	Baldantoni et al. (2016)
Germany		8.1	3	2.7	Hindersmann and Mansfeldt (2014)
Iran		2.15	3	0.7	Khanlari and Jalali (2008)
Germany	Arsenic	15.5	20	0.8	Antoniadis et al. (2017)
Spain		7490	20	374.5	Beesley et al. (2014)
Korea		131	20	6.6	Ko et al. (2015)
Germany		35.9	20	1.8	Hindersmann and Mansfeldt (2014)
Germany		90.8	20	4.5	Shaheen and Rinklebe (2015)
Bolivia		64	20	3.2	Acosta et al. (2015)
China	Lead	1988	100	19.9	Niu et al. (2015)
Brazil		302	100	3.0	Carvalho et al. (2015)
Germany		294	100	2.9	Antoniadis et al. (2017)
Germany		412.1	100	4.1	Shaheen and Rinklebe (2015)
Uganda		452	100	4.5	Nabulo et al. (2011)
Spain	Nickel	373	50	7.5	Arenas-Lago et al. (2016)
Sri Lanka		6567	50	131.3	Herath et al. (2015)
Italy		1582	50	31.6	Bini et al. (2017)
Mexico		2603	50	52.1	Torres et al. (2012)
Germany		98	50	2.0	Hindersmann and Mansfeldt (2014)

## 9 Toxicological Consequences of Heavy Metal Contamination in Global Ecosystems

### 9.1 *Metal Essentiality*

Metals are essential in today's industrial civilizations and have a vast array of applications. It takes specific metals and metalloids to survive (biologically). Because they can be a part of biomolecules, they can increase the body's biological activity (Ali et al., 2021).

### 9.2 *Significance and Modes of Contamination*

Technically, metals and metalloids, weight  $\geq 5 \text{ g/cm}^3$ , are classified as HM. However, because of their large dose, these elements penetrate the food chain and manifest as extremely deadly substances for plant and animal communities (Lakherwal, 2014). Their toxicity causes both direct and indirect disruptions to the environment and life systems. It has been found that heavy metals are teratogenic, mutagenic, and carcinogenic. They produce reactive oxygen species (ROS), which lead to oxidative stress. Loss of hemoglobin and major and minor diseases are caused by exposure to HM in humans. HM exposure also damages biological entities of human (Zeraatkar et al., 2016). Because these HM are persistent in the system, they cannot decompose and can accumulate in huge quantities over time, and their toxicity remains in the environment for an extended period. With industrialization progressing at an alarming rate, the presence of HM in ecosystems has become inevitable. This can be attributed to an increase in anthropogenic sources. Regardless, various natural sources also contribute to the increasing toxicity. Excessive chemicals as well as indiscriminate irrigation with brackish water are major sources of harmful metals in agriculture (Ghuge et al., 2023).

Toxic metal emissions into the environment can occur naturally or as a result of human activity. Leaching, erosion of soil and metals, and volcanic eruptions are examples of natural causes; industrial, geothermal, pharmaceutical, and agricultural sources are other sources. Anthropogenic causes include unintentional releases like fires and mining accidents, incidents at oil refineries that involve the intended use of biocides like vector control, and the disposal of waste materials like sewage and industrial effluent. Heavy metal toxicity is assessed using many criteria, including dose, mode of exposure, and medium (Kumar et al., 2022). Additional variables that regulate pollutants' movement and dispersion include the partition coefficient and polarity (Walker et al., 2012).

### ***9.3 Biomagnification in Ecosystems***

These toxic metals accumulate while ingested/breathed in—bioaccumulation is the process wherein the organism's body increases. This might result from consuming food tainted with heavy metals regularly. HM are dispersed anthropogenically and accumulate in substrates, including soil, water, sediments, plants, and so on. For example, dumping solid waste and industrial effluent into adjacent aquatic sources contaminates the water and sediments. The intake or inhalation of the metal, its velocity of entry, its distribution in tissues, the concentration attained, its rate of excretion, and an excessive amount of the metal and its negative effects. The amount of heavy metal buildup in the biota has been defined with particular vocabulary (Ali et al., 2021). Many factors, including soil physiochemical factors and metal speciation, affect the bioavailability of metal and affect how well plants absorb heavy metals.

### ***9.4 Toxicity in Various Ecosystems***

Reactive oxygen species production is an indirect mode of toxicity, while structural alteration is the direct method. Biological components like enzymes, mitochondria, nuclei, lysosomes, and cell membranes cause damage (Tchounwou et al., 2012). Metal poisoning occasionally results in the production of free radicals, damages DNA, affects sulfhydryl equilibrium, and induces lipid peroxidation (Briffa et al., 2020). Organisms can eliminate metal ions by encasing the active ingredient in amino acid or accumulating inside particles within the cell as unsolvable condition for subsequent expulsion in the organism's stool.

Metals with lower limits are considered potentially harmful, while those with higher levels are considered relatively less dangerous. Because the limitations for lead in soil are greater than those for zinc, copper, and cadmium, even low concentrations of cadmium may be hazardous. Copper is found in higher concentrations in plants, followed by lead, zinc, and cadmium.

### ***9.5 Absorption of HM in Aquatic Ecosystems***

In aquatic species with sources such as sediments, overflow and erosion of soil, dust and aerosol depositions in the air, and wastewater discharges absorb these toxic metals. These metals absorbed by the bodies of aquatic species eventually are absorbed by humans. A few incidents from the twentieth century have demonstrated the seriousness of this poisoning to human health. Fish contaminated with mercury (Hg) and rice polluted with copper (Cu) cause diseases. Organic forms of metals are more available for absorption than ionic forms. Metals can be absorbed through the

skin if they are dissolved in water or through food if they are in particle form (Sonone et al., 2020).

It is acknowledged that sediments are an important source of toxic metals in aquatic environments (Singh et al., 2017). When metals enter the water, they spread throughout the water, settle in the sediments, or group together. Sediments act as a long-term reservoir for heavy metals in aquatic environments. Lake sediments are rich natural archives that provide long-term records of historical climate and environmental changes, including catchment processes and biological community shifts, and record human-caused environmental issues. Lake sediments acquire diverse chemicals through production and adsorption mechanisms. Metals build up in sediments through various processes like forming solid compounds, attaching to small particles, combining with organic molecules, or mixing with metal or manganese oxides or carbonates with conditions in water and sediments. Because the metals can be remobilized, they pose a continuous threat of contamination.

## 9.6 *Terrestrial Ecosystem*

Heavy metals accumulate in soil due to transportation, trash stacking, sewage irrigation, industrial pollutants, and pesticide and fertilizer use (Long et al., 2021). In terrestrial ecosystems particularly soil, HM pollution has a profound effect on microbial communities. It has been observed that the activities of soil enzymes are inhibited. Long-term overuse of inorganic enrichers and pest control stimulants accumulates heavy metals in cultivation and lowers soil fertility, which in turn lowers crop growth. For instance, phosphatic fertilizers are made mostly from apatite mineral which consists of HM are used for extended periods, agricultural soil has a larger potential for Cu, Zn, and Cd accumulation. HM imparts toxicity to the native soil microorganisms, disrupts the growth and morphological and metabolic activities of soil microorganisms by causing protein denaturation (Naz et al., 2022) and cell membrane damage, and affects the production of enzymes like dehydrogenase, phosphatases, ureases, etc. Besides soil microbes, HM has adverse consequences for earthworms, including decreased reproduction, reduced biomass, altered cytokinesis and antioxidant enzyme activity, nephridia damage, and DNA damage.

The Cu availability is typically influenced by several factors, including soil pH, as it is more readily available in lower pH. Application with pesticides like cypermethrin and acetochlor adds Cu to the soil. Cu poisoning could dramatically lower the microbiological activity of the soil. Additionally, Cu poisoning can cause bacterial protein denaturation and disrupt cell membranes. The bacteria that the toxin had the biggest negative effects on happened to be in a particular order: bacteria > actinomycetes > fungi. Zn is a significant element for crop growth; nevertheless, higher levels of zinc disturb soil equilibrium. Zn is a key mineral that stimulates the production of hormones and proteins. An excess of Zn can result in negative properties in crops such as photosynthetic inhibition, loss of chlorophyll, and nutritional imbalances at various stages (Mossa et al., 2020). Zinc toxicity is strongly linked to soil

enzyme active sites, where it replaces specific cations that are crucial for cellular functions. High soil pH improved Zn bioavailability. Furthermore, suppression of microbial enzymatic activity was observed.

