Heavy Metal Pollution in Water: Cause and Remediation Strategies

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Abstract

Heavy metals are naturally present in earth's crust, and some of them are essential to living organisms for carrying out life processes. Due to their high persistence and nonbiodegradable nature, heavy metal accumulation beyond recommended concentrations may lead to hazardous effect on various life forms and environment. Contamination of water bodies may be due to natural and anthropogenic sources. Unchecked discharge from industrial sites and agricultural runoff in to adjoining water bodies makes the water unfit for human consumption. Escalating levels of these pollutants pose a threat to aquatic life forms and surrounding environment. Heavy metals can execute various health problems that may range from mild to severe. They can be toxic to living organisms at very low levels of exposure. Excessive usage of heavy metals has raised concerns over time, and

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consequently, their impact on the overall environment is being studied by researchers extensively. To safeguard human health and environment, proper management and greener technologies for removal of heavy metal from water bodies is required. This chapter will discuss the source, toxicity, and permitted concentrations of some of the major heavy metals in water bodies. Remediation approaches for mitigation of these toxic compounds have also been described. Physical and chemical remediation processes for heavy metal cleanup are highly expensive and sometimes generate a significant amount of secondary pollutants; therefore, the focus has now shifted toward eco-friendly approaches such as bioremediation and phytoremediation. Further research needs to be carried out to maximize the applicability of the existing techniques and developing highly efficient technologies for heavy metal removal from water bodies.

Keywords

Bioremediation · Heavy metal toxicity · Phytoremediation · Water pollution

8.1 Introduction

Metals are elements with high atomic weight and density ranging from 3.5 to 7 g cm^{-3}. These are found to be deposited on earth's crust naturally as minerals in the form of sulfates, phosphates, oxides, etc. (Singh et al. 2022). In aquatic system, these are naturally present in low amounts, but a variety of natural and anthropogenic activities have unavoidably escalated metal concentrations in water bodies (Ansari et al. 2003). Expansion of industries that extensively utilize metals and metalloids, mining operations, improper e-waste disposal, transportation, and fossil fuel burning are some major human activities that significantly increase concentration of heavy metals in aquatic systems. Animals and plants use some heavy metals such as Fe, Cu, Zn, and Mn at low concentrations for carrying out their physiological processes, but they become hazardous at higher concentrations (Pratush et al. 2018). Some of them are important for activity of enzymes as cofactors and also help to maintain osmotic balance. However, their accumulation over time can harm human health and other life forms. Escalating levels of heavy metals in aquatic systems is one of the most serious global concerns. About 40% of the world's lakes and rivers have been contaminated with heavy metals (Zhou et al. 2020; Bhatt et al. 2022).

Due to their toxic nature, heavy metals are considered as potent pollutants in water bodies and soil (Duffus 2002). Drinking water contaminated with heavy metals is a potential threat to public health. Consumption of polluted water may lead to cardiovascular disorders and renal failure and in severe cases may also lead to life-threatening disease like Parkinson's disease, Alzheimer's disease, and cancer (Singh et al. 2022). These metals come into touch with human bodies via digestion and respiration. People who work or live close to industrial regions associated with these heavy metals and their equivalent compounds have a significant risk of exposure and cause increased mortality rates globally (Rehman et al. 2018).

Biodiversity in aquatic ecosystem is also hampered due to toxic effects of these metals, and reports indicate their accumulation and deposition within tissues of fishes and other aquatic life forms.

With increasing industrialization, generation of heavy metals also increases, and thus, their disposal is of paramount importance. Unlike organic pollutants, inorganic metal ions are resistant to degradation. Their persistence in environment and bio-accumulation in different organisms through food chain is major problem associated with heavy metals (Wuana and Okieimen 2011). Bioaccumulation of heavy metals and their toxicity level in food chain increases with time as their separation and purification is not easy. Although metal ions are resistant to degradation, their bioavailability and chemical forms can be changed. Heavy metals can easily run into water bodies via industrial effluents, agriculture runoff, and household, but there are many technologies and strategies that are employed to remediate heavy metals. Treatment of heavy metal-laden wastewater is an arduous job. The prominent strategies that are employed include thermal treatment, chlorination, electrokinetic, bioleaching, precipitation and coagulation, ion exchange, membrane filtration, bioremediation, heterogenous photocatalyst, and adsorption and are some commonly used methods for heavy metal removal from wastewater (Selvi et al. 2019). However, most of these methods have certain disadvantages and sometimes may generate toxic compounds; therefore, integrated approaches and safer technologies need to be introduced. This chapter highlights toxicity and remediation strategies for heavy metal removal from water bodies.

8.2 Sources of Heavy Metal Pollution in Water Bodies

In water bodies, main source of heavy metal contamination includes landfill leaches, petrochemical spillage, urban runoff, industrial and mining wastewaters particularly from the electronic, metal finishing, and electroplating industries (Khan et al. 2008). Mining and metallurgical operations are prominent cause of increased concentration of these hazardous metals. Heavy metals often reach the aquatic environment through natural physical sources such as volcanic eruptions, air deposition, forest fire, runoffs, and geological matrix erosion. Occurrence of metals in lakes, rivers, and ponds is related to the type of soil and waterflow through sewage and surface runoffs from soils. Additional natural sources of heavy metal contamination of water include the wet and dry deposition of atmospheric salts, water-rock contact, and water-soil interaction (Gautam et al. 2014).

