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REVIEW ARTICLE

Phytoremediation of toxic metals present in soil and water environment: a critical review

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Abstract

Heavy metals are one of the most hazardous inorganic contaminants of both water and soil environment composition. Normally, heavy metals are non-biodegradable in nature because of their long persistence in the environment. Trace amounts of heavy metal contamination may pose severe health problems in human beings after prolonged consumption. Many instrumental techniques such as atomic absorption spectrophotometry, inductively coupled plasma-mass spectrometry, X-ray fluorescence, neutron activation analysis, etc. have been developed to determine their concentration in water as well as in the soil up to ppm, ppb, or ppt levels. Recent advances in these techniques along with their respective advantages and limitations are being discussed in the present paper. Moreover, some possible remedial phytoremediation approaches (phytostimulation, phytoextraction, phyotovolatilization, rhizofiltration, phytostabilization) have been presented for the removal of the heavy metal contamination from the water and soil environments.

Keywords Heavy metal · Toxicity · Phytoremediation · Phytoextraction · Rhizofiltration · Phytofiltration · Immobilization

Introduction

Heavy metals have been considered as one of the most lethal inorganic contaminants mainly originated due to anthropogenic activities (Nyarko et al. 2008). Manufacturing units or industries are the major sources of environmental degradation because they liberate various types of pollutants such as heavy metals [e.g., arsenic (As), cadmium (Cd), chromium (Cr), zinc (Zn), etc.] as well as toxic organics (Kim et al. 2005, Ahluwalia and Goyal 2007, Kumar et al. 2015). These heavy metals do not decompose naturally (because of their inorganic nature) and stay for a long time in the soil and water environments. The quality of agriculture crops and groundwater also gets spoiled due to their transfer from contaminated soil as reported by some researchers (Yoon et al. 2006; Jamali et al. 2009; Ekmekyapar et al. 2012; Srivastav et al. 2019). Throughout the world, the water environment is in worse condition due to the mixing of diverse types of toxicants including hydrocarbons, pesticides, antibiotics, cosmetics, and lethal heavy metals (Chowdhury et al. 2016; Kim et al. 2018; Khanam et al. 2020). High concentrations of heavy metals, fluoride, nitrate, etc. have been found beyond the permissible levels in groundwater in many parts of the world including India (Srivastav et al. 2013; Ranjan et al. 2019). According to the reports of both the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), only in developing countries are approximately 2.2 million people dying annually due to the long-term intake of bad-quality drinking water and insanitation (Azizullah et al. 2011). Presence of arsenic (metalloid), fluoride, iron, nitrate, and heavy metals

Highlights

- Heavy metals have been considered as one of the most lethal inorganic contaminants of water and soil.
- Major sources of toxic heavy metals are mining activities, industries, atmospheric pollution, etc.
- Heavy metal intake can cause carcinogenicity, teratogenicity, cardiovascular problems, etc.
- AAS, XRF, and NAA are the best determination techniques of heavy metals.
- Phytoextraction and phyotovolatilization are the best approaches of heavy metal removal from the soil and water, respectively.

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(Cd, Hg, Cr, etc.) in water can make it unfit for drinking purpose. In groundwater, arsenic, fluoride, and iron are naturally added because of their presence in the earth and nitrate, phosphate, and heavy metals (Cd, Cr, Pb, Hg, etc.) are appended by human activities including poor sewer systems, chemical-based agricultural practices, industrial ejections, etc. (Srivastav 2013). Heavy metals like As, Cd, Cr, Pb, Hg, and Ni have greater stability and least biodegradability (Lim et al. 2008; Mehta et al. 2016). Due to their frequent disposal in water and soil, human health has become an easy victim of many severe diseases (Hamilton et al. 1998; Aragay et al. 2011). Diagnosis and remedial options of any existing problems are the backbone of research. Therefore, in the present paper, many advance and sophisticated instrumental options of heavy metal determinations in water as well as soil environment have been reviewed in detail. Some possible remedial approaches have also been included herein for the detoxification of heavy metals present in water and soil.

Sources of heavy metals in soil and water

Heavy metal contaminations of water and soil have attracted the attention of the world because of their lethality to living beings (both flora and fauna) through bioaccumulation (Ekmekyapar et al. 2012). Different researchers have defined that usually heavy metals are those metals or metalloids which have higher elemental density. The definition of heavy metals is based on their elemental density, atomic number, or weight and also their chemical reactivity (Duruibe et al. 2007; Kumar et al. 2017). However, Oves et al. (2016) defined that the metals and metalloids which possess 5 g/cm^3 densities are known as heavy metals. In contrast, Ali et al. (2019a, b) have given a different criterion that a heavy metal should have $> 4 \pm 1$ g/cm^3 elemental density and cited many examples such as Cd, Co, Cr, Cu, Hg, Ni, Pb, Zn, etc. Terrestrial as well as aquatic ecosystems are getting affected severely even with the trace amount of heavy metals present in the environment (Bansod et al. 2017). These may come from the diffused sources like atmospheric impurities which have also been found to be the most important cause of soil and water contaminations (Kelly et al. 1996). These are the most hazardous and destructive water contaminants for natural systems as well as human health (Wanekaya 2011; Kim et al. 2012). The natural source includes volcanoes, erosion of soil and disintegration of rocks, etc. whereas the incomplete burning of fossils, mineral extraction, land filling, urban water discharge, mining and smelting, industrial discharge, agricultural chemicals, metal refining, manufacturing of electronic goods, coloring dyes, military operations, vehicular emissions, etc. are among human activities which are responsible for heavy metal contamination of water (Baldwin and Marshall 1999; Franzen et al. 2004; Senesi et al. 2009; Barakat 2011; Oves et al. 2012; Harvey et al. 2015; Häder et al. 2020). Generally, wastewaters from mines, smelters, sewage, battery industries, dyes, alloys, and electronic factories are the source of toxic heavy metals such as As, Cd, Cr, Cu, Hg, Pb, Zn, etc. (Ene et al. 2010). However, the contribution of anthropogenic activities in environmental contamination is greater than that of natural sources (Duruibe et al. 2007). According to Kumar et al. (2017), most of the heavy metals are very reactive in nature which ultimately have detrimental effects to the environment as well as human beings (Fig. 1).

Major anthropogenic activities which could increase the level of toxic heavy metals in the environmental systems are as follows:

- Mining activities and smelters may add As, Cd, Pb, and Hg metals.
- Industries (thermal power plants, electronics, automobiles, etc.) may add As, Cd, Cr, Co, Cu, Hg, Ni, and Zn metals.
- Through atmospheric dispersion and deposition, As, Cd, Cr, Cu, Pb, Hg, and U may be added.
- Excessive use of agrochemicals may add As, Cd, Cu, Pb, Se, U, and Zn.
- Improper solid/liquid waste disposal may add As, Cd, Cr, Cu, Pb, Hg, and Zn.