Among other heavy metals, lead pollution most commonly originates from geogenic sources, and it also lowers soil microbial activity decreasing fertility, microbial diversity, and soil nutrients. The key variables impacted by Pb deposition were soil pH and cation exchange capability (Kumar et al., 2020a, b), suggesting that a malfunction is caused by Pb absorption.

At high Pb concentrations, the number of bacteria and actinomycetes reduced. The release of Cd in ecosystem is caused by manmade actions, like mining, the use of manures, landfills, sewage sludge, transportation, wastewater, and chemical fertilizer (Han et al., 2023).

Natural sources produce low quantities of chromium in the atmosphere and aquatic habitats. Chromium toxicity to ecosystems mainly comes from anthropogenic sources like electroplating industries, tanning units, alloys, dyes, paints, combustion of coal, etc. Because it is not easily dissolved in water, it tends to settle deeper in the soil and enter underground water. It accumulates in benthic aquatic life; small fish to large fish in aquatic ecosystem store significant quantities of chromium and are magnified up the food chain. Complexes containing Cr<sup>3+</sup>, peptides, DNA, and proteins inside the cell can cause DNA lesions, including DNA-protein, or DNA-DNA cross-links, DNA-Cr adducts, changes in cellular signaling pathways, and DNA strand breaks. These lesions may contribute to chromium toxicity and carcinogenesis (Briffa et al., 2020). A more detailed review of heavy metals and toxicity effects on humans is reviewed by (Alengebawy et al., 2021) (Table 1.3).

**Table 1.3** Toxicity of some heavy metals in humans and plants

S. no.	Metal	Toxicity	Reference
1.	Arsenic	Hormonal effects, respiratory illness, black foot disease, carcinogenic, enzyme inhibition, process inhibition in plants	Ahmed et al. (2022)
2.	Cadmium	Nervous system damage, DNA damage, root damage, altered protein contents, nutrient uptake inhibition, etc.	Aslam et al. (2022)
3.	Chromium	Immune system damage, kidney and liver damage, lung cancer, damage to hereditary materials, inhibits plants' morphological growth	Singh et al., (2023); Srivastava et al. (2021)
4.	Zinc	Anemia, damage to the immune system, disrupts soil microbial enzyme activities, root damage, inhibition of plant growth	Briffa et al., (2020); Kaur & Garg, (2021)
5.	Copper	Nausea, liver damage, kidney problems, respiratory illness, decreased root and shoot formation	Alengebawy et al. (2021); Kumar et al. (2022)
6.	Mercury	Organ damage like the brain and kidney, long-term neurological damage, weakens the immune system, oxidative stress in plants	Briffa et al. (2020); Jadaa & Mohammed (2023); Natasha et al. (2020)

## 9.7 Mitigation Measures for Contamination of Heavy Metals

Bioaccumulative nature had a disastrous effect, raising severe concerns. Therefore, it is important for remediation approaches (Qasem et al., 2021; Zehra et al., 2020).

**Physical remediation:** Its primary purpose is to either stabilize or eliminate pollutants from soil to stop them from spreading throughout the ecosystem. Techniques such as excavation and land filling and thermal desorption are examples of ex situ remediation, while the in situ methods comprise of surface capping, encapsulation, vitrification, electrokinetics, etc. (Sánchez-Castro et al., 2023a, b).

**Chemical remediation:** Various chemical reactions can be utilized to change the movement and bioavailability of heavy metal pollutants. It includes chemical solubilization, chemical stabilization, redox transformations, and chemical coagulation (Zamora-Ledezma et al., 2021).

**Bioremediation:** Using plants, animals, and microorganisms for the toxic heavy metal removal from polluted soil and waste waters is a sustainable approach with prolonged environmental benefits at low cost (Dixit et al., 2015). A number of writers have recently used phytoremediation and bioremediation. Living things are known to detoxify harmful substances in the environment. Remediation techniques with treatment removal efficiency, economic and environmental viability, etc. However, the conventional treatments (Fig. 1.1) for heavy metal remediation are discussed below.



Fig. 1.1 Conventional heavy metal contamination remediation techniques

## **9.8 Adsorption**

Adsorption is one of the less expensive methods for remediating heavy metals (Burakov et al., 2018), wherein the adsorbate (heavy metal) migrates to the adsorbent and then bonds through physisorption (weak van der Waals force) or chemisorption (strong covalent bonds).

Most adsorbent for remediation is the activated carbon (Kaveeshwar et al., 2018). Activated carbon derived from agro-industrial residue following the activation process reached adsorption capacity of wastewater (Yunus et al., 2020). Several reports indicate adsorbent efficiencies generated from agricultural wastes like wheat wastes (70.71), rice husk (66.67), and industrial wastes like blast furnace slag (83.84) and fly ash (75–77) (Qasem et al., 2021).

## **9.9 Membrane Filtration**

This process separates the elements through selective membranes solution concentration. The main techniques include RO, ultrafiltration, nanofiltration, and microfiltration (Gunatilake, 2015). Membranes are inclined by various factors like size and pore distribution, hydrophobicity, surface charge, and presence of functional groups (Abdullah et al., 2019). Reverse osmosis membranes can eliminate up to 99% of metals such as arsenic ( $\text{As}^+$ ), cadmium ( $\text{Cd}^{2+}$ ), etc. from wastewaters (Bodzek, 2015). Shukla et al. (2018) recommended that nanocomposite membranes can achieve around 80–98% removal efficiency of arsenic, chromium, lead, and cadmium from water resources.

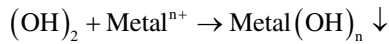
## **9.10 Chemical Coagulation and Flocculation**

Upon addition of coagulant such as aluminum sulfate (alum), ferric sulfate, polymeric ferric sulfate, etc. to water, it excites coalescence of colloids into smaller aggregates called flocs. They further agglomerate under gentle agitation, resulting in slurry after settling (Teh et al., 2016).

## **9.11 Biochemical Precipitation**

It is the considerable method to remediate toxic metals through various industrial effluents. Chemical precipitants like alum, lime and polymers, etc. react with heavy metals in the effluent forming insoluble precipitates that can be removed directly (Verma & Balomajumder, 2020). However, the removal efficiency depends on

factors like temperature, pH, heavy metal concentrations, etc. The mechanism of chemical precipitation for heavy metals removal is as follows:



where (OH) is the precipitant. This method is reported to have high remediation of toxic metals (Carolin et al., 2017).

## 9.12 Ion Exchange

This remediation progression is broadly implemented for toxicity exclusion owing to kinetics, slurry disposal complications, and higher removal efficiency. This process involves using an ion-exchange resin to substitute cations and anions in electrolytic materials (Lalmi et al., 2018). The ionic conversation resin may be synthetic or natural material, while synthetic resins are more effective in heavy metal removal. Following the removal of the loaded resin from the contaminated area (Azimi et al., 2017).

# 10 Bioremediation

## 10.1 Microbial Remediation

Microorganisms like bacteria, fungi, yeast, and algae have the prospective in removal, and this utilization progression is termed as microbial remediation (Enerijiofi, 2021). Most important mechanisms involved in microbial remediation include sequestration, detoxification, exclusion, and complex formation (da Silva Ferreira et al., 2020). Microorganisms respond differently to diverse heavy metals under various environmental factors (Maier and Gentry, 2015). Bioaccumulation, biotransformation, bioleaching, bioprecipitation, biosorption, etc. are types of microbial remediation. Bacterial metabolites exhibit heavy metal detoxification potential by sequestering metal ions inside their cells and siderophores produced from HM (Nnaji et al., 2023; Hassan et al., 2017; Rajkumar et al., 2010). Biotransformation of toxic heavy metals in sediment by microbes is reported (Rajapaksha et al., 2013). Bioleaching is an oxidation process occurring directly through bacterial metabolic activity or indirectly through their by-products (Abd Elnabi et al., 2023). Biosorption refers to sorption of heavy metals onto binding sites of microbial cell walls (adsorbent) which is a metabolism-independent process, and heavy metal toxicity does not disturb the microbial performance (Sánchez-Castro et al., 2023a, b) The cell structure, intracellular accumulation, and extracellular precipitation impact the biosorption process. Few microbial organisms involved in microbial remediation are listed in Table 1.4.