Anthropogenic activities account for vast accumulation of heavy metals in water. Rapid urbanization and industrialization are the main anthropogenic factors that pollute water. The primary causes are mining, metallurgical activities, coal and oil combustion, and agricultural runoff entering waterways (Wang et al. 2004). Other anthropogenic sources include alloy production, atmospheric deposition, battery production, coating, explosive manufacturing, improper stacking of industrial solid waste, leather tanning, mining, pesticides, phosphate fertilizer, photographic materials, printing pigments, sewage, smelting, steel and electroplating industries, textiles, and dyes and wood preservation (Dixit et al. 2015). Untreated wastewater from municipal, domestic sewage, and industry directly discharged into the natural water system leads to water contamination, industrial effluents, water tank leakages, dumping beside water bodies, and atmospheric deposition, which are some major sources through which these heavy metals entry into aquatic ecosystem. Electroplating is a major contributor to pollution because it releases heavy metals via water, air emissions, and solid waste in an environment that has been reported to contain high levels of heavy metals such as nickel, iron, lead, zinc, chromium, cadmium, and copper (Baby et al. 2010). Mining and ore processing are important sources of heavy metal contamination in the soil, and the recovery of ecosystems from mining operations might take decades. These activities generated a vast number of piles and dumps, which are usually discarded without treatment, and these abandoned mines contaminate water system through chemical runoff (Adler et al. 2007). Pesticide overuse and misuse in response to rising food demand have resulted in greater pollutant burdens in the environment, including rivers, lakes, aquifers, and coastal waterways. Anthropogenic sources of heavy metal have been observed to be more ahead than natural sources. Besides, lack of awareness for proper disposal of metal waste and failure of implementation of strict government policies and not following the recommended guidelines also contribute to the problem. Table 8.1 enlist major sources of some common heavy metal pollutants.

8.3 Potential Risks Associated with Heavy Metals

Heavy metals generally have negative impact on the ecosystem and aquatic life, and even trace amounts of heavy metals in water can be hazardous to aquatic life and human health. Ayangbenro and Babalola (2017) defined toxicity of metal as its capability to cause undesirable effects on organisms. Metal toxicity is determined by the environmental factors such as pH, temperature, salinity and dissolved oxygen, the presence of other toxicants, the condition of the test organism, the kinetics of toxic reactions, etc. (Ansari et al. 2003). Metal ions frequently penetrate cells, get accumulated and interact with various elements of cells, and target molecules (Chiarelli and Roccheri 2014). Heavy metals have a negative impact on the health of humans and other living organisms in both the terrestrial and aquatic environments (Das et al. 2013). Toxicity of metal ions on any living system depends upon the duration of exposure and its dose. These cause oxidative damage to biological macromolecules and may end up in damaging DNA and even halt metabolic machinery of exposed life forms. High toxicity of heavy metals can be seen in fetus and newborn babies of industrial workers that are constantly exposed to its high concentrations. Metal ion exposure in newborn babies can harm brain memory and central nervous system, disrupt the function of red blood cells, and cause physiological and behavioral problems, and its severe toxicity may cause cancer. Plants exposed to heavy metals may undergo morphological and physiological changes, which can reduce the photosynthesis rate and may trigger mutagenic changes in several plant species. Heavy metal exposures also obstruct the microbial

Table 8.1 Sources of some heavy metal pollutants

Metal	Sources	References
Iron (Fe)	• Suspended sediment • Aeolian dust transport • Hydrothermal activity • Recycling from shelf sediments • Combustion of coal, petroleum, biofuel, fossil fuel, and biomass • Wet and dry deposition of atmospheric aerosols, vertical mixing, and upwelling	Raiswell and Canfield (2012), Wang et al. (2015), Wells et al. (1995)
Zinc (Zn)	• Pigments and paints • Coal burning, metal smelting, steel works, and waste incineration • Pesticides (Zn-based fungicides) and phosphatic fertilizers • Alloys and solders • Sewage sludge • Mining work and industrial effluents (e.g., from smelting and refining) • Urban runoff from abrasion of galvanized roofs and tire rubber	Shah (2021), Rieuwerts (2015)
Lead (Pb)	• Drainage from mining sites • Smelting, manufacturing, and recycling activities • Lead batteries • Pigments and paints • Alloys and solders • Lead plumbing system • Drainage from leaded roofs and gutters • Fossil fuel and waste combustion (PVC products)	WHO (2017), Jaishankar et al. (2014)
Cadmium (Cd)	• Phosphate mining and fertilizers • Detergents and refined petroleum products • Runoff from agricultural and mining activities	Wuana and Okieimen (2011), Gautam et al. (2014), Reichelt-Brushett (2012), Rieuwerts (2015)
Nickel (Ni)	• Domestic wastewater (detergents) • Combustion of oil and coal and incineration of waste and sewage • Opencast mining of Ni laterite ore and metal smelting • Phosphatic fertilizers and sewage sludge • Leakage from plumbing	Gillmore et al. (2020), Cempel and Nikel (2006)
Copper (Cu)	• Antifouling paints • Pesticides (algicides) • Copper polishing, mining, smelting, discharge of wastewater • The use of wood preservatives • Dumping of sewage sludge	Brown and Eaton (2001), Rieuwerts (2015)