Moreover, some bacterial actions are also responsible for the addition of toxic organic mercury (mono- and/or dimethylmercury) to the environment (especially water and soil) which ultimately degrade the quality of drinking water as well as food stuffs (Kumar et al. 2017). Recently, the United Kingdom Environment Agency (UKEA) identified around 1300 plus mining places which contaminated the soil as well as nearby water reservoirs (e.g., rivers) through adding various types of heavy metals such as copper, cadmium, lead, and zinc (Foulds et al. 2014). Similarly, some researchers reported smelting and mineral mining being the chief sources of heavy metal pollution (surface and groundwater, farming soils, crops, etc.) in China as a huge quantity of wastewater (containing heavy metals) is being generated in these practices and it creates high risks to the health of society at large scale (Zhuang et al. 2009; Sun et al. 2010). In addition to the above, cosmetic items and chemical fertilizers are also responsible for heavy metal contamination (Callender 2004). Interestingly, it has been also observed that the heavy metals emitted by vehicles may be deposited on leaves as well as on the soil surface (Harrison et al. 1981). Hence, soil or agriculture fields close to the roads may have several types of toxic heavy metals as reported by many researchers (Turer and Maynard 2003; Viard et al. 2004; Kalavrouziotis et al. 2006).

Many recent studies have supported that untreated industrial wastewater is a main culprit of heavy metal contamination (arsenic, cadmium, mercury, etc.) of water and other parts of the environment. Moreover, heavy metals create a severe

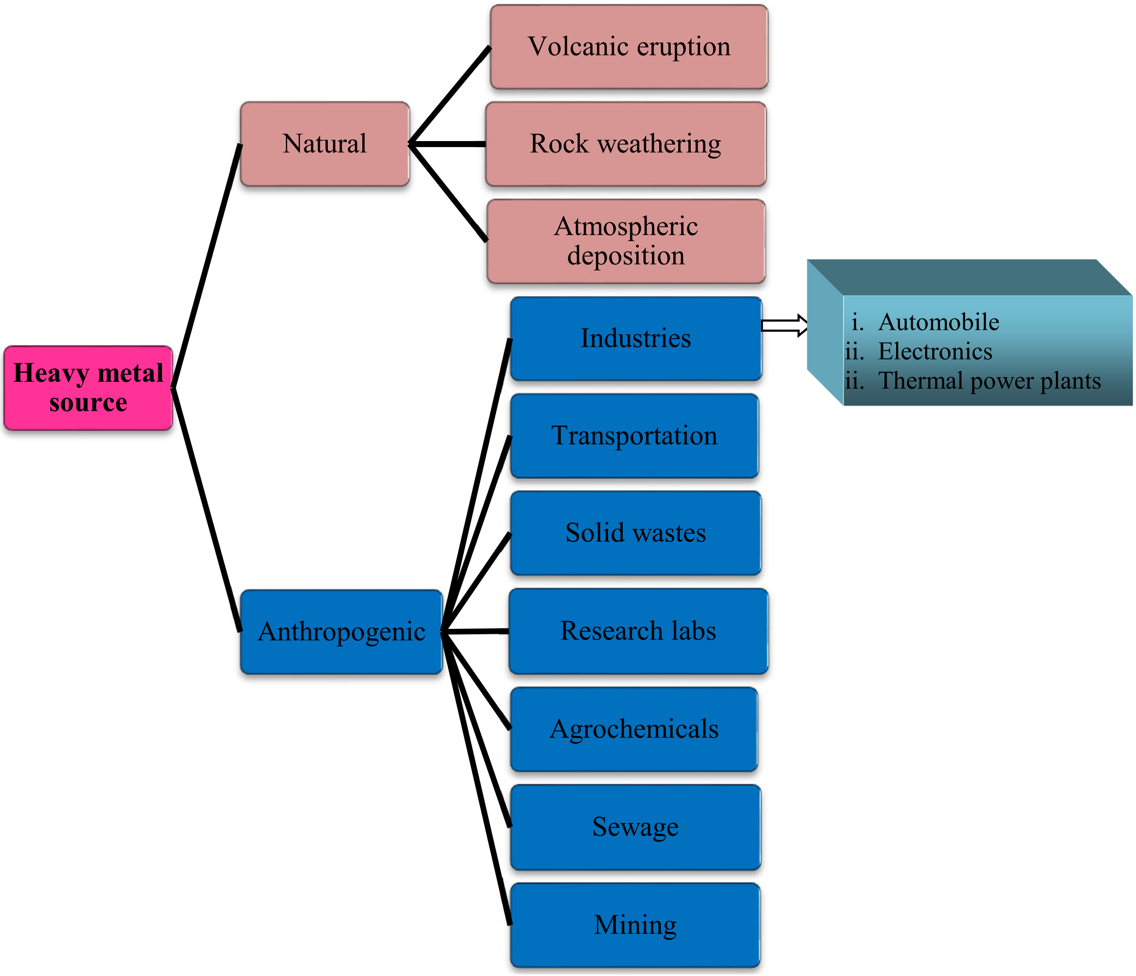


Fig. 1 Sources of heavy metals in the environment

threat to the living entity of the planet earth (Cao et al. 2019; Dumont et al. 2019; Sandhu et al. 2019; Nanda et al. 2019). According to Alloway (2012), soil samples of industrial and urban areas can have relatively greater levels of heavy metal contaminations (for example, cadmium, copper, lead, and zinc) coming from diffused sources such as automobiles, disposal of untreated wastewater, paint and varnishes, etc. However, soil texture (rocks), atmospheric impurities (metal-containing aerosols), fossil fuel burning, and agrochemicals (nitrogenous and phosphate fertilizers, and pesticides) are the major contributors of heavy metals in agricultural soils. Sun et al. (2013) studied 114 black soil samples collected from the farming lands of China for the determination of chromium, copper, nickel, lead, and zinc. Out of these metals, copper and lead were added by human activities, chromium, nickel, and zinc were added by geological reasons; agricultural practices were responsible for copper elevation; and lead was emitted due to the burning of fossils and municipal garbage. Peralta et al. (2020) observed metallic contaminations of arsenic, copper, lead, and zinc in the soil of a 40-year-old vineyard (Catalonia, northeast Spain) that used Bourdeaux (a copper-based fungicide) via portable ED-XRF. It was found that the upper soil was containing 70–128 mg/kg of copper, which is more than the Spain government-prescribed standard (90 mg/kg). However, the levels of arsenic, lead, and zinc were found insignificant. According to Shah and Daverey (2020), Europe (central and eastern), USA, and China are found to have metal-contaminated soil sites of around 1.7 million, 0.6 million, and > 20 million ha agriculture area, respectively. Natural sources of heavy metals in soils are volcanoes and disintegration of rocks, whereas industrial discharge, urban expansion, the automobile sector, and the wide application of agrochemicals are human sources of heavy metals in the soils (Pan et al. 2016; Ali et al. 2019a, b). Moreover, mining activities, municipal solid wastes, and industrial sludge are the significant contributors of heavy metal contamination in the soil (Ye et al. 2017; Bello et al. 2019; Vardhan et al. 2019). Wang et al. (2020a) reported that the exponential growth of industries and metropolitan areas is mostly responsible for the metallic contamination of soil. In the southwest part of China, cadmium and nickel are being added frequently into the soil (Sun et al. 2014). Moreover, metals like cadmium, chromium, nickel, and zinc can enter the human body via the food chain (Mclaughlin et al. 1999, Wang et al. 2003). Apart from these, many researchers reported the deterioration in the quality of crops, environmental imbalance, soil health decline, and loss of agriculture could also be possibly due the elevated concentrations of heavy metals in soil (Ahmad et al. 2016; Shah and Daverey 2020; Zhang et al. 2020). Further, Zhang et al. (2020) estimated the concentration of antimony, arsenic, cadmium, chromium, lead, thallium, mercury, manganese, and nickel in tea leaves. They noticed that apart from human factors, geological reason is also a significant factor for metal addition in the soil as evident in some studies. It has been observed that the soil generated from the carbonate-bearing rocks or/and intermediate-acid rocks may contain greater levels of heavy metals (Jia et al. 2020; Zhang et al. 2020). The source of heavy metal contamination in water may be natural or anthropogenic or both. However, they do not degrade easily; only transformation in their oxidation state is possible (Park et al. 2019), which ultimately causes severe disturbances in the metabolism of aquatic lives along with ecological turbulence (Baby et al. 2010). Marella et al. (2020) examined that many activities are responsible for the addition of heavy metals (common metals are cadmium, chromium, copper, lead, mercury, and zinc) in the aquatic environment. Cadmium can also be added from plastic manufacturing, from steel and battery industries, and also by some natural ores in the aquatic environment. It can disturb entire trophic levels of organisms after consuming contaminated fishes (Rizwan et al. 2019). The presence of heavy metals in soil can lead to contamination of water (surface and ground), killing of agriculture-friendly microbes, and poor soil health along with loss of agricultural yield (Singh et al. 2018; He et al. 2019). Moreover, these metals accumulate in the crops and may become risky for ecological frameworks including human beings (Yin et al. 2016; Chai et al. 2018; Wang et al. 2020b).