**Table 1.4** Microorganisms for bioremediation of heavy metals

Microorganisms	Removal of HM	Reference
<b>Bacteria</b>		
<i>Pseudomonas veronii</i>	Cd, Zn, Cu	Sadia and Kabir (2023)
<i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i>	Cr	
<i>Bacillus</i> sp.	Pb, Cd	Desoky et al. (2020)
<i>Bacillus cereus</i> S13 and S25	Pb, Co, Cr	Olubode et al. (2022)
<i>Bacillus</i> sp. SW2 and SW4	As	Dey et al. (2016)
<b>Fungi</b>		
<i>Aspergillus niger</i>	Cr, Cu, Zn, Pb, Th, Co	Gururajan and Belur (2018); Taştan et al. (2010)
<i>Aspergillus fumigatus</i>	Pb	
<i>Rhizopus arrhizus</i>	Cd, Th, Cu, Zn	
<i>A. versicolor</i>	Ni, Cu	

## 10.2 Phytoremediation

Plant based technology for pollutant removal is termed as phytoremediation, a low cost and simple approach. The phytoremediation technique involves phytoextraction, phytoaccumulation, phytovolatilization, phytodegradation, phytostabilization, and rhizofiltration (Gaur et al., 2021). Table 1.2 shows a list of potential heavy metal accumulator plants. Hyperaccumulator shrubs by means of higher chelators are also adapted genetically to expand metal accumulation capacity (Cristaldi et al., 2017). Rafati et al. (2011) examined the accumulation potential in *Morus alba* and *Populus alba* from soil and found the accumulation of heavy metals in leaves and stem. The process of phytovolatilization reduces the toxicity of the absorbed harmful heavy metals (Agarwal et al., 2019; Edwards et al., 2011). The process of phytovolatilization reduces the toxicity of the absorbed harmful heavy metals (Leduc and Terry, 2005). By preventing heavy metal mobility by adsorption on roots and precipitation in the rhizosphere, the phytostabilization reduces the movement of contaminants in soil (Awa and Hadibarata, 2020). However, this process only inactivates and stabilizes heavy metals. Rhizofiltration is widely used to remediate aqueous environment with HM. The plants absorb and precipitate the contaminants through rhizosphere. *Helianthus annuus* and *Phaseolus vulgaris* were reported with more than 90% removal efficiency for uranium from contaminated groundwater through rhizofiltration (Sharma & Pandey, 2014). Various factors influencing the phytoremediation efficiency are plant species selection and its microbial interaction, soil properties, contaminant concentration, environmental conditions, etc. (Salifu et al., 2024) (Fig. 1.2; Table 1.5).

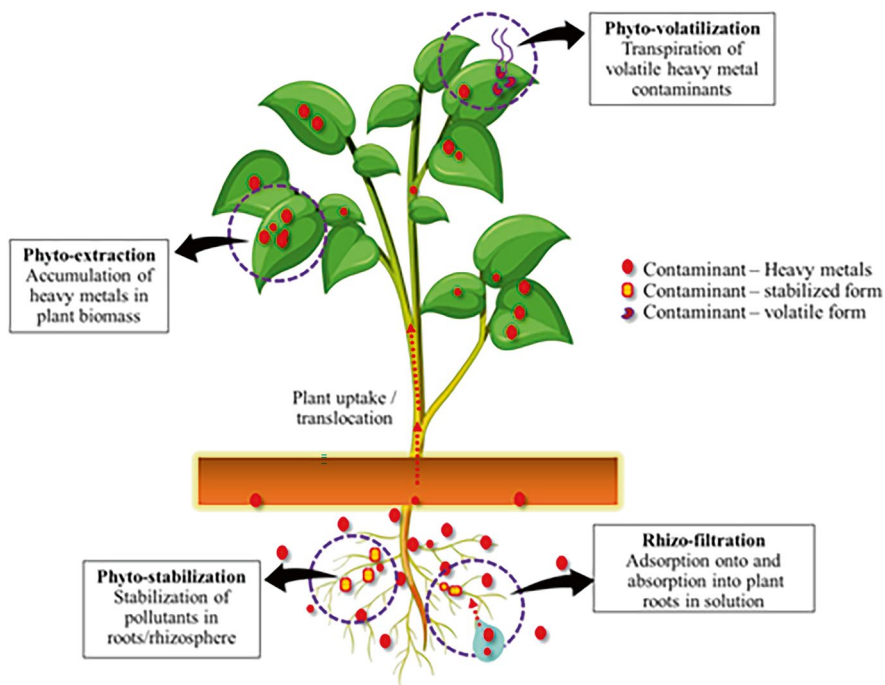


Fig. 1.2 Phytoremediation strategies for heavy metal removal: a schematic representation

Table 1.5 List of few heavy metal accumulator plants for phytoremediation

Botanical name	HM	Reference
<i>Corrigiola telephiiifolia</i>	As	García-Salgado et al., (2012)
<i>Pteris vittata</i>		Kalve et al. (2011)
<i>Eleocharis acicularis</i>		Sakakibara et al. (2011)
<i>Turnip landraces</i>	Cd	Li et al. (2016)
<i>Phytolacca americana</i>		Peng et al. (2008)
<i>Prosopis laevigata</i>		Buendía-González et al. (2010)
<i>Haumaniastrum robertii</i>	Co	Marques et al. (2009)
<i>Achillea millefolium</i>	Hg	Wang et al. (2012)
<i>Silene vulgaris</i>		Pérez-Sanz et al. (2012)
<i>Marrubium vulgare</i>		Rodríguez et al., (2003)
<i>Alyssum murale</i>	Ni	Bani et al. (2010)
<i>Alyssum serpyllifolium</i>		Prasad (2005)
<i>Isatis pinnatifolia</i>		Altinözlü et al. (2012)
<i>Medicago sativa</i>	Pb	Koptsik (2014)
<i>Brassica juncea</i>		
<i>Lecythis ollaria</i>	Se	Marques et al. (2009)
<i>Astragalus racemosus</i>		

### ***10.3 Biomagnification in Food Chain***

Agriculture, urbanization, population growth, rapid industrialization, and extensive heavy metal contamination, especially in developing nations. These activities send large amounts of heavy metals into rivers, where they can accumulate and biomagnify, producing sublethal in aquatic populations. Fish are regarded as one of the most common bioindicators of pollution due to their higher trophic status in the food chain. Again, humans have long relied on fish as a key source of protein (Ali & Khan 2018). It has the potential to disturb the growth of plankton, crustaceans, and mollusks while also reducing photosynthetic activities, hence impacting ecological processes and aquatic ecosystem productivity. The first avenue of accumulation is known as bioaccumulation, while the second is known as food accumulation. Biomagnification, also known as biological magnification or biomagnification, is the progressive surge in the levels of a pollutant at each trophic level in a food chain (Danovaro et al., 2023).

### ***10.4 Bioaccumulation and Trophic Transfer***

Bivorous insects are the main eaters of plants and serve a vital role in providing many animal groups with proteinrich food in the majority of Earth's ecosystems. These insects are exposed to heavy metals primarily via consuming plants directly, transporting to humans (Cristaldi et al., 2017). The arthropods then transport the toxicity, up the food chain. The toxicity is subsequently passed up the food chain by the arthropods. Through detoxifying mechanisms, physiological concentrations of heavy metals, including hazardous and trace elements, build up (Dar et al., 2020).

### ***10.5 Policy Implications***

A significant amount of China is covered with heavy metal polluted soils, and the dangers these soils pose to individuals, livestock, vegetation, and groundwater are getting worse. As a result, it's critical to create standards and criteria that may be applied to determine the level of danger associated with contaminated soils or to set parameters for their remediation. In agricultural land located in industrial towns, Chinese government agencies have released pertinent prevention and protection policies (Wang et al., 2015). These efforts are part of an effort to create an efficient framework for such treatment and management (Qin et al., 2020).

A comprehensive (RD&D) strategy has been implemented by the Chinese government to encourage the creation of cutting-edge technology for the reduction and prevention of pollution.

## 11 Future Perspectives and Challenges in Addressing Heavy Metal Toxicity

Heavy metal (HM) contamination endures to be a significant environmental and public health challenge, necessitating advanced and comprehensive approaches for mitigation and management. Globally, there are over ten million recorded sites with contaminated soil, and over 50% of those sites contain HM and/or other contaminants (Sánchez-Castro et al., 2023a, b). Though they show an important role in humans and animals, the excess levels cause severe health hazards. Various organs and body systems are affected. HM toxicity creates major issues in both grown-ups and children through inhalation, ingestion, and skin adsorption.

## 12 Advances in Detection and Monitoring

One of the foremost challenges is the detection and monitoring of HM pollution. Rapid and precise detection of HM, as well as knowing their spatial distribution, is crucial for managing and preventing regional pollution. HM ion detection techniques fall into three categories: spectroscopic, electrochemical, and optical (Malik et al., 2019). Spectroscopic methods employ light to calculate the intensity of a substance when it absorbs or emits the incident light. It takes considerable sample preparation before testing, which increases the likelihood that the sample will become contaminated with another type of contamination. Thus, there is always the potential that reliable detection findings will not be achieved. Other than these, chemiluminescence and ion-exchange methodologies are also employed widely for detecting HM yet have many disadvantages (Kumar Shakya & Singh, 2022).