(continued)

Table 8.1 (continued)

Metal	Sources	References
Chromium (Cr)	• Metal processing • Industrial effluents (tannery sludge, textile dyes) • Chromate production and smelting • Sewage sludge and phosphate fertilizers	Geisler and Schmidt (1991), Bielicka et al. (2005), Shah (2021)
Arsenic (As)	• Smelting process of nickel, copper, zinc, and lead ores • Paints and wood preservatives • Mining, pesticides, fertilizers	Rieuwerts (2015)
Silver (Ag)	• Emissions from smelting operations • Manufacture and disposal of photographic and electrical supplies • Combustion • Industrial and municipal wastewater outfalls	Shah (2021)
Mercury (Hg)	• Agricultural practices • Municipal and industrial wastewater (chlor-alkali industry) discharge • Mining activities (artisanal gold mining) and combustion of fossil fuels • Natural degassing and direct atmospheric deposition • Sewage sludge and phosphate rock fertilizer	Jaishankar et al. (2014), UNEP (2013)
Tin (Sn)	• Mining • Coal and oil combustion • Atmospheric deposition, riverine input, and sediment resuspension • Antifoulant compounds (tributyltin)	Duan et al. (2012)

growth (Wase and Forster 1997). Presence of these heavy metals even at low concentration is toxic for humans and animals, for example, Pb exposure to human cause dysfunction in nervous system, reproductive system and kidneys. Cd is another heavy metals that get accumulated in aquatic environment from metal ore refining, alloy decomposition, and fertilizer input, which causes renal dysfunction, bone degenerations, and liver damage in humans (Dojlido and Best 1993). Cd is also associated with itai-itai disease in Japan. Hg is also one of common heavy metals that is associated with many human dysfunctions like Minamata disease. Hg toxicity has also been reported to cause abortion and physiological stress. The high concentration of even Fe and Mn in water bodies also reported to effect animal system although both of these metals are required by the body in consistent amount but in case of water contamination level of these metals tend to get increase, which poses threat to human health. Countries rapidly undergoing industrialization are found to have a high number of heavy metal-related disorders (Esslemont 1998). A correlation between historical events and the metal toxicity along with responsible metal is presented in Table 8.2.

Table 8.2 Historical events due to heavy metal toxicity

Year	Historical events	References
Late 1800s	Drainage water from Summerford Bing industrial area containing high concentration of chromium causing Cr toxicity in Scotland	Esslemont (1998)
1932	Minamata Bay in Japan is contaminated with sewage containing Hg, leading Hg poisoning	Harada (1995), Lenntech (2006)
1910s–1940s	Jinzu river in Japan contaminated with waste sludge containing Cd from Kamioka zinc mines, which gradually reached to drinking water and groundwater	Rieuwerts (2015)
1950s	Cd toxicity in Japan (Itai-itai disease)	Esslemont (1998)
1952	Minamata Syndrome (mass human mortality in Japan as a result of consuming Hg-polluted fish)	Lenntech (2006)
1986	At Sandoz in Germany, water used to put out a large fire releases 30 tons of fungicide containing mercury into the Upper Rhine, killing a huge number of fish	Giga (2009)
1998	A Spanish natural reserve has been contaminated by toxic chemicals from a burst dam	Lenntech (2006)
2010	Chemical spill into a river from a Cu mining-smelting complex resulting significant fish kill in China	Rieuwerts (2015)
2011	Illegal dumping of thousands of tons of waste tailings from the production of the tanning chemical chromium sulphate resulting Hexavalent Cr poisoning of drinking water in China	Rieuwerts (2015)
2014	8×10^4 tons of coal spilled into the Dan River in North Carolina, USA, causing As and Cr toxicity	Rieuwerts (2015)

Toxic effects of some heavy metals have been discussed under this section in brief.

8.3.1 Cadmium

Cadmium is considered to be one of the most toxic heavy metals. Its minute concentrations in food chain has been found to cause *itai-itai* disease. Cadmium is not an essential element for biological system unlike other heavy metals. Cadmium metal is used in the manufacturing of plastics, pigments, and nickel-cadmium batteries. It enters into the environment mostly through waste dumping and phosphate fertilizers. Due to its potential to be hazardous for both humans and animals even at minute concentrations, there is an increased concern over the function and toxicity of cadmium in the environment. The Restriction of Hazardous Chemicals (RoHS) directive of the European Union forbids the use of six substances, including cadmium, in electrical and electronic equipment, while allowing for some exceptions and exclusions from the rule (European Commission 2006). Numerous disorders, such as early atherosclerosis, hypertension, osteomalacia, cardiovascular conditions, and renal dysfunction, are all linked to cadmium exposure, including lung cancer (ARL: Cadmium toxicity 2016; Medinews direct 2009). In the 1950s, a large population near the Jinzu River in Japan is found to have kidney dysfunction and osteomalacia, resulting in deformed and fragile bones, which is caused by the ingestion of Cd for a long time. This disease is called as itai-itai named after the excruciating pain that people who had consumed Cd-contaminated rice had experienced. Klaassen et al. (2009) reported Cd to be a metallothioneins (metal-binding proteins) interfering metal that disrupts the homeostasis of an organism. Once ingested by an organism, Cd shows high bio-persistence without biomagnifying properties (Wuana and Okieimen 2011; Kumar et al. 2019).