The soil of firing ranges also gets heavily polluted with lead as it accumulates bullets that can change the fundamental properties of soil including pH, ability of exchanging cations, moisture content, etc. (Etim 2018; Dinake et al. 2019). According to Moon et al. (2013a), normally Pb (97%), Sb (2%), As (0.5%), Ni (0.5%), and Cu (0.1%) may be present in one bullet shot. Many previous studies observed > 90% lead presence in a single bullet (Dermatas et al. 2006; Robinson et al. 2008; Chrastný et al. 2010; Moon et al. 2013a). Somewhere, the range of lead was diagnosed even more than 1000 mg/kg in the soil of an army firing range (Lin et al. 1995; Cao et al. 2003). Further, Moon et al. (2013b) stated that in the soil of military shooting ranges, significant concentrations of Pb^{2+} as well as Cu^{2+} were present and they can reach the groundwater after dissolution and in the air as fine aerosol. Lead has a great tendency to accumulate in the top layer of soil as it shows little mobility (Martin et al. 2014; Etim, 2018; Lago-Vila et al. 2019).

Discarded electronic products such as air conditioners, mobile phones, laptops, desktops, music players, etc. generated ~ 41.8 MT throughout the world in year 2014 (Ouabo et al. 2019). These e-wastes possess many harmful metals such as arsenic, cadmium, chromium, mercury, lead, selenium, etc. These metals are being used in the development of circuiting, electrification, galvanic cells, etc. (Otsuka et al. 2012; Zeng et al. 2014) and the careless disposal of e-wastes (open dumping and/or burning, etc.) can lead severe environmental contamination of the atmosphere and hydrosphere as well as lithosphere (Wei and Liu 2012; Ouabo et al. 2019; Wu et al. 2019a, b; Yu et al. 2019). Friedlander et al. (2019) examined the 29 soil samples around an e-waste incineration area of East Jerusalem and found concentrations of copper, iron, lead, manganese, and zinc in the vicinity of the burning site. Moreover, it was also observed that these metallic concentrations were governed by the local weather and soil compositions. E-waste has become a global concern because of containing poisonous metals which deteriorates the quality of the environment as well as human life (Zhang et al. 2012a, b). A similar finding of soil contamination due to multiple heavy metals (Cd, Cr, Hg, Pb, and Sb) from the burning of e-waste is also reported by many studies (Santos et al. 2011; Stenvall et al. 2013; Jiang et al. 2018; Han et al. 2019). Processing of e-waste materials is a significant supplier of many heavy metals and other pollutants in the soil and water as well (Salam and Varma 2018; Kumar 2018; Kumar and Fulekar 2019). For example, Yin et al. (2018) observed 4.61, 6.3, and 10.3 times greater copper, mercury, and antimony, respectively, in the soil of e-waste processing site as compared to a reference soil sample. Thus, it can be seen that there are many types of diffused and non-diffused sources of toxic metals. These sources may be natural or human generated; however, anthropogenic activities are the significant contributor of toxic metals in the environment.

Traces of heavy metals in plants and animals

Accumulation of heavy metals is observed frequently in the body of living creatures due to their highly reactive as well as permeable nature that eventually causes irreversible damage to the health of biota (Zou et al. 2016; Zhang et al. 2018; Wu et al. 2019a, b). Even a little concentration may cause stern troubles to humans as well as the environment (Gumpu et al. 2015; Chu et al. 2019). Ene et al. (2010) used X-ray fluorescence to determine the several types of heavy metal concentration in water and soil samples collected from the surrounding areas of some iron and steel workshops (Romania). A high metal concentration was observed in the soil samples collected from the adjacent areas of this workshop as compared to the distant location from the workshop. However, the areas with high traffic density as well as industries possess enhanced levels of heavy metals. Therefore, it can be understood that increasing distance from the pollution sites may have lesser detrimental effects on the environmental systems or biota. Similarly, Ekmekyapar et al. (2012) reported heavy metal contamination in the soil samples and these metals got transferred from the contaminated soil to the wheat crop which was cultivated near the roads in Turkey. As per their findings, the level of lead was detected to be greater than the standards prescribed for soils. Interestingly, the levels of Cu, Fe, Mn, and Ni were found to be higher in the wheat plants before washing as compared to those of the cleansed wheat plants. The higher level of metal contamination was attributed to the heavy traffic load as well as the effect of wind direction. Liu et al. (2013) also studied the accumulation of metals by several crop plants including barley, clover, grapes, spinach, wheat, etc. The samples were extracted from the edible parts of these crops as these parts are consumed by humans or other living organisms. Roots and leaves are the main parts of any plant through which heavy metals get absorbed from the contaminated soils (Liang et al. 2017). Likewise, Byers et al. (2019) determined the heavy metal contents in the algal plants using portable energy-dispersive X-ray fluorescence(ED-XRF) as this instrument can be used for onsite determination of metallic contents in the samples. Moreover, atomic absorption spectrometry (AAS), inductively coupled plasma-atomic emission spectrometry (ICP-AES), inductively coupled plasma-atomic mass spectrometry (ICP-MS), and wavelength dispersive XRF (WD-XRF) are also some of the important techniques for metal determination in various types of samples. Fishes are also reported to have heavy metal contamination as studied by Mehouel et al. (2019). Researchers noticed that species of fishes found along with Algerian coasts like sardine (*Sardina pilchardus*) and swordfish (*Xiphias gladius*) were also having higher levels of Cd, Hg, and Pb as prescribed by the health authorities of Algeria as well as Europe (Mehouel et al. 2019).