Portable and real-time monitoring devices using nanotechnology and biosensors are being developed, and they could revolutionize how we track and manage heavy metal levels in the environment. However, the challenge remains in scaling these technologies for widespread use and ensuring their robustness in different environmental conditions.

## 13 Remediation Technologies

Currently, there are four techniques for disposing of contaminated crops after phytoextraction by plants: direct disposal, incineration, ash, and liquid extraction (Cui et al., 2021). Since these metals cannot be degraded but can only be transferred from one form or medium to another, the phytoremediation itself poses several challenges. Nonetheless, in future investigations, scientists should discover strategies for extracting or permanently removing heavy metals from the soil. As mentioned earlier, phytoremediation, using plants to absorb and detoxify metals, and

bioremediation, employing microorganisms to degrade or immobilize metals, further need to be explored. The primary challenge is optimizing these technologies for large-scale applications and ensuring they do not introduce secondary pollutants into the environment.

## **14 Understanding Bioavailability and Toxicity Mechanisms**

The challenge lies in translating these scientific findings into practical applications that can be used in clinical and environmental settings. Workers in industries releasing heavy metals should wear protective gear to minimize everyday exposure through inhalation, digestion, or touch. Appropriate diagnosis is crucial, as symptoms can mimic other neurological conditions.

## **15 Regulatory and Policy Frameworks**

Effective management of heavy metal toxicity requires robust regulatory and policy frameworks that are informed by scientific evidence and public health considerations. Some metals have such policy implications. Nonetheless, management practices range greatly from one country to the next since only a few have or are prepared to deploy the necessary technology and infrastructure. Because of developing economies' lax environmental rules, mercury-containing wastes are generated in part because of the use of mercury for manufacturing and consumer goods. In general, HM-containing wastes, particularly mercury, should be stabilized and consolidated before disposal or permanent storage in specially built landfills and facilities. Future policies need to be adaptive and responsive to emerging threats and new scientific insights. This involves setting stringent standards for permissible levels of HM in various environments and ensuring compliance through regular monitoring and enforcement. The challenge is achieving global consensus and cooperation, as heavy metal pollution is often transboundary, requiring coordinated international efforts.

## **16 Public Awareness and Education**

Education campaigns can encourage people to support laws meant to lessen the contamination caused by heavy metals and to take preventative measures. The difficulty lies in effectively making complex scientific information understandable and useful to the general people. Collaborations between industry, government, and academia as well as multidisciplinary research projects may accelerate the development of complete remedies. Breaking down organizational divisions and fostering a

cooperative culture with shared goals among diverse stakeholders are difficult. When summed up, the management of heavy metal toxicity in the future will likely include a blend of scientific inquiry, technological innovation, regulatory action, and public participation. A coordinated and cooperative effort can open the door to a more sustainable and healthier environment, even though there are still many important obstacles to overcome.

## 17 Conclusion

Exposure to the “toxic trio” of cadmium, lead, and mercury causes a variety of negative effects, including oxidative stress, growth inhibition, acute toxicity, and increased mortality. These substances are therefore important objectives in global environmental pollution monitoring programs. A thorough understanding of the threat, as well as the emission sources, migration routes, and heavy metal transformation processes, is necessary to develop an effective strategy. Many scientific reports indicate that despite strict regulations covering the emission, they are still present in aquatic ecosystems and in the organisms inhabiting them. These techniques, which include ecohydrological biotechnologies and nature-based solutions, are affordable and socially acceptable ways to safely, noninvasively, and effectively remove heavy metals from the environment, reducing the negative effects of human impact on it again. Most importantly, though, these methods are consistent with the universal concept of “One Health,” which refers to the well-being.

## References

- Abd Elnabi, M. K., Elkaliny, N. E., Elyazied, M. M., Azab, S. H., Elkhalfifa, S. A., Elmasry, S., ... & Mahmoud, Y. A. G. (2023). Toxicity of heavy metals and recent advances in their removal: a review. *Toxics*, 11(7), 580.
- Abdullah, N., Yusof, N., Lau, W. J., Jaafar, J., & Ismail, A. F. (2019). Recent trends of heavy metal removal from water/wastewater by membrane technologies. *Journal of Industrial and Engineering Chemistry*, 76, 17–38.
- Acosta, J. A., Arocena, J. M., & Faz, A. (2015). Speciation of arsenic in bulk and rhizosphere soils from artisanal cooperative mines in Bolivia. *Chemosphere*, 138, 1014–1020.
- Ahmed, M., Matsumoto, M., Ozaki, A., Thinh, N. V., & Kurosawa, K. (2019). Heavy metal contamination of irrigation water, soil, and vegetables and the difference between dry and wet seasons near a multi-industry zone in Bangladesh. *Water*, 11(3), 583.
- Ahmed, S. F., Kumar, P. S., Rozbu, M. R., Chowdhury, A. T., Nuzhat, S., Rafa, N., Mahlia, T. M. I., Ong, H. C., & Mofijur, M. (2022). Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil. *Environmental Technology & Innovation*, 25, 102114. <https://doi.org/10.1016/J.ETI.2021.102114>
- Agarwal, P., Sarkar, M., Chakraborty, B., & Banerjee, T. (2019). Phytoremediation of air pollutants: prospects and challenges. *Phytomanagement of polluted sites*, 221–241.

- Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. In *Toxics* (Vol. 9, Issue 3, pp. 1–34). MDPI AG. <https://doi.org/10.3390/toxics9030042>.
- Ali, H., & Khan, E. (2018). Bioaccumulation of non-essential hazardous heavy metals and metalloids in freshwater fish. Risk to human health. *Environmental chemistry letters*, 16(3), 903–917.
- Ali, M. M., Hossain, D., Al-Imran, A., Khan, M. S., Begum, M., & Osman, M. H. (2021). Environmental pollution with heavy metals: A public health concern. *Heavy metals-their environmental impacts and mitigation*, 771–783.
- ALTINÖZLÜ, H., Karagöz, A., Polat, T., & Ünver, İ. (2012). Nickel hyperaccumulation by natural plants in Turkish serpentine soils. *Turkish Journal of Botany*, 36(3), 269–280.
- Anaman, R., Peng, C., Jiang, Z., Liu, X., Zhou, Z., Guo, Z., & Xiao, X. (2022). Identifying sources and transport routes of heavy metals in soil with different land uses around a smelting site by GIS based PCA and PMF. *Science of the Total Environment*, 823, 153759.
- Antoniadis, V., Shaheen, S. M., Boersch, J., Frohne, T., Du Laing, G., & Rinklebe, J. (2017). Bioavailability and risk assessment of potentially toxic elements in garden edible vegetables and soils around a highly contaminated former mining area in Germany. *Journal of Environmental Management*, 186, 192–200.
- Ao, M., Chen, X., Deng, T., Sun, S., Tang, Y., Morel, J. L., et al. (2022). Chromium biogeochemical behaviour in soil-plant systems and remediation strategies: A critical review. *Journal of Hazardous Materials*, 424, 127233.
- Arenas-Lago, D., Andrade, M., Vega, F., & Singh, B. (2016). TOF-SIMS and FE-SEM/EDS to verify the heavy metal fractionation in serpentinite quarry soils. *Catena*, 136, 30–43.
- Asare, M. O., & Afriyie, J. O. (2020). Tracing the past from the analysis of Cu, Zn, Mn, Sr, and Rb in Archaeological Dark Earth soils from the tropics and temperate zone. *Quaternary International*, 562, 13–26.
- Aslam, M. M., Okal, E. J., & Waseem, M. (2022). Cadmium toxicity impacts plant growth and plant remediation strategies. *Plant Growth Regulation* 2022 99:3, 99(3), 397–412. <https://doi.org/10.1007/S10725-022-00917-7>
- Athukorala, A. S. N. (2021). Solubilization of micronutrients using indigenous microorganisms. *Microbial Technology for Sustainable Environment*, 365–417.
- Awa, S. H., & Hadibarata, T. (2020). Removal of heavy metals in contaminated soil by phytoremediation mechanism: a review. *Water, Air, & Soil Pollution*, 231(2), 47.
- Azimi, A., Azari, A., Rezakazemi, M., & Ansarpour, M. (2017). Removal of heavy metals from industrial wastewaters: a review. *ChemBioEng Reviews*, 4(1), 37–59.
- Baig, M. A., Qamar, S., Ali, A. A., Ahmad, J., & Qureshi, M. I. (2020). Heavy metal toxicity and tolerance in crop plants. *Contaminants in agriculture: sources, impacts and management*, 201–216.
- Baldantoni, D., Morra, L., Zaccardelli, M., & Alfani, A. (2016). Cadmium accumulation in leaves of leafy vegetables. *Ecotoxicology and Environmental Safety*, 123, 89–94.
- Bani, A., Pavlova, D., Echevarria, G., Mullaj, A., Reeves, R. D., Morel, J. L., & Sulçe, S. (2010). Nickel hyperaccumulation by the species of *Alyssum* and *Thlaspi* (Brassicaceae) from the ultramafic soils of the Balkans. *Botanica Serbica*, 34(1), 3–14.
- Beesley, L., Inneh, O. S., Norton, G. J., Moreno-Jimenez, E., Pardo, T., Clemente, R., & Dawson, J. J. (2014). Assessing the influence of compost and biochar amendments on the mobility and toxicity of metals and arsenic in a naturally contaminated mine soil. *Environmental Pollution*, 186, 195–202.
- Beltran-Peña, A., Rosa, L., & D’Odorico, P. (2020). Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. *Environmental Research Letters*, 15(9), 095004.
- Bermudez, G. M., Jasan, R., Plá, R., & Pignata, M. L. (2012). Heavy metals and trace elements in atmospheric fall-out: their relationship with topsoil and wheat element composition. *Journal of Hazardous Materials*, 213, 447–456.