8.3.2 Chromium

Chromium is a highly toxic metal that poses varying levels of harm to the ecosystem. Cr is mainly introduced to the environment through discharge of untreated or inadequately treated residues from tanning and leather industries, rubber manufacturing, and pulp and paper industries (Chiarelli and Roccheri 2014). Among various oxidation states of Cr, only +3 and +6 are chemically and biologically stable (Ducros 1992). Hexavalent Cr is the most toxic form of chromium for animal and human health, which is considered to be mutagenic and carcinogenic (Chiarelli and Roccheri 2014). High exposure to Cr may cause liver, kidney, and central nervous system damage. Hematological problems can be observed in fishes of freshwater contaminated with Cr.

8.3.3 Copper

Copper enters the water bodies mostly via mining, dumping of sewage sludge, and use of Cu-based pesticides in agriculture. Cu has been used by human civilization since pre-historic times. It is well known that Cu is an essential element for all living organisms. However, its high concentration may cause toxic effects (Bielmyer-Fraser et al. 2018). Excess Cu may alter enzyme functions, acid/base balance, iono-regulation, and endocrine disruption in aquatic organisms (Rieuwerts 2015). Cu shows bioaccumulation in organisms like plankton and oysters but does not magnify in the food chain (Rieuwerts 2015). At higher concentrations in human, it may damage kidney and stomach and cause diarrhea, vomiting, and loss of strength.

8.3.4 Lead

Leaded gasoline had been a significant contributor to the environmental dispersion of Pb. Tetraethyl lead was added in gasoline to boost its octane levels since the 1920s (ATSDR 2017). However, lead use has been banned in gasoline in the United States since January 1996, and USEPA has encouraged all the countries to do so (EPA 2017). Pb is a nonessential element that could be hazardous to most of the living forms. Lead can be present in water bodies in four different forms: ionic (mobile and bioavailable), organic complex (bound with limited mobility and bioavailability), strongly bound (attached to solid particles like iron oxides with limited mobility), and very strongly bound (attached to clay, dead remains, or solid particle with very low mobility) (ILA 2018). Exposure of high concentrations of Pb to human may cause severe toxicity to the central nervous system, damage the fetus, alter hemoglobin synthesis, and harm kidney and reproductive system. Poisoning of agricultural food may be caused by airborne Pb by its deposition on soils, water, and fruits (WHO 1984). Bio-magnification of Pb has not been observed in the food chain (De Pooter 2013).

8.3.5 Mercury

Mercury (Hg) is a nonessential, persistent and highly toxic element, which is present in the environment in elemental, organic, and inorganic forms that are all interconvertible and toxic (Jaishankar et al. 2014). Elemental Hg^0 is a volatile liquid at room temperature, inorganic Hg is present in mercuric (Hg^{2+}: HgS, $HgCl_2$) and mercurous (Hg^{1+}: Hg_2Cl_2) forms, and organic Hg is present in the form of methylated Hg (mono and dimethyl mercury) and phenyl mercury. Toxic effects related to Hg gained global attention due to the outbreak of Minamata disease in Japan in the year 1956 (Ye et al. 2016). Methylmercury containing waste from a fertilizer industry as a byproduct of acetaldehyde discharged into the Minamata Bay for a long time polluted the marine ecosystem harming organisms. Contaminated seafood consumption caused injury to the nervous system, brain, heart, eyes, kidney, and lungs. Methylmercury also shows bio-magnification, and it dissolves well in water and can persist fatty tissues by crossing biological membrane (Solomon 2008).

8.3.6 Nickel

Opencast mining for the extraction of nickel (Ni) ore Ni laterite leads to major landscape alteration and increased soil erosion rates (Gillmore et al. 2020). This can cause entering of Ni into water bodies such as rivers, later contaminating the sea (Clark 2001). Ni is an essential element that plays an important role in the synthesis of red blood cells. Trace amounts of nickel do not harm cells but at higher concentrations may damage liver and heart and decrease body weight. Nickel at very high concentrations may cause nervous system damage, reduced cell growth, and cancer (WHO 1984). Ni does not have bio-magnification properties and considered to be moderately toxic metal.

8.3.7 Zinc

Zinc (Zn) is found in earth's crust and an essential element for living organisms as it acts as a cofactor in more than 300 enzymes and contributes to the metabolism

(Morel et al. 1994). Excessive introduction of Zn into water bodies from rubber, plastic, cosmetic, and pesticide industries may cause phytoxicity in plants, anemia, lack of muscular coordination, and abdominal pain in humans. Bioaccumulation of Zn is not observed, but higher concentrations in environmental may lead to its bioaccumulation in organisms (De Pooter 2013).