Furthermore, Marques et al. (2008) observed that terrestrial vertebral organisms of contaminated areas are also at risk because of the bioaccumulation of heavy metals in their body. Baby et al. (2010) reported that the liver is a major body organ of mammalians as well as fishes where most of the heavy metals get accumulated. Sarah et al. (2019) examined the presence of heavy metals in the body of an edible fish, i.e., *Channa punctatus* of Ramganga River. A study has shown that heavy metals were accumulated in the liver of the fish in an order of Fe > As > Cd > Zn > Pb, whereas in the kidney, these metals were present in an order of Zn > Fe > As > Cd > Pb. These metals were present more than the standards and may cause human health disorders after fish consumption. The source of heavy metals in the river was the agrochemicals and other human activities. Spyra et al. (2019) reported heavy metal accumulation (including copper, cadmium, lead, and zinc) in a snail species, i.e., *Physell aacuta*, which is generally found in freshwater ecosystems. According to Hao et al. (2019), marine organisms have a greater ability for bioaccumulation of heavy metals as they studied crabs and marine fish for cadmium, chromium, copper, lead, mercury, and zinc. Copper and zinc were highly accumulated metals in crabs and marine fish. Goretti et al. (2019) reported on the heavy metal accumulation in the body of the honeybee (*Apis mellifera ligustica*) in central Italy. A study has shown that cadmium was present in higher concentrations with respect to copper, manganese, and zinc. Sources of these heavy metals were PM_{10} (particulate matter of 10 micron size) and agrochemicals used in soil. Hu et al. (2020a, b) developed a model to determine heavy metal accumulation in the crops coming from the contaminated farmlands. One thousand eight hundred twenty-two samples (both crops and soils) were collected for the calculation of bioaccumulation factors for all the crops. Arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc metals were determined in all the samples, and cadmium was accumulated in the highest concentration among all the crops. Lethal effects on human beings are observed due to the intake of heavy metal-contaminated vegetables and crops as these crops were irrigated with metal-contaminated water (Jacob et al. 2018). Kumar et al. (2019) reported the contamination in cauliflower (*Brassica oleracea* L.) which was irrigated with industrial wastewater. Analyses have shown that iron was present in the highest level and cadmium was accumulated in the lowest concentration in the roots, leaves, and florescence of cauliflower. Liu et al. (2019) investigated the presence of many heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn) in mollusk species, crabs, and fish. However, molluskans were found to have elevated concentrations of metals as compared to crabs and fishes. Quina et al. (2019) studied the effect of heavy metal contamination of the population of wild Algerian mice (*Mus spretus*). Heavy metal-contaminated environments caused changes in enzyme secretions, tissue disorders, and blood poisoning as well as mutations in the mice species. According to Zhang and Reynolds (2019), cadmium easily gets accumulated in the vegetations and animal tissues (terrestrial and aquatic). The lethality of cadmium is comparatively greater because it can persist for longer times in the environment as compared to other metals. Kidney, liver, and DNA disorders, and growth obstacles, are the common problems due to cadmium poisoning.

Human health disorders due to heavy metal contamination

Heavy metals are very lethal, sometimes carcinogenic, and also can create big problems to the health of many kinds of living creatures (Leong and Chang 2020). If the concentration of heavy metals exceeds the level prescribed by WHO, it will create toxic effects for the soil and aquatic systems (Ali et al.

2019a, b). Their existence in the soil environment can deteriorate the quality of food, groundwater, agriculture-friendly microorganisms' growth and vegetation growth, etc. (Vries et al. 2007; Popescu et al. 2009). Heavy metals are well known for higher reactivity and rapid complexation as well as biochemical processes (Salem et al. 2000a, b; Mohammed et al. 2011). Moreover, these heavy metals get circulated among all the living systems of any ecosystem through the food chain (Ali et al. 2019a, b). The presence of heavy metals in soil, water, and food can harm human health as it could reach inside the body through direct intake, dermal contact, and inhalation (Liang et al. 2017). In addition to these, the food chain is the easiest route of heavy metals to reach the inside of the human body and causes several fatal diseases. It is noteworthy that the levels of several essential nutrients including ascorbic acid (vitamin C) and iron in the human body will be decreased if they are taking meals contaminated with arsenic, cadmium, chromium, lead, etc. like toxic metallic ions and may have weaker immune systems, many functional disorders, disabilities, and malnutrition (Liu et al. 2005) as these metals have been considered as extremely toxic in nature (Bansod et al. 2017). Heavy metals are importunate contaminants of the environment, and they may be present for hundreds of years (Kumar et al. 2017; Bansod et al. 2017) as these metals are not easily decomposable in the environment and most likely get accumulated inside the bodies of living creatures after being exposed to contaminated air, food, soil, and/or water (Kumar et al. 2017). After prolonged accumulation, these chemicals attack the central nervous system, immune system, and reproductive system as well as gastrointestinal system (Turdean 2011; Gong et al. 2016). These human health disorders may include severe diseases like carcinogenicity, mutagenicity, and toxicological diseases to the various body organs (Trautwein and Deutsche 1997; Lim et al. 2008; Mehta et al. 2016). Several human body organs may also have severe risk due to heavy metal intake such as brain retardation, neurons, blood poisoning, liver, cancer, skin problems, DNA dysfunction, lung disorders, kidney and cardiotoxicity (Oves et al. 2016; Kumar et al. 2017; Wallace and Djordjevic 2020; Sevim et al. 2020). Moreover, prolonged intake of these metals may also promote other diseases like Alzheimer's, Parkinson's, collapse in skeletal muscles, nerves of brain, vertebra as well as optic nerves (Kampa and Castanas 2008; Guilarte 2011). Conversely, some metals like copper, selenium, and zinc play essential and advantageous roles in the physiology of the human body as copper is linked with the proper functioning of many enzymes (Farhan et al. 2016). Major impacts of heavy metals are illustrated in Fig. 2.

Mercury is a deadly toxic heavy metal and its poisoning can have several destructive effects on the central nervous systems, respiratory organs, muscle dystrophy, memory disorders, disability to the limbs, etc. (Kim et al. 2016; Ha et al. 2017; Kim et al. 2019). Mercury can enter the body through various routes such as air, water, food (fishes), etc. (Maria 2011; Prabhakar et al. 2012; Pujol et al. 2014). Some common effects of heavy metal contamination, their speciation, and route of entry are summarized in Table 1.

Risk assessment of human health hazard due to heavy metal consumption

Some researchers have been trying to explore the level of hazardness on human health due to the heavy metal contamination because of their toxicity (either carcinogenic or non-carcinogenic disease) (Singh et al. 2010; Christou et al. 2017). Moreover, some researchers have identified the location wise hazard level of heavy metals. For example, people living nearby any mining area may have the greater health risk of arsenic, lead, and/or cadmium poisoning (Li et al. 2014a, b). Comparatively, the level of hazardness of mercury (Hg^{2+}), lead (Pb^{2+}), and arsenic ($As^{3-)}$ is greater than that of nickel (Ni^{2+}), copper (Cu^{2+}), cadmium (Cd^{2+}), and chromium (Cr^{3+} and Cr^{6+}). Hence, for heavy metals having greater risks, their standard has been set up to ppb levels and those are having less hazard their standard is up to ppm levels (WHO 2011).