- Bharti, R., & Sharma, R. (2022). Effect of heavy metals: An overview. *Materials Today: Proceedings*, 51, 880–885.
- Bini, C., Maleci, L., & Wahsha, M. (2017). Potentially toxic elements in serpentine soils and plants from Tuscany (Central Italy). A proxy for soil remediation. *Catena*, 148, 60–66.
- Bodzek, M. (2015). Application of membrane techniques for the removal of micropollutants from water and wastewater. *Copernican Letters*, 6, 24–33.
- Borah, P., Kumar, M., & Devi, P. (2020). Types of inorganic pollutants: metals/metalloids, acids, and organic forms. In *Inorganic pollutants in water* (pp. 17–31). Elsevier.
- Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*, 6, 9.
- Buendía-González, L., Orozco-Villafuerte, J., Cruz-Sosa, F., Barrera-Díaz, C. E., & Vernon-Carter, E. J. (2010). *Prosopis laevigata* a potential chromium (VI) and cadmium (II) hyperaccumulator desert plant. *Bioresource Technology*, 101(15), 5862–5867.
- Burakov, A. E., Galunin, E. V., Burakova, I. V., Kucherova, A. E., Agarwal, S., Tkachev, A. G., & Gupta, V. K. (2018). Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review. *Ecotoxicology and Environmental Safety*, 148, 702–712.
- Carolin, C. F., Kumar, P. S., Saravanan, A., Joshiba, G. J., & Naushad, M. (2017). Efficient techniques for the removal of toxic heavy metals from aquatic environment: A review. *Journal of Environmental Chemical Engineering*, 5(3), 2782–2799.
- Carvalho, D. O., McKemey, A. R., Garziera, L., Lacroix, R., Donnelly, C. A., Alphey, L., Malavasi, A., & Capurro, M. L. (2015). Suppression of a field population of *Aedes aegypti* in Brazil by sustained release of transgenic male mosquitoes. *PLoS Neglected Tropical Diseases*, 9(7), e0003864.
- Cheng, K., Tian, H., Zhao, D., Lu, L., Wang, Y., Chen, J., Liu, X., Jia, W., & Huang, Z. (2014). Atmospheric emission inventory of cadmium from anthropogenic sources. *International journal of Environmental Science and Technology*, 11, 605–616.
- Cristaldi, A., Conti, G. O., Jho, E. H., Zuccarello, P., Grasso, A., Copat, C., & Ferrante, M. (2017). Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. *Environmental Technology & Innovation*, 8, 309–326.
- Cui, X., Zhang, J., Wang, X., Pan, M., Lin, Q., Khan, K. Y., Yan, B., Li, T., He, Z., Yang, X., & Chen, G. (2021). A review on the thermal treatment of heavy metal hyperaccumulator: Fates of heavy metals and generation of products. *Journal of Hazardous Materials*, 405, 123832. <https://doi.org/10.1016/J.JHAZMAT.2020.123832>
- Danovaro, R., Coccozza di Montanara, A., Corinaldesi, C., Dell'Anno, A., Illuminati, S., Willis, T. J., & Gambi, C. (2023). Bioaccumulation and biomagnification of heavy metals in marine micro-predators. *Communications Biology*, 6(1), 1206.
- da Silva Ferreira, M., Fontes, M. P. F., Pacheco, A. A., Lima, H. N., & Santos, J. Z. L. (2020). Risk assessment of trace elements pollution of Manaus urban rivers. *Science of the Total Environment*, 709, 134471.
- Dar, F. A., Pirzadah, T. B., & Malik, B. (2020). Accumulation of heavy metals in medicinal and aromatic plants. *Plant Micronutrients: Deficiency and Toxicity Management*, 113–127.
- Desoky, E. S. M., Merwad, A. R. M., Semida, W. M., Ibrahim, S. A., El-Saadony, M. T., & Rady, M. M. (2020). Heavy metals-resistant bacteria (HM-RB): Potential bioremediators of heavy metals-stressed *Spinacia oleracea* plant. *Ecotoxicology and Environmental Safety*, 198, 110685.
- Dey, U., Chatterjee, S., & Mondal, N. K. (2016). Isolation and characterization of arsenic-resistant bacteria and possible application in bioremediation. *Biotechnology Reports*, 10, 1–7.
- Dixit, R., Wasiullah, X., Malaviya, D., Pandiyan, K., Singh, U. B., Sahu, A., et al. (2015). Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability*, 7(2), 2189–2212.
- Edwards, M. R., Hetu, M. F., Columbus, M., Silva, A., & Lefebvre, D. D. (2011). The effect of ethylene glycol on the phytovolatilization of 1, 4-dioxane. *International Journal of Phytoremediation*, 13(7), 702–716.