8.3.8 Arsenic

Arsenic (As) has been considered to be one of the most concerning environmental pollutants around the globe (Kaur et al. 2011; Dash et al. 2021). Insecticides, herbicides, fungicides, and other pesticides are the largest source of As pollution in water bodies (El-Sorogy et al. 2016). Marine organisms are mostly contaminated with highly stable pentavalent form of As which is nontoxic and metabolically inert but may get bio-accumulated in some fishes and algae. Water contaminated with As may cause toxicity to blood and central nervous system, breathing problems, nausea, and lung and skin cancer. As is a geogenic issue that affects everyone, but man-made sources such as pesticide manufacturing and metal processing raise the environmental As content.

8.3.9 Silver

Silver (Ag) is a rare but naturally occurring metal that has been used by human civilization for a long time. Ag is extremely toxic in its +1 oxidation state (Ag^{1+}) to plankton and invertebrates (Luoma et al. 1995). Increasing use of Ag as a biocide in recent years raises concerns about its potential as a pollutant (Purcell and Peters 1998). Since Ag^{+} ion can be taken up by cell via cell membrane ion transporters, its high concentrations may bio-accumulate in some fish, algae, and shrimps (Clark 2001).

8.3.10 Iron

Iron (Fe) and phosphorus (P) along with some other trace elements act as a limiting nutrient for nitrogen fixation (Mills et al. 2004). As nitrogen-fixing organisms require higher concentrations of Fe, sometimes due to this higher concentration, microbes in remote waters may produce more dimethyl sulfide (DMS) and organic carbon, which in turn may have an impact on the radiative forcing in the atmosphere.

8.3.11 Manganese

Manganese being the 12th most abundant element in earth's crust is a broadly distributed metal in nature (Pinsino et al. 2012). Although low level of manganese intake is necessary for human health, exposure to high Mn concentrations is toxic. Excessive exposure to high levels of Mn for a long period may lead to neurological disorders (Manganism: a disease starting from feeling of weakness and lethargy and leading to speech disturbances, clumsy gait and a masklike face) and respiratory and reproductive problems. The individual metals determine the method by which heavy metals impact human bodies, but eventually, all metals create reactive oxygen radicals, which cause a variety of illnesses in living things. Therefore, setting a threshold at which harmful substances were deemed was crucial (Mahurpawar 2015).

8.4 Permissible Limits of Some Common Heavy Metals

The regulatory limits of heavy metals are defined by several well-known organizations based on their toxicities. Given that humans directly consume water, the residential water supply is regarded as the most significant use of water. The National Water Policy has prioritized drinking as the best use of water resources. Drinking water standards have been developed in India by organizations like the Indian Council of Medical Research (ICMR) and the Bureau of Indian Standards (BIS). Table 8.3 lists the drinking water requirements for hazardous and trace metals according to BIS code 10500-2012 (Hussain and Rao 2018). All water delivery systems must adhere to these restrictions. Some heavy metals are regularly present in naturally occurring water (both surface and groundwater) at concentrations 100 or 1000 times higher than the MCL standards. Additionally, drinking water standards have been established by the USA Environmental Protection Agency (USEPA) and World Health Organization (WHO), which are regarded as global standards. Table 8.4 contains some harmful heavy metal ions that have maximum allowable levels in surface waters in accordance to WHO and USEPA. These heavy metals are important resources for various industrial uses; thus, their removal, recovery, and recycling are more crucial than ever. Regulatory authorities have developed drinking

Table 8.3 Drinking Water Standards for Trace & Toxic metals (BIS-10500-2012; Hussain and Rao 2018)

S. no.	Toxic metal	Requirement (acceptable limit; mg/L)	Permissible limit in the absence of alternative source (mg/L)
1.	Cadmium	0.003	No relaxation
2.	Iron	0.030	No relaxation
3.	Chromium	0.05	1.5
4.	Lead	0.01	No relaxation
5.	Copper	0.05	1.5
6.	Zinc	5	15
7.	Lead	0.01	No relaxation
8.	Nickel	0.0	No relaxation
9.	Arsenic	0.01	0.05

Table 8.4 Based on WHO and US EPA rules, some harmful heavy metal ions have maximum allowable levels in surface waters is tabulated (Hussain and Rao 2018)

Toxicity rank	Heavy metals	USEPA (μg/L)	WHO (μg/L)
1	Arsenic	10	10
2	Lead	15	10
3	Mercury	2	1
8	Cadmium	5	3
17	Chromium	100	50
57	Nickel	100	70
75	Zinc	5000	No guideline
125	Copper	1300	2000

water standards in line with toxicity data gathered from human clinical examinations and numerous other research, such as animal tests. A succinct overview is provided in Table 8.5 in which various international regulatory bodies standards are mentioned.

8.5 Remediation Strategies

Different methods such as membrane filtration, adsorption, ion exchange, chemical precipitation, etc. are some of the most commonly used methods to eliminate heavy metals from wastewaters (Türkmen et al. 2022). Presently, many researchers are working on the remediation of heavy metals from water, soil, and air by natural methods rather than chemical methods. Remediation is the method of removing toxic compounds from environmental media or replacing them with less toxicones. The strategies used to reduce or remove pollutants from soil and other environmental mediums use both in situ and ex situ procedures. The three major categories of remediation techniques are (1) physical approaches, (2) chemical ways, and (3) biological methods (Fig. 8.1).