Risk of cancer development in any person may depend on the level as well as the exposure to carcinogenic chemicals and it can be understood by using Eq. (1):

$$\text{Cancer risk} = \text{CDI} \times \text{SF} \quad (1)$$

where cancer risk = probability of developing cancer in an individual, CDI = prolonged consumption of carcinogenic chemicals in milligrams per kilogram per day, and SF = slope factor for carcinogenicity in milligrams per kilogram per day (Cai et al. 2015). This slope factor (SF) is the ratio of average daily intake and expected lifelong exposure to heavy metal as it has a direct connection in escalating the probability of cancer growth in a person (USEPA 1989).

However, carcinogenic chemicals mean several types of carcinogens. Moreover, non-carcinogenic threat can also be estimated after making comparison of exposure level vs time and daily intake by using Eq. (2) (Liang et al. 2017).

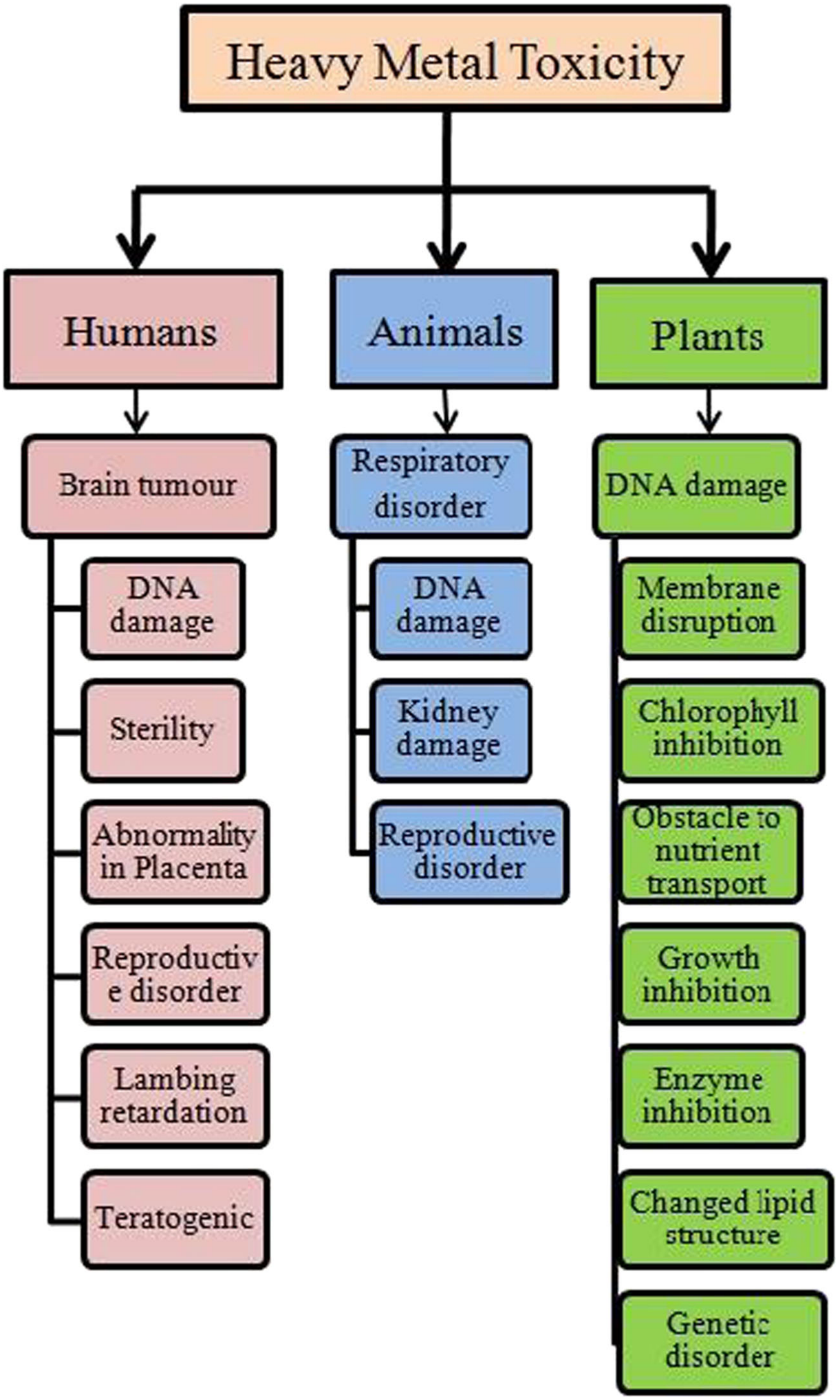
$$\text{HQ} = \text{CDI}/\text{RFD} \quad (2)$$

where HQ = hazard quotient, CDI = chronic daily intake, and RFD = reference dosage.

Further, USEPA (1989) and Wu et al. (2019a, b) employed Eq. (2) to compute the probability of developing human health disorders (noncancerous only) after the consumption of heavy metal-contaminated rice grains. If the value of HQ is < 1, then it would be less harmful. However, it may have greater risk, if it is > 1 (Wu et al. 2019a, b).

Transfer factor (can give the amount of heavy metal transfer into plant biomass) can also be calculated by some

Fig. 2 Impacts of heavy metal contamination on biota



researchers (Mirecki et al. 2015) as the formula given below:

$$\text{Transfer factor} = \text{metal content in plant (mg/kg)/metal content in soil (mg/kg)} \quad (3)$$

Many researchers have observed that heavy metals present along the roads can cause human health problems through breathing, skin absorption, and direct intake. However, direct ingestion of heavy metal-contaminated things (eatables, water etc.) is the biggest hazard for the human health followed by skin absorption and breathing (Tang et al. 2017; Li et al. 2017; Hou et al. 2019).

Qiao et al. (2020) used a formula, i.e., pollution index (P_i), to evaluate heavy metal contamination in water and soil as given below:

$$P_i = C_i / S_i \quad (4)$$

in which C_i = metal concentration in the sample and S_i = reference metal concentration.