- Enerjiöfi, K. E. (2021). Bioremediation of environmental contaminants: a sustainable alternative to environmental management. In *Bioremediation for environmental sustainability* (pp. 461–480). Elsevier.
- Fazeli, G., Karbassi, A., Khoramnejadian, S., & Nasrabadi, T. (2019). Evaluation of urban soil pollution: a combined approach of toxic metals and polycyclic aromatic hydrocarbons (PAHs). *International Journal of Environmental Research*, *13*, 801–811.
- Gangwar, C., Choudhari, R., Chauhan, A., Kumar, A., Singh, A., & Tripathi, A. (2019). Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk. *Environment International*, *125*, 191–199.
- García-Salgado, S., García-Casillas, D., Quijano-Nieto, M. A., & Bonilla-Simón, M. M. (2012). Arsenic and heavy metal uptake and accumulation in native plant species from soils polluted by mining activities. *Water, Air, & Soil Pollution*, *223*, 559–572.
- Gaur, V. K., Sharma, P., Gaur, P., Varjani, S., Ngo, H. H., Guo, W., et al. (2021). Sustainable mitigation of heavy metals from effluents: toxicity and fate with recent technological advancements. *Bioengineered*, *12*(1), 7297–7313.
- Ghuge, S. A., Nikalje, G. C., Kadam, U. S., Suprasanna, P., & Hong, J. C. (2023). Comprehensive mechanisms of heavy metal toxicity in plants, detoxification, and remediation. *Journal of Hazardous Materials*, *450*, 131039. <https://doi.org/10.1016/J.JHAZMAT.2023.131039>
- Guagliardi, I., Cicchella, D., De Rosa, R., & Buttafuoco, G. (2015). Assessment of lead pollution in topsoils of a southern Italy area: Analysis of urban and peri-urban environment. *Journal of Environmental Sciences*, *33*, 179–187.
- Gunatilake, S. K. (2015). Methods of removing heavy metals from industrial wastewater. *Methods*, *1*(1), 14.
- Gururajan, K., & Belur, P. D. (2018). Screening and selection of indigenous metal tolerant fungal isolates for heavy metal removal. *Environmental Technology & Innovation*, *9*, 91–99.
- Han, R., Wang, Z., Wang, S., Sun, G., Xiao, Z., Hao, Y., Nriagu, J., Teng, H. H., & Li, G. (2023). A combined strategy to mitigate the accumulation of arsenic and cadmium in rice (*Oryza sativa* L.). *Science of the Total Environment*, *896*, 165226. <https://doi.org/10.1016/J.SCITOTENV.2023.165226>
- Hasnine, M. T., Huda, M. E., Khatun, R., Saadat, A., Ahasan, M., Akter, S., Uddin, M. F., Monika, A. N., Rahman, M. A., & Ohiduzzaman, M. (2017). Heavy metal contamination in agricultural soil at DEPZA, Bangladesh. *Environment and Ecology Research*, *5*(7), 510–516.
- Hassan, Z. U., Ali, S., Rizwan, M., Ibrahim, M., Nafees, M., & Waseem, M. (2017). Role of bio-remediation agents (bacteria, fungi, and algae) in alleviating heavy metal toxicity. *Probiotics in Agroecosystem*, *5*, 517–537.
- Herath, I., Kumarathilaka, P., Navaratne, A., Rajakaruna, N., & Vithanage, M. (2015). Immobilization and phytotoxicity reduction of heavy metals in serpentine soil using biochar. *Journal of Soils and Sediments*, *15*, 126–138.
- Hindersmann, I., & Mansfeldt, T. (2014). Trace element solubility in a multimetal-contaminated soil as affected by redox conditions. *Water, Air, & Soil Pollution*, *225*, 1–20.
- Huddart, D., & Stott, T. A. (2020). *Earth environments*. John Wiley & Sons.
- Jadaa, W., & Mohammed, H. (2023). Heavy Metals—Definition, Natural and Anthropogenic Sources of Releasing into Ecosystems, Toxicity, and Removal Methods—An Overview Study. *Journal of Ecological Engineering*, *24*(6), 249–271. <https://doi.org/10.12911/22998993/162955>
- Kalve, S., Sarangi, B. K., Pandey, R. A., & Chakrabarti, T. (2011). Arsenic and chromium hyperaccumulation by an ecotype of *Pteris vittata*—prospective for phytoextraction from contaminated water and soil. *Current Science*, *888*–894.
- Kaur, H., & Garg, N. (2021). Zinc toxicity in plants: a review. *Planta*, *253*(6), 1–28. <https://doi.org/10.1007/S00425-021-03642-Z/FIGURES/2>
- Kaveeshwar, A. R., Kumar, P. S., Revellame, E. D., Gang, D. D., Zappi, M. E., & Subramaniam, R. (2018). Adsorption properties and mechanism of barium (II) and strontium (II) removal from fracking wastewater using pecan shell based activated carbon. *Journal of Cleaner Production*, *193*, 1–13.

- Khalid, S., Shahid, M., Niazi, N. K., Murtaza, B., Bibi, I., & Dumat, C. (2017). A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of Geochemical Exploration*, 182, 247–268.
- Khalilzadeh, R., Pirzad, A., Sepehr, E., Khan, S., & Anwar, S. (2020). Long-term effect of heavy metal-polluted wastewater irrigation on physiological and ecological parameters of *Salicornia europaea* L. *Journal of Soil Science and Plant Nutrition*, 20, 1574–1587.
- Khanlari, Z. V., & Jalali, M. (2008). Concentrations and chemical speciation of five heavy metals (Zn, Cd, Ni, Cu, and Pb) in selected agricultural calcareous soils of Hamadan Province, western Iran. *Archives of Agronomy and Soil Science*, 54(1), 19–32.
- Ko, M.-S., Kim, J.-Y., Park, H.-S., & Kim, K.-W. (2015). Field assessment of arsenic immobilization in soil amended with iron rich acid mine drainage sludge. *Journal of Cleaner Production*, 108, 1073–1080.
- Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International*, 132, 105078.
- Koptsik, G. N. (2014). Problems and prospects concerning the phytoremediation of heavy metal polluted soils: a review. *Eurasian Soil Science*, 47, 923–939.
- Kowalska, J. B., Mazurek, R., Gąsiorek, M., & Zaleski, T. (2018). Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination—A review. *Environmental Geochemistry and Health*, 40, 2395–2420.
- Kumar Shakya, A., & Singh, S. (2022). State of the art in fiber optics sensors for heavy metals detection. *Optics & Laser Technology*, 153, 108246. <https://doi.org/10.1016/J.OPTLASTEC.2022.108246>
- Kumar, A., Cabral-Pinto, M. M. S., Chaturvedi, A. K., Shabnam, A. A., Subrahmanyam, G., Mondal, R., Gupta, K., Malyan, S. K., Kumar, S. S., Khan, S. A., & Yadav, K. K. (2020a). Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches. *Mdpi.Com*, 17, 2179. <https://doi.org/10.3390/ijerph17072179>
- Kumar, V., Sharma, A., Pandita, S., Bhardwaj, R., Thukral, A. K., & Cerda, A. (2020b). A review of ecological risk assessment and associated health risks with heavy metals in sediment from India. *International Journal of Sediment Research*, 35(5), 516–526. <https://doi.org/10.1016/J.IJSRC.2020.03.012>
- Kumar, R., Ivy, N., Bhattacharya, S., Dey, A., & Sharma, P. (2022). Coupled effects of microplastics and heavy metals on plants: Uptake, bioaccumulation, and environmental health perspectives. *Science of the Total Environment*, 836, 155619.
- Lakherwal, D. (2014). Adsorption of heavy metals: a review. *International Journal of Environmental Research and Development*, 4(1), 41–48.
- Lalmi, A., Bouhidel, K. E., Sahraoui, B., & el Houda Anfic, C. (2018). Removal of lead from polluted waters using ion exchange resin with Ca (NO<sub>3</sub>)<sub>2</sub> for elution. *Hydrometallurgy*, 178, 287–293.
- LeDuc, D. L., & Terry, N. (2005). Phytoremediation of toxic trace elements in soil and water. *Journal of Industrial Microbiology and Biotechnology*, 32(11-12), 514–520.
- Li, X., Zhang, X., Yang, Y., Li, B., Wu, Y., Sun, H., & Yang, Y. (2016). Cadmium accumulation characteristics in turnip landraces from China and assessment of their phytoremediation potential for contaminated soils. *Frontiers in Plant Science*, 7, 1862.
- Li, C., Zhou, K., Qin, W., Tian, C., Qi, M., Yan, X., & Han, W. (2019). A review on heavy metals contamination in soil: effects, sources, and remediation techniques. *Soil and Sediment Contamination: An International Journal*, 28(4), 380–394.
- Lin, Y., Huang, R., & Yao, X. (2021). Air pollution and environmental information disclosure: An empirical study based on heavy polluting industries. *Journal of Cleaner Production*, 278, 124313.
- Liu, G., Wang, J., Zhang, E., Hou, J., & Liu, X. (2016). Heavy metal speciation and risk assessment in dry land and paddy soils near mining areas at Southern China. *Environmental Science and Pollution Research*, 23, 8709–8720.