8.5.1 8.5.1 Physicochemical Methods

These methods involve electrodialysis, chemical precipitation, reverse osmosis, evaporation recovery, physical adsorption, ion exchange, etc. (Qasem et al. 2021). Some of these techniques have been described in Table 8.6. Although these conventional physicochemical methods can remove heavy metal ions, there are certain environmental considerations associated with them. These processes generate some secondary waste products that contaminate the environment (Diep et al. 2018). Besides, certain methods such as chemical precipitation and electrochemical treatment are not effective when concentration of heavy metals is low. Techniques that use membrane, activated carbon, nanoadsorbents, and ion exchange technologies are expensive (Dhankhar and Hooda 2011).

Table 8.5 Standards for drinking water quality for trace elements that might have an impact on public health (Hattingh 1977; Gupta 1999)

Parameter	Lead (Pb)	Arsenic (As)	Cadmium (Cd)	Mercury (Hg)	Zinc (Zn)	Chromium (Cr)	Barium (Ba)	Selenium (Se)	Copper (Cu)
Australia (1973)	50	50	10	–	5000	50	1000	10	10000
FRG (1975)	40	40	6	4	2000	50	–	8	–
Japan (1968)	100	50	–	1	100	50	–	–	10000
NAS (1972)	50	100	10	2	5000	50	1000	10	1000
SABS (1971)	50	50	50	–	5000	50	–	–	1000
US EPA (1975)	50	50	10	2	–	50	1000	10	–
USPHS (1962)	50	10	10	–	5000	50	1000	10	1000
USSR (1970)	100	50	10	5	1000	100	4000	1	100
WHO European (1970)	100	50	10	–	5000	50	1000	10	50
WHO Intern. (1971)	100	50	10	1	5000	–	–	10	50

All values are in μg/L

USPHS US Public Health Service, *SABS* South African Bureau of Standards, *USSR* Russia, *NAS* USA National Academy of Sciences

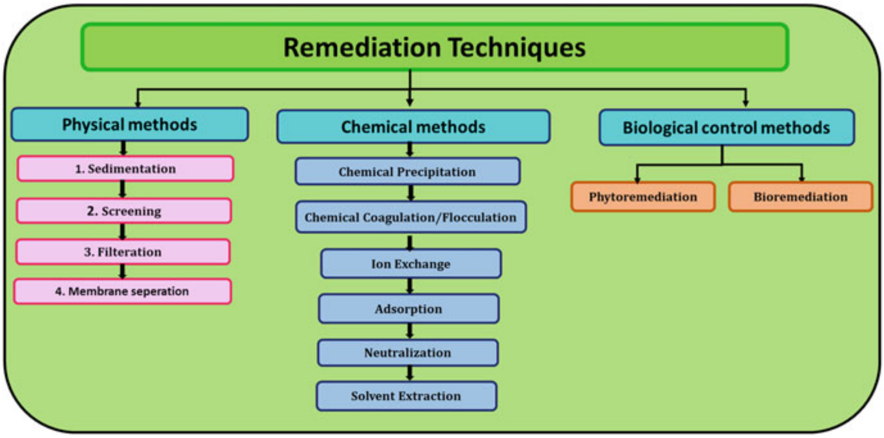

Fig. 8.1 Methods for heavy metal removal

Table 8.6 Physicochemical remediation technologies

S. no.	Physical methods	Description
1.	Screening	This method involves removal of large nonbiodegradable and floating solids
2.	Sedimentation	This technique involves gravity to remove suspended solids from water
3.	Membrane filtration	Membranes are in the form of complex structure which contains dynamic elements on the nanometer scale. In this method different types of membranes are included, namely, reverse osmosis, ultrafiltration, nanofiltration, and electrodialysis
4.	Membrane separation	This process involves membrane to separate the components in a solution by rejecting unwanted substances and allowing others to pass the membrane
5.	Chemical precipitation	This method changes the form of dissolved metal ions into solid particles to facilitate their sedimentation. The coagulant precipitates metal ions by changing pH, electro-oxidizing potential, or co-precipitation
6.	Chemical coagulation/ flocculation	Coagulation is the destabilization of colloids by neutralizing the forces that keep them parted, while flocculation is the agglomeration of destabilized particles.
7.	Electrochemical methods	This method involves the recovery of the heavy metals in the elemental metallic state by using the anodic and cathodic reactions in the electrochemical cell
8.	Ion exchange	This method is a reversible chemical reaction used to replace the undesirable metal ion in an ecofriendly manner
9.	Adsorption	Adsorption method is a solid-liquid mass transfer operation, where the heavy metal (adsorbate) is migrated from the wastewater to the solid surface (called adsorbent) and then bonded due to chemical or physical adsorption over the adsorbent surface