Table 1 Common oxidation states of heavy metals and human health disorders due to overconsumption of it

Heavy metal	Sources	Common oxidation states	Route of entry	Human health disorders	References
Arsenic	Contaminated water, industries (e.g., smelters, coal-based thermal power plants), fine particulates, pesticides containing arsenic derivatives, preservatives, etc.	− 3, 0, + 3, and + 5	Drinking water and foodstuff	Affects ATP formation, brain disorders, heart diseases, conjunctivitis, skin problems, respiratory problems, carcinogenicity, neuron disorders, etc.	(Tripathi et al. 2007; Singh et al. 2011; Hashim et al. 2011; Islam et al. 2017; El and Abdel 2018; Bhat et al. 2019; Rehman et al. 2019; Qiao et al. 2019; Qiao et al. 2020; Zhang et al. 2020; Hu et al. 2020a, b)
Cadmium	Chemical fertilizers, industrial wastes, batteries and alloys, cigarettes, etc.	0 and + 2	Food items, smoking, gastrointestinal absorption	Carcinogenicity (e.g., lung, prostate, etc.), mutagenicity, and teratogenicity, endocrine disorders, malfunctioning of calcium, coughing, emphysema, headache & hypertension, itai-itai disease, microcytic, anemia, fragile bones, etc.	(Brama et al. 2007; Peralta et al. 2020; Sughis et al. 2011; Hashim et al. 2011; Koedrith et al. 2013; Rai et al. 2019; Bhat et al. 2019; Qiao et al. 2020; Zhang et al. 2020; Hu et al. 2020a, b; Marella et al. 2020)
Chromium	Industries (electroplating, textile, etc.), wastewater and sludge of industries	0, + 3, and + 6	Contaminated eatables, crops, and water	Dizziness, fatigue, bronchitis, diarrhea, emphysema, migraine, skin diseases, respiratory problems, liver ailment, reproductive system disorders, toxicity, vomiting, etc.	(Salem et al. 2000a, b; Dong et al. 2007; Peralta et al. 2009; Hashim et al. 2011; Rai et al. 2019; Bhat et al. 2019; Qiao et al. 2019; Qiao et al. 2020; Zhang et al. 2020; Hu et al. 2020a, b; Marella et al. 2020)
Copper	Irrigation of crops with contaminated water	0, + 1, and + 2	Contaminated food items and water	Diseases of brain, kidney, liver, anemia, intestinal problems, etc.	(Salem et al., 2000a, b; Hough et al. 2004; Wuana and Okieimen 2011; Singh et al. 2011; Hashim et al. 2011; Rai et al. 2019; Qiao et al. 2020; Peralta et al. 2020; Hu et al. 2020a, b; Marella et al. 2020)
Mercury	Tools/devices, amalgams used in dentistry, industries (e.g., energy, chloralkali), thermal power plants	0, + 1, and + 2	Biomethylation	Muscle problems; eye, ear, and kidney disorders; infertility; memory loss; dizziness; speech problems; gastric problems; dental diseases; respiration disturbance; weak immune system; brain problem; threat to the embryo; etc.	(Heaton et al. 2003; Jansson et al. 2007; Guzzi and La 2008; Peralta et al. 2009; Hashim et al. 2011; Park and Zheng 2012; Jaishankar et al. 2014; El and Abdel 2018; Bhat et al. 2019; Qiao et al. 2020; Zhang et al. 2020; Hu et al. 2020a, b; Marella et al. 2020)
Lead	Industries (mining, smelters, paint, thermal power plants, etc.), raw petroleum	0 and + 2	Fine particulate matter exposure on crops, industrial works	Growth retardation, loss of appetite, neuron disorders, sleeplessness, kidney failures, etc.	(Salem et al. 2000a, b; Hough et al. 2004; Lam et al. 2007; Peralta et al. 2009; Wuana and Okieimen 2011; Hashim et al. 2011; El and Abdel 2018; Bhat et al. 2019; Lago-Vila et al. 2019; Qiao et al. 2020; Zhang et al. 2020; Hu et al. 2020a, b; Marella et al. 2020)
Zinc	Contaminated wastewaters of industrial units and sewage	0 and + 2	Contaminated food items	Faintness, tiredness, ataxia (muscle problems), dejection, intestine disorders, urine infection, jaundice, infertility, renal and liver dysfunctions, fever, prostate cancer, nausea, etc.	(Eisler 2000; Damek and Sawicka 2003; Hough et al. 2004; Hashim et al. 2011; Ayangbenro and Babalola 2017; Lal et al. 2018; Qiao et al. 2020; Hu et al. 2020a, b; Marella et al. 2020)
Nickel	Batteries (Ni and Cd based) and industrial wastewater	–	Contaminated food items	Skin allergy, cancers (lungs, nose, throat, stomach), hepatotoxic, immunotoxic, neurotoxic, genotoxic, reproductive disorders, pulmonary toxic, nephrotoxic, and hepatotoxic, causes hair loss, etc.	(Salem et al. 2000a, b; Hough et al. 2004; Das et al. 2008; Shaumloffel 2012; Lal et al. 2018; Zhang et al. 2020; Hu et al. 2020a, b)

The values of P_i were observed as 22 and 15 for copper present in sediment and upper layer of soil and it was categorized as highly polluted, and the P_i value was 2 for zinc in both the mediums (stated as moderately polluted). Similarly, arsenic was present in the level of moderately polluted as it had 1 and 4 P_i values in the same mediums (Qiao et al. 2020).

Hakanson (1980) provided 4 classes of heavy metal contamination level based on the P_i values as mentioned below (Table 2).

Moreover, a pollution load index was also employed by the researchers to examine the level of heavy metal contamination present in soil (Suresh et al. 2012; Kumar and Fulekar 2019). This parameter can be calculated by using Eq. (5):

$$\text{Pollution load index} = \sqrt[n]{P_i1 \times P_i2 \times P_i3 \times \ldots.. \times P_i\ ofn\ \text{number}} \tag{5}$$

where n = number of total analyzed metals; P_i1, P_i2 = first and second metal concentrations, respectively; and so on (Kumar and Fulekar 2019). According to Seshan et al. (2010), if the pollution load index is less than 1, it shows zero pollution due to heavy metals, whereas, if it is more than 1, it may have metallic pollution. Such types of equations can provide us an idea about the transfer of metals into plant biomass. Moreover, it can also help to screen the hyperaccumulator plants which are having greater potential for the phytoremediation of toxic heavy metals present in soil and/or water systems.

Advanced techniques of heavy metal determination

Detection of heavy metals in water is vital, and hence, renowned international organizations such as WHO, FAO, and USEPA as well as EU have inferred that these chemicals must be monitored regularly in water to meet the set standards (WHO 2011; Gumpu et al. 2015). For this purpose, highly sensitive and sophisticated advanced instruments are required which should have the capability of determination up to ppm and/or ppb levels in biological samples including blood, serum, saliva, etc.; aqueous medium; air; food; and soil as well (Bansod et al. 2017). Conventional approaches of heavy metal determination have several drawbacks as compared to the advanced instruments in terms of precision, accuracy, reliability, determination time, etc. (Zhang et al. 2011; Lamine et al. 2019). The techniques which are capable of detecting the level of heavy metals up to ppb levels in a variety of environmental, biological, and geological samples mentioned below:

- Atomic absorption spectroscopy (AAS)
- Inductively coupled plasma-atomic emission spectrometry (ICP-AES) or inductively coupled plasma-mass spectrometry (ICP-MS) or inductively coupled plasma-optical emission spectrometry (ICP-OES)
- X-ray fluorescence spectrometry (XRF) or wavelength dispersive XRF (WD-XRF) or bench-mounted energy-dispersive XRF (ED-XRF) or portable ED-XRF or synchrotron XRF
- Neutron activation analysis (NAA)
- Particle-induced X-ray emission (PIXE)

The above analytical techniques are well documented for the detection of heavy metals present in environmental systems because of their efficiency and wide range of detection (Knecht and Sethi 2009; Bings et al. 2010; Zhang and Fang 2010; Srungaram et al. 2013) as the salient features are compiled in Table 3.