- Long, Z., Huang, Y., Zhang, W., Shi, Z., Yu, D., Chen, Y., Liu, C., & Wang, R. (2021). Effect of different industrial activities on soil heavy metal pollution, ecological risk, and health risk. *Environmental Monitoring and Assessment*, 193, 1. <https://doi.org/10.1007/s10661-020-08807-z>
- Malik, L. A., Bashir, A., Qureashi, A., & Pandith, A. H. (2019). Detection and removal of heavy metal ions: a review. *Environmental Chemistry Letters*, 17(4), 1495–1521. <https://doi.org/10.1007/S10311-019-00891-Z/METRICS>
- Maier RM, Gentry TJ (2015) Microorganisms and organic pollutants. In: Environmental microbiology: Third Edition, pp 377–413. Else vier Inc, Amsterdam. <https://doi.org/10.1016/b978-0-12-394626-3.00017-x>
- Marques, A. P., Rangel, A. O., & Castro, P. M. (2009). Remediation of heavy metal contaminated soils: phytoremediation as a potentially promising clean-up technology. *Critical Reviews in Environmental Science and Technology*, 39(8), 622–654.
- Mishra, S., Bharagava, R. N., More, N., Yadav, A., Zainith, S., Mani, S., & Chowdhary, P. (2019). Heavy metal contamination: an alarming threat to environment and human health. *Environmental biotechnology: For sustainable future*, 103–125.
- Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University-Science*, 34(3), 101865.
- Mossa, A. W., Young, S. D., & Crout, N. M. J. (2020). Zinc uptake and phyto-toxicity: Comparing intensity- and capacity-based drivers. *Science of the Total Environment*, 699, 134314. <https://doi.org/10.1016/J.SCITOTENV.2019.134314>
- Nabulo, G., Black, C., & Young, S. (2011). Trace metal uptake by tropical vegetables grown on soil amended with urban sewage sludge. *Environmental Pollution*, 159(2), 368–376.
- Natasha, S., Khalid, S. M., Bibi, I., Bundschuh, J., Khan Niazi, N., & Dumat, C. (2020). A critical review of mercury speciation, bioavailability, toxicity and detoxification in soil-plant environment: Ecotoxicology and health risk assessment. *Science of the Total Environment*, 711, 134749. <https://doi.org/10.1016/J.SCITOTENV.2019.134749>
- Naz, M., Dai, Z., Hussain, S., Tariq, M., Danish, S., Khan, I. U., Qi, S., & Du, D. (2022). The soil pH and heavy metals revealed their impact on soil microbial community. *Journal of Environmental Management*, 321. Academic Press. <https://doi.org/10.1016/j.jenvman.2022.115770>
- Niu, L.-Q., Jia, P., Li, S.-P., Kuang, J.-L., He, X.-X., Zhou, W.-H., Liao, B., Shu, W.-S., & Li, J.-T. (2015). Slash-and-char: an ancient agricultural technique holds new promise for management of soils contaminated by Cd, Pb and Zn. *Environmental Pollution*, 205, 333–339.
- Nnaji, N. D., Onyeaka, H., Miri, T., & Ugwa, C. (2023). Bioaccumulation for heavy metal removal: a review. *SN Applied Sciences*, 5(5), 125.
- Nunes, N., Ragonezi, C., Gouveia, C. S., & Pinheiro de Carvalho, M. Â. (2021). Review of sewage sludge as a soil amendment in relation to current international guidelines: A heavy metal perspective. *Sustainability*, 13(4), 2317.
- Olubode, T. P., Amusat, A. I., Olawale, B. R., & Adekola, F. F. (2022). Biosorption of heavy metals using bacterial isolates from e-waste soil. *African Journal of Microbiology Research*, 16(7), 268–272.
- Panagopoulos, I., Karayannis, A., Kollias, K., Xenidis, A., & Papassiopi, N. (2015). Investigation of potential soil contamination with Cr and Ni in four metal finishing facilities at Asopos industrial area. *Journal of Hazardous Materials*, 281, 20–26.
- Peana, M., Pelucelli, A., Chasapis, C. T., Perlepes, S. P., Bekiari, V., Medici, S., & Zoroddu, M. A. (2022). Biological effects of human exposure to environmental cadmium. *Biomolecules*, 13(1), 36.
- Peng, K., Luo, C., You, W., Lian, C., Li, X., & Shen, Z. (2008). Manganese uptake and interactions with cadmium in the hyperaccumulator—*Phytolacca Americana* L. *Journal of Hazardous Materials*, 154(1–3), 674–681.

- Pérez-Sanz, A., Millán, R., Sierra, M. J., Alarcón, R., García, P., Gil-Díaz, M., et al. (2012). Mercury uptake by *Silene vulgaris* grown on contaminated spiked soils. *Journal of Environmental Management*, 95, S233–S237.
- Prasad, M. N. V. (2005). Nickelophilous plants and their significance in phytotechnologies. *Brazilian Journal of Plant Physiology*, 17, 113–128.
- Qasem, N. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water*, 4(1), 1–15.
- Qin, C., Yuan, X., Xiong, T., Tan, Y. Z., & Wang, H. (2020). Physicochemical properties, metal availability and bacterial community structure in heavy metal-polluted soil remediated by montmorillonite-based amendments. *Chemosphere*, 261, 128010.
- Rafati, M., Khorasani, N., Moattar, F., Shirvany, A., Moraghebi, F., & Hosseinzadeh, S. (2011). Phytoremediation potential of *Populus alba* and *Morus alba* for cadmium, chromium and nickel absorption from polluted soil. *International Journal of Environmental Research*, 5(4), 961–970.
- Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F., & Kim, K.-H. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, 125, 365–385.
- Rajapaksha, A. U., Vithanage, M., Ok, Y. S., & Oze, C. (2013). Cr (VI) formation related to Cr (III)-muscovite and birnessite interactions in ultramafic environments. *Environmental Science & Technology*, 47(17), 9722–9729.
- Rajkumar, M., Ae, N., Prasad, M. N. V., & Freitas, H. (2010). Potential of siderophore-producing bacteria for improving heavy metal phytoextraction. *Trends in Biotechnology*, 28(3), 142–149.
- Rani, N., Singh, D., & Dhingra, N. (2024). Transformations of native and added chromium among soil fractions under combined effect of amendments and ageing. *Journal of the Indian Society of Soil Science*, 72(2), 156–169.
- Rashid, A., Schutte, B. J., Ulery, A., Deyholos, M. K., Sanogo, S., Lehnhoff, E. A., & Beck, L. (2023). Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. *Agronomy*, 13(6), 1521.
- Rinklebe, J., Antoniadis, V., Shaheen, S. M., Rosche, O., & Altermann, M. (2019). Health risk assessment of potentially toxic elements in soils along the Central Elbe River, Germany. *Environment International*, 126, 76–88.
- Rodríguez, L., Lopez-Bellido, F. J., Carnicer, A., & Alcalde-Morano, V. (2003). Phytoremediation of mercury-polluted soils using crop plants. *Fresenius Environ. Bull.*, 12(9), 967–971.
- Ruba, U. B., Chakma, K., Senthil, J. Y., & Rahman, S. (2021). Impact of industrial waste on natural resources: A review in the context of Bangladesh. *Current World Environment*, 16(2), 348.
- Sacristán, D., Rossel, R. A. V., & Recatalá, L. (2016). Proximal sensing of Cu in soil and lettuce using portable X-ray fluorescence spectrometry. *Geoderma*, 265, 6–11.
- Sadia, H. E., & Kabir, M. S. (2023). Mitigation of Heavy Metal Pollution-An Overview Of Microbial Remediation And Prospect In Bangladesh. *Stamford Journal of Microbiology*, 13(1), 42–51.
- Sakakibara, M., Ohmori, Y., Ha, N. T. H., Sano, S., & Sera, K. (2011). Phytoremediation of heavy metal-contaminated water and sediment by *Eleocharis acicularis*. *CLEAN–Soil, Air, Water*, 39(8), 735–741.
- Salifu, M., John, M. A., Abubakar, M., Bankole, I. A., Ajayi, N. D., & Amusan, O. (2024). Phytoremediation Strategies for Heavy Metal Contamination: A Review on Sustainable Approach for Environmental Restoration. *Journal of Environmental Protection*, 15(4), 450–474.
- Sánchez-Castro, I., Molina, L., Prieto-Fernández, M. Á., & Segura, A. (2023a). Past, present and future trends in the remediation of heavy-metal contaminated soil—Remediation techniques applied in real soil-contamination events. In *Heliyon* (Vol. 9, Issue 6). Elsevier Ltd. <https://doi.org/10.1016/j.heliyon.2023.e16692>
- Sánchez-Castro, I., Molina, L., Prieto-Fernández, M. Á., & Segura, A. (2023b). Past, present and future trends in the remediation of heavy-metal contaminated soil—Remediation techniques applied in real soil-contamination events. *Heliyon*.
- Shaheen, S. M., & Rinklebe, J. (2015). Phytoextraction of potentially toxic elements by Indian mustard, rapeseed, and sunflower from a contaminated riparian soil. *Environmental Geochemistry and Health*, 37, 953–967.