8.5.2 Phytoremediation Technique

Phytoremediation is a technique in which plants act as filters to remove contaminants from soil, water, and air. It is precisely a collection of plant-based technologies that cause removal of contaminants from environment by the use of plants and weeds (Ali et al. 2013). This technique is very cheap and alternative to present treatment methods. In several years, phytoremediation technique is gaining attention due to its cost-effectiveness, eco-friendly nature, and wide acceptance across the globe. Plants accumulate the toxic metals or contaminants from the environment through their body parts (shoots, roots, and stem). Phytoremediation is also identified by different names such as agro-remediation, green remediation, vegetative remediation, green technology, and botano remediation. It is very cheap method that requires technical strategy, knowledge of plants species and cultivars for particular contaminants, and regions. With the help of phytoremediation techniques, a variety of wastewater can be treated as municipal wastewater, industrial water, landfill leachate, paper industry, mine drainage, contaminated lands, and groundwater. This technique reduces the organic and inorganic pollutants from industrial wastewater by using plants. The performance of plants seems to be good in lowering the concentration of pollutants. Phytoremediation techniques follow different mechanisms such as phytoextraction, phytostabilization, phytovolatilization, phytodegradation, and rhizo-filtration during the uptake of heavy metals in the plant (Fig. 8.2). The summary of the phytoremediation techniques and mechanisms is shown in Fig. 8.2 and Table 8.7.

8.5.2.1 Bioremediation

Bioremediation is a technique of converting environmental pollutants into less hazardous forms using living organisms, primarily bacteria. It uses plants, naturally existing bacteria, and fungi to break down or detoxify pollutants that are harmful to the environment or to human health. This technique is advantageous over physico-chemical methods due to their eco-friendly nature (Gunatilake 2015). The basis of

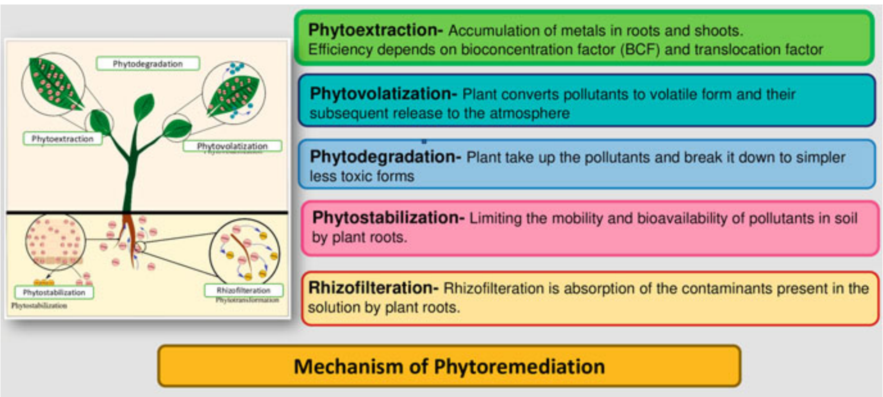

Fig. 8.2 Mechanisms of phytoremediation

Table 8.7 Phytoremediation for different heavy metals using different plant species

Phytotechnology	Pollutants	Plants	Metal-accumulated in plant parts	References
Phytoextraction	Pb, Hg, Cu, Cr, Ni, Zn	Water hyacinth	Roots and shoots	Molisani et al. (2006)
	As	*Hordeum vulgare*	Roots and shoots	Mains et al. (2006)
	Cr and Cd	*Cyperus rotundus*	Roots and shoots	Subhasini and Swamy (2014)
	Pb, Zn, and Cu	*Hordeum hirta*	Roots and shoots	Conesa et al. (2007)
	As	*Eleocharis acicularis*	Shoots	Sakakibara et al. (2011)
	Pahs	*Chrysopogon zizanioides*	–	Un Nisa and Rashid (2015)
	Pb	*Zea mays and Ambrosia artemisiifolia*	–	Shahandeh and Hossner (2000)
	Ni	*Alyssum heldreichii*	Leaves	Rizzi et al. (2004)
	As	*Tagetes minuta*	Shoots	Salazar and Pignata (2014)
	Cu	*Cannabis sativa* L.	Aboveground plant parts	Ahmad et al. (2015)
	Pb and Cd	*Betula occidentalis* and *Thlaspi caerulescens*	Shoots	Koptsik (2014)
	As	*Pteris vittata*	Shoots	Kalve et al. (2011)
	Cd	*Thlaspi caerulescens*	Shoots	Sheoran et al. (2009)
	Zn	*Euphorbia cheiradenia*	Shoots	Chehregani and Malayeri (2007)
Phytovolatilization	Se	*Salicornia bigelovii*	–	Huang et al. (2013)
	Se	*Typha latifolia* L.	–	LeDuc and Terry (2005)
	Se and Hg	*Chara canescens* (musk-grass) and *Brassica juncea*	–	Ghosh and Singh (2005)
	Zn, Mn, Co, Cd, Cr, Ni and As	*Typha latifolia* L.	–	Varun et al. (2011)
	Cd and Zn	*Sorghum bicolor* L.	–	Soudek et al. (2012)
	Cu, Pb, and Zn	*Agrostis castellana*	–	Pastor et al. (2015)