The techniques mentioned in Table 3 are non-destructive which can also detect the presence of multi-elements at the same time. These techniques are being used in industrial applications along with research because of their accuracy, precision, trace level determination, and sensitivity for the heavy metal detection in various types of samples such as historical, organic, industrial, geographical, environmental, etc. (Ene et al. 2010; Pujol et al. 2014; Bansod et al. 2017). *Biosensors*: Heavy metal presence can also be detected by using some biosensors after their interaction with biological units of living organisms such as proteins, enzymes, antibodies, nucleotides, nucleosides, etc. (Blake et al. 2001; Mehta et al. 2016). *Nanoparticles*: Similarly, developments of nanomaterial-based techniques are also an important factor of detecting heavy metals in different types of materials.

Table 2 Pollution index with respect to heavy metal contamination

S. no.	Values of P_i for heavy metal in water or/and soil	Expected level of heavy metal toxicity
1.	Less than 1	Low
2.	1–3	Moderate
3.	3–6	High
4.	More than 6	Very high

Source: Kumar and Fulekar (2019)

Table 3 Salient features of advance techniques of heavy metal determination

S. no.	Technique	Lower detection limit	Salient features	Limitations	References
1.	(i) Atomic absorption spectrophotometer (AAS) (ii) Graphite furnace atomic absorption spectrophotometer (GFAAS)	ppm-ppb	Most widely used technique for chemical analyses, requires less time, relatively suitable spectroscopic and highly precise and accurate method	Not better than ICP-OES, ICP-MS; unable to detect non-metals, requires multi-sample preparation and attached with chromatographic devices for metal ion speciation, not suitable for in situ measurements, expensive and complex structure, flame and furnace required low detection limits and trace metal analyses	(Feldmann et al. 2009; Soodan et al. 2014; Cui et al. 2015; Wilberforce J.O. 2016; Bansod et al. 2017; Byers et al. 2019)
2.	(i) Inductively coupled plasma-atomic emission spectrometry (ICP-AES) (ii) Inductively coupled plasma-mass spectrometry (ICP-MS) (iii) Inductively coupled plasma-optical emission spectrometry (ICP-OES)	ppb (0.1–10 ng/ml for many elements)	Simultaneous multi-elemental and ultratrace detection capability, speciation analyses possible, highly precise, simple spectrum-based method, lower detection limit, rapid analysis of isotopes, samples (water, food, algae, geochemical, environmental, biological, etc.), determines 70 elements even in <2 min, lower sample size (e.g., 2 ml solution)	Matrix effects (higher concentration of dissolved solids may have clogging problems), need of pretreatment of samples	(Beauchemin 2017; Soodan et al. 2014; Bansod et al. 2017; Byers et al. 2019)
3.	Electrochemical techniques (e.g., potentiostatic, galvanostatic, impedance measurement, electrochemiluminescence, etc.)	ppm	Economical, user friendly, highly reliable, suitability of in situ applications, rapid analysis	Inferior sensitivity and detection limit with respect to spectroscopic and optical methods	(Pujol et al. 2014; Cui et al. 2015; Bansod et al. 2017; Kim et al. 2018)
4.	(i) X-ray fluorescence spectrometry (XRF) (ii) Wavelength dispersive XRF (WD-XRF) (iii) Energy-dispersive XRF (ED-XRF) (iv) Synchrotron XRF	ppb	Fast analytical method, simple sample preparation, acid digestion not required, simultaneous multi-elemental analysis in a small-time, high-accuracy, non-destructive method, samples (soil, water, food, etc.)	Comparatively bigger sample size required (normally > 1 g), matrix effects, complexity in determining elements lighter than sodium, difficult in distinguishing isotopes or speciation of an element or ions in different valence state, expensive, etc.	(Ene et al. 2010; Soodan et al. 2014; Wilberforce 2016; Bansod et al. 2017; Singh et al. 2017; Byers et al. 2019; Hu et al. 2020a, b)
5.	Neutron activation analysis (NAA)	ppt	Highly efficient and precise for trace elements in diverse types of samples (including rare elements), non-destructive method, small irradiation time, multielement analysis	Difficulty in determination of the elements cannot having long half-life (e.g., radionuclides) or who do not emit gamma radiation	(Suciu et al. 2008; Ene et al. 2009; Soodan et al. 2014; Bansod et al. 2017)

Application of many types of nanomaterials is illustrated in the research papers which includes metallic nanoparticles, quantum dots, metal organic frameworks, magnetic nanoparticles, carbon nanotubes, and nanocomposites (Wallace 2009; Knecht and Sethi 2009; Zhang and Fang 2010; Kumar et al. 2017).

XRF is an important technique of heavy determination in the diverse types of samples, and it is an extremely responsive technique which follows the principle of interaction of atoms with radiation (Torok et al. 1998; Anjos et al. 2000; Soodan et al. 2014). During XRF spectroscopy, emission of secondary or fluorescent X-rays of the materials has atomized due to the exposure of high-energy X-rays or gamma rays. It can be used to know the precise elemental composition of the different types of samples like archaeological things, ceramics, construction materials, forensic materials, geo-chemicals, glass, and metals (Jekins 1999; Wilberforce 2016). Also, both quantitative and qualitative analyses of these samples (along with simultaneous multi-element determination) can be carried out without acid digestion in much less time (Ene et al. 2010). Further, the XRF technique has been categorized into different types as already mentioned in Table 2. The synchrotron-based XRF technique is non-destructive and is the most precise and accurate method of heavy metal determination in soil as well as water samples. Synchrotron radiation can be used to characterize the various types of materials which have a very precise accurate detection of the chemicals. Furthermore, it can simultaneously determine many elements present in single sample (Radtke et al. 2016). In India, this facility is available at RRCAT-Indore. Researchers can collaborate with the institute to perform the experiments on highly advanced synchrotron radiation XRF/TXRF facility at BL-16 of RRCAT-Indore.

Remediation techniques for heavy metals

The World Health Organization (WHO) and Environmental Protection Agency (EPA) both have reported that heavy metal contamination is a big menace for us, and therefore, they have given several options of controlling the expansion of heavy metals in the environmental systems (Merkoc and Alegret 2007; Aragay et al. 2011). According to Mu'azu et al. (2019), some sustainable techniques are available in the research documents for the remediation of heavy metal-contaminated soils as well as water. Water purification can be carried out by chemical precipitation and oxidation, reverse osmosis, adsorption, electrodialysis, reverse osmosis, ion-exchange etc. (Ali and Gupta 2006; Ali et al. 2011; Chen et al. 2018). However, adsorption has been reported as a relatively better technique than any others in terms of operation, cost, and practical aspects as well as water contaminant removal efficiency (Chowdhury and Balasubramanian 2014; Park et al. 2019), and also, it does not require any post treatment of treated water (Santhosh et al. 2016; Ersana et al. 2017). In order to protect human health, people should get safe drinking water as well as contamination-free foodstuff. Therefore, it is imperative to stop the release of metallic contaminate at their source. Moreover, eco-friendly, economical, and efficient techniques are required to mitigate the heavy metals present in the environment (Rai et al. 2019). Zou et al. (2017) reported that a concept namely H-G has the ability to provide effective and precise remediation steps for the soil contaminated with heavy metals as it incorporates threats to the human well-being with geospatial parameters. In the H-G concept, human well-being assessment (H) was integrated with the geographical parameters (G) of heavy metal-contaminated soil. Therefore, it can help in developing geospatial technology-based decision support system to provide remediation options for contaminated soil even with a small cluster of samples (Zou et al. 2017). Further, wisely developed land use policies for agricultural practices (for example, sufficient distance from the cause of heavy metal generations) and production of organic food items have got much wide attention to prevent human health from any chemical toxicity (Rock et al. 2017). Rai et al. (2019) have specified the types of approaches for the management of heavy metals present in water and soil environment such as reduction at source of generation, ecological remediation, physical and chemical processes, and nanomaterial-based techniques.