- Shaheen, S. M., Rinklebe, J., Rupp, H., & Meissner, R. (2014). Temporal dynamics of pore water concentrations of Cd, Co, Cu, Ni, and Zn and their controlling factors in a contaminated floodplain soil assessed by undisturbed groundwater lysimeters. *Environmental Pollution*, 191, 223–231.
- Sharma, P., & Pandey, S. (2014). Status of phytoremediation in world scenario. *International Journal of Environmental Bioremediation & Biodegradation*, 2(4), 178–191.
- Sharma, S., Rana, S., Thakkar, A., Baldi, A., Murthy, R. S. R., & Sharma, R. K. (2016). Physical, chemical and phytoremediation technique for removal of heavy metals. *Journal of Heavy Metal Toxicity and Diseases*, 1(2), 1–15.
- Shi, G. L., Zhu, S., Bai, S. N., Xia, Y., Lou, L. Q., & Cai, Q. S. (2015). The transportation and accumulation of arsenic, cadmium, and phosphorus in 12 wheat cultivars and their relationships with each other. *Journal of Hazardous Materials*, 299, 94–102.
- Shifaw, E. (2018). Review of heavy metals pollution in China in agricultural and urban soils. *Journal of Health and Pollution*, 8(18), 180607.
- Shtiza, A., Swennen, R., & Tashko, A. (2005). Chromium and nickel distribution in soils, active river, overbank sediments and dust around the Burrel chromium smelter (Albania). *Journal of Geochemical Exploration*, 87(3), 92–108.
- Shukla, A. K., Alam, J., Alhoshan, M., Dass, L. A., Ali, F. A. A., Mishra, U., & Ansari, M. A. (2018). Removal of heavy metal ions using a carboxylated graphene oxide-incorporated polyphenyl-sulfone nanofiltration membrane. *Environmental Science: Water Research & Technology*, 4(3), 438–448.
- Siddiqui, E., & Pandey, J. (2022). Atmospheric deposition: an important determinant of nutrients and heavy metal levels in urban surface runoff reaching to the Ganga River. *Archives of Environmental Contamination and Toxicology*, 1–15.
- Sinduja, M., Sathya, V., Maheswari, M., Kalpana, P., Dhevagi, P., Dinesh, G. K., & Chitdeshwari, T. (2023). Chemical transformation and bioavailability of chromium in the contaminated soil amended with bioamendments. *Bioremediation Journal*, 27(3), 229–250.
- Singh, N., Gupta, V. K., Kumar, A., & Sharma, B. (2017). Synergistic effects of heavy metals and pesticides in living systems. *Frontiers in chemistry*, 5, 70.
- Singh, V., Singh, N., Rai, S. N., Kumar, A., Singh, A. K., Singh, M. P., Sahoo, A., Shekhar, S., Vamanu, E., & Mishra, V. (2023). Heavy metal contamination in the aquatic ecosystem: Toxicity and its remediation using eco-friendly approaches. In *Toxics* (Vol. 11, Issue 2). MDPI. <https://doi.org/10.3390/toxics11020147>
- Soleimani, M., Amini, N., Sadeghian, B., Wang, D., & Fang, L. (2018). Heavy metals and their source identification in particulate matter (PM<sub>2.5</sub>) in Isfahan City, Iran. *Journal of Environmental Sciences*, 72, 166–175.
- Sonone, S. S., Jadhav, S., Sankhla, M. S., & Kumar, R. (2020). Water contamination by heavy metals and their toxic effect on aquaculture and human health through food chain. *Letters in Applied NanoBioScience*, 10(2), 2148–2166.
- Srivastava, D., Tiwari, M., Dutta, P., Singh, P., Chawda, K., Kumari, M., & Chakrabarty, D. (2021). Chromium Stress in plants: Toxicity, Tolerance and Phytoremediation. *Sustainability*, 13(9), 4629. <https://doi.org/10.3390/SU13094629>
- Taştan, B. E., Ertuğrul, S., & Dönmez, G. (2010). Effective bioremoval of reactive dye and heavy metals by *Aspergillus versicolor*. *Bioresource Technology*, 101(3), 870–876.
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *EXS*, 101, 133–164. [https://doi.org/10.1007/978-3-7643-8340-4\\_6](https://doi.org/10.1007/978-3-7643-8340-4_6)
- Teh, C. Y., Budiman, P. M., Shak, K. P. Y., & Wu, T. Y. (2016). Recent advancement of coagulation–flocculation and its application in wastewater treatment. *Industrial & Engineering Chemistry Research*, 55(16), 4363–4389.
- Teimoory, H. (2019). Spatial distribution of heavy metals in surface sediments of Kalametiya Lagoon in Sri Lanka and accumulation of heavy metals by *Typha angustifolia*; Eco-sustainable Phytoremediation for wetland management (Doctoral dissertation, University of Malaya).
- Torres, L. G., Lopez, R. B., & Beltran, M. (2012). Removal of As, Cd, Cu, Ni, Pb, and Zn from a highly contaminated industrial soil using surfactant enhanced soil washing. *Physics and Chemistry of the Earth, Parts a/b/c*, 37, 30–36.

- Ukaogo, P. O., Ewuzie, U., & Onwuka, C. V. (2020). Environmental pollution: causes, effects, and the remedies. In *Microorganisms for sustainable environment and health* (pp. 419–429). Elsevier.
- Verma, B., & Balomajumder, C. (2020). Hexavalent chromium reduction from real electroplating wastewater by chemical precipitation. *Bulletin of the Chemical Society of Ethiopia*, 34(1), 67–74.
- Walker, J. M., Philip, S., Martin, R. V., & Seinfeld, J. H. (2012). Simulation of nitrate, sulfate, and ammonium aerosols over the United States. *Atmospheric Chemistry and Physics*, 12(22), 11213–11227.
- Wang, J., Feng, X., Anderson, C. W., Xing, Y., & Shang, L. (2012). Remediation of mercury contaminated sites—a review. *Journal of Hazardous Materials*, 221, 1–18.
- Wang, Q., Liu, J., & Cheng, S. (2015). Heavy metals in apple orchard soils and fruits and their health risks in Liaodong Peninsula, Northeast China. *Environmental Monitoring and Assessment*, 187, 1–8.
- Wang, J., & Qiao, Z. (2024). A comprehensive review of landfill leachate treatment technologies. *Frontiers in Environmental Science*, 12, 1439128.
- Weissmannová, H. D., Pavlovský, J., & Chovanec, P. (2015). Heavy metal contaminations of urban soils in Ostrava, Czech Republic: assessment of metal pollution and using Principal Component Analysis. *International Journal of Environmental Research*, 9, 2.
- Xu, D., Zhou, B., & Yuan, R. (2019, March). Optimization of coagulation-flocculation treatment of wastewater containing Zn (II) and Cr (VI). In *IOP Conference Series: Earth and Environmental Science* (Vol. 227, p. 052049). IOP Publishing.
- Yadav, I. C., Devi, N. L., Singh, V. K., Li, J., & Zhang, G. (2019). Spatial distribution, source analysis, and health risk assessment of heavy metals contamination in house dust and surface soil from four major cities of Nepal. *Chemosphere*, 218, 1100–1113.
- Yan, K., Wang, H., Lan, Z., Zhou, J., Fu, H., Wu, L., & Xu, J. (2022). Heavy metal pollution in the soil of contaminated sites in China: Research status and pollution assessment over the past two decades. *Journal of Cleaner Production*, 373, 133780.
- Yuan, X., Xue, N., & Han, Z. (2021). A meta-analysis of heavy metals pollution in farmland and urban soils in China over the past 20 years. *Journal of Environmental Sciences*, 101, 217–226.
- Yunus, Z. M., Al-Gheethi, A., Othman, N., Hamdan, R., & Ruslan, N. N. (2020). Removal of heavy metals from mining effluents in tile and electroplating industries using honeydew peel activated carbon: A microstructure and techno-economic analysis. *Journal of Cleaner Production*, 251, 119738.
- Zamora-Ledezma, C., Negrete-Bolagay, D., Figueroa, F., Zamora-Ledezma, E., Ni, M., Alexis, F., & Guerrero, V. H. (2021). Heavy metal water pollution: A fresh look about hazards, novel and conventional remediation methods. *Environmental Technology & Innovation*, 22, 101504.
- Zeraatkar, A. K., Ahmadzadeh, H., Talebi, A. F., Moheimani, N. R., & McHenry, M. P. (2016). Potential use of algae for heavy metal bioremediation, a critical review. *Journal of environmental management*, 181, 817–831.
- Zehra, A., Meena, M., Swapnil, P., Raytekar, N. A., & Upadhyay, R. S. (2020). Sustainable approaches to remove heavy metals from water. *Microbial Biotechnology: Basic Research and Applications*, 127–146.
- Zhang, Q., & Wang, C. (2020). Natural and human factors affect the distribution of soil heavy metal pollution: a review. *Water, Air, & Soil Pollution*, 231, 1–13.
- Zhao, H., Wu, Y., Lan, X., Yang, Y., Wu, X., & Du, L. (2022). Comprehensive assessment of harmful heavy metals in contaminated soil in order to score pollution level. *Scientific Reports*, 12(1), 3552.
- Zulfiqar, U., Ayub, A., Hussain, S., Waraich, E. A., El-Esawi, M. A., Ishfaq, M., et al. (2022). Cadmium toxicity in plants: Recent progress on morpho-physiological effects and remediation strategies. *Journal of Soil Science and Plant Nutrition*, 22(1), 212–269.
- Zwolak, A., Sarzyńska, M., Szyrka, E., & Stawarczyk, K. (2019). Sources of soil pollution by heavy metals and their accumulation in vegetables: A review. *Water, Air, & Soil Pollution*, 230, 1–9.