Phytodegradation	Trinitrotoluene	*Myriophyllum aquaticum*	–	Rajakaruna et al. (2006)
	Hg	*Azolla caroliniana*	–	Bennicelli et al. (2004)
	As	*Arundo donax* L.	–	Mirza et al. (2011)
Phytostabilization	Pb	*Sorghum halepense* L.	Reduction in rhizosphere	Salazar and Pignata (2014)
	Cu	*Spartina alterniflora*	Accumulation of metal in roots	Chai et al. (2014)
	Cd	*Phragmites australis*	Accumulation of metal in roots	Nunes da Silva et al. (2014)
	Se	*Salicornia bigelovii*	–	Huang et al. (2013)
	Zn	*Halimione portulacoides*	Accumulation of metal in tissues	Andrades-Moreno et al. (2013)
	Pb and Zn	*Suaeda salsa*	Accumulation of metals in roots	Wu et al. (2013)
	Cd	*Salicornia ramosissima*	Accumulation of metal in roots	Pedro et al. (2013)
	Cd	*Arthrocnemum macrostachyum*	Accumulation of metal in roots	Redondo-Gómez et al. (2010)
	Cu	*Commelina communis*	Accumulation of metal in roots	Wang and Zhong (2011)
	Cd, Ni, and As	*Salicornia brachiata*	Accumulation of metal in roots	Xu et al. (2010)
	Cd, Zn, Cu, and Co	*Sarcocornia perennis*	Accumulation of metal in roots	Lefèvre et al. (2010)
	As, Ag, Cr and Sb	*Solanum tuberosum* L.	–	Baghour et al. (2001)
Rhizofilteration	Cd	*Azolla pinnata*	–	Rai (2008)
	Pb	*Noccaea caerulescens*	Aerial part and shoot	Dinh et al. (2018)
	As	*Cynara cardunculus*	–	Llugany et al. (2012)
	Al, Fe, and Mn	*Pistia stratiotes*	–	Veselý et al. (2012)
	Sb	*Cynodon dactylon*	–	Xue et al. (2018)
	Fe	*Typha domingensis*	–	Hegazy et al. (2011)

removal and transportation of wastes for treatment basically is the two methods, namely, biosorption and bioaccumulation (Diep et al. 2018). Biological methods are sustainable and cost-effective in comparison to other methods. Figure 8.2 demonstrates bioremediation strategies commonly used for heavy metal removal.

8.5.2.2 Biosorption

This technique involves a rapid and passive adsorption mechanism. In this method, both living and dead biomass may be present for biosorption process. The biomass is derived from algae, fungi, plants, and bacteria (Ali Redha 2020). This strategy is inexpensive because it is possible to repeatedly renew and repurpose the biomass obtained from industrial waste. Various low-cost adsorbents are those derived from by-products of industry and agriculture such as rice husk, coconut shell, maize cob, etc. Biosorption involves two components: one is solid (biosorbent), and the other is liquid phase that contains an aqueous solution of contaminants such as heavy metals (Abbas Ali et al. 2016). Functional groups present on the solid phase are the major determinants for removal of a particular heavy metal.

8.5.2.3 Bioaccumulation

Bioaccumulation is a natural process by which microorganisms uptake metal ions using specific proteins from their surroundings (Diep et al. 2018). Researchers have also engineered some microorganisms to enhance their bioaccumulation process by introducing metal uptake proteins in their cell envelopes (Ueda 2016). Bioaccumulation utilizes live microorganisms in their metabolically active state, and major concerns associated with this process is the toxicity of wastewater to the organism, expression level of metal sequestering proteins, and exhaustive screening for selection of organism with high bioaccumulative potential. Genetic engineering helps to enhance the bioaccumulative potential of microorganism numerous folds and thus helps in efficient cleanup of water bodies contaminated with heavy metals (Fig. 8.3).

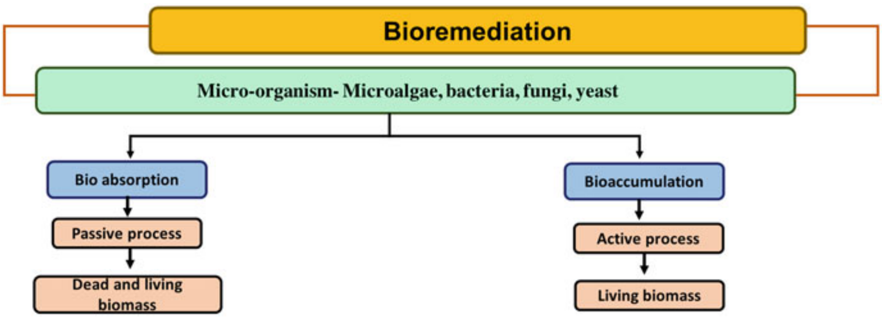

Fig. 8.3 Biosorption and bioaccumulation for heavy metal removal

8.6 Conclusion

Heavy metals become noxious when their concentrations exceed certain level. Increasing concerns regarding their toxicity and hazardous effect on aquatic as well as terrestrial life forms requires extensive study to better understand basic chemistry, toxicity, and selection of appropriate remedial options in order to restore environmental health. To choose an appropriate technique, it is important to consider the type of contaminant, degree of contamination, and cost-effectiveness of the strategy. Besides, efforts to improve their commercialization in developing countries considering environmental sustainability are also important. Implementation of biotechnological aspects and integrated approaches is gaining interest these days. Future research needs to focus on evaluation methods for assessing remediation effectiveness while developing new remediation technologies in future research.

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