Phytoremediation has been considered an eco-friendly and sustainable approach to eliminate heavy metals or other hazardous chemicals from water as well as soil environment (Bian et al. 2019). The term "phytoremediation" originated from the Greek word of *phyto* which means "plant" and *remedium*, a Latin word to remove or to correct an evil (USEPA 2000; Erakhrumen and Agbontalor 2007). Several researchers have wisely explained the term "phytoremediation" according to their experimentation and illustrations. Most of them have documented that phytoremediation is an approach or technique which uses plants or microbes to reduce the level of hazard of noxious contaminants of water, air, and soil environments. It may include removal, destruction, sequestration, remediation, extraction, uptake, immobilization, and stabilization of contaminants (USEPA 2000; Bhattacharya et al. 2006; Van Ginneken et al. 2007; Moreno et al. 2008; Tangahu et al. 2011). Rai et al. (2019) illustrated heavy metal contamination of soil and water and their proper management using appropriate strategies as given in Fig. 3.

The phytoremediation approach has many advantages in environmental cleanup because of the exclusive potential of removing hazardous chemicals through their plant root system either by the mechanism of bioaccumulation, contaminant degradation, and/or translocation (Akpor and Muchie 2010; Tangahu et al. 2011). Cho-Ruk et al. (2006) found that arsenic, cadmium, chromium, mercury, nickel, and lead can be

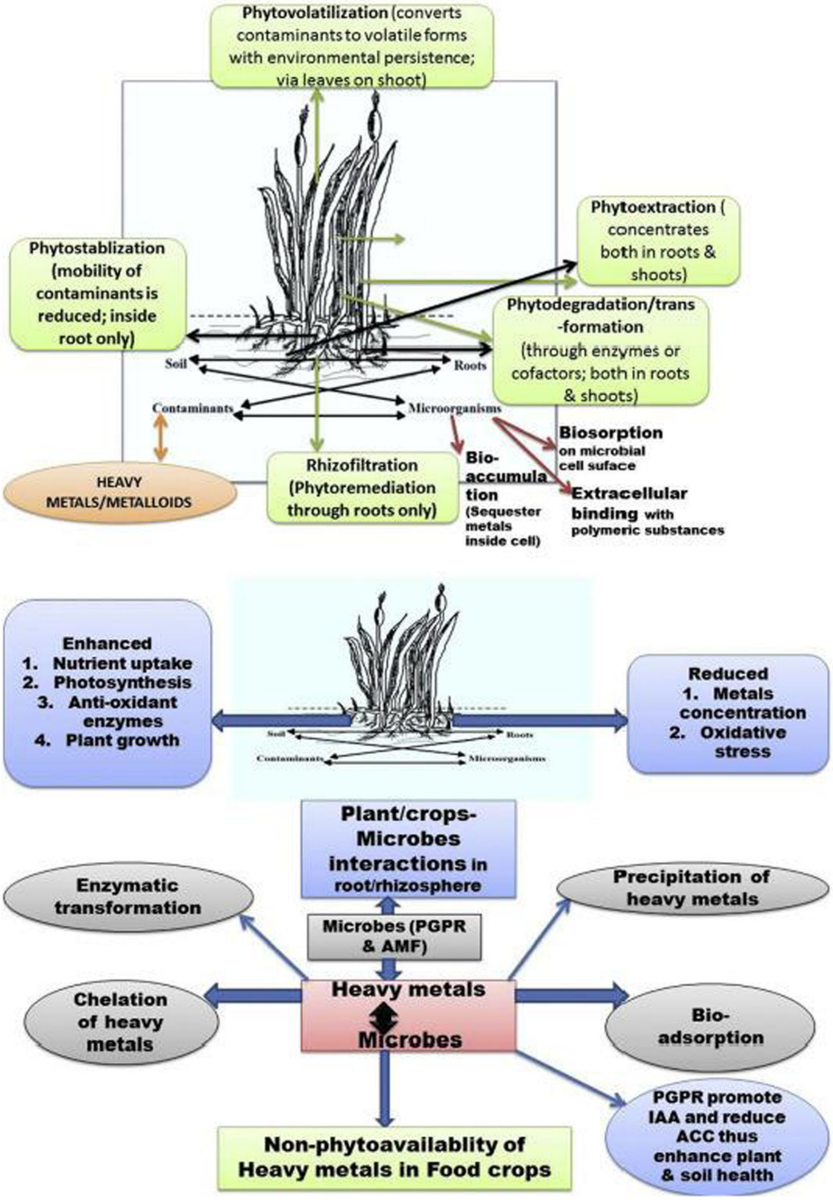


Fig. 3 Approaches for the remediation of heavy metal present in water and soil environment (adapted from Rai et al. 2019)

removed from the soil along with some radionuclide chemicals as well using the phytoextraction mechanism. Phytoremediation is a widely accepted approach for heavy metal remediation because of its less disturbing, efficiency, relatively 60–80% less costly, eco-friendly nature, etc. (Salido et al. 2003; Olguín and Sánchez-Galván 2012; Al-Thani and Yasseen 2020), and it is relatively better for in situ removal of toxic chemicals present in soil or water (USEPA 2000). A large number of heavy metals and other inorganic and organic contaminants can also be removed using plants (Liu et al. 2000; Mwegoha 2008). It is noteworthy that oil crops can also be cultivated on the heavy metal-contaminated soils for biodiesel (or bioenergy) production (Van Ginneken et al. 2007). Moreover, the important advantages are mentioned in Fig. 4.

From Fig. 4, it can be seen that plants used in the process of phytoremediation can improve the ambient environment by producing oxygen. Moreover, it can be applicable for in situ as well as ex situ remediation of multiple toxic metals present in water and soil environments. Apart from these merits, some limitations of this technique are also well documented in the research papers. It may be considered as a time-consuming process because of taking much time to grow on the contaminated site. Furthermore, if the contaminants are likely to be cytotoxic to the accumulator, plants will die and the approach will fail (USEPA 2000; Akpor and Muchie 2010; Tangahu et al. 2011). The efficiency of this technique will depend on the nature of contaminants, level of contaminants, and nature of the plant accumulator as well as the climatic conditions of the field to be treated (Mwegoha 2008). However, the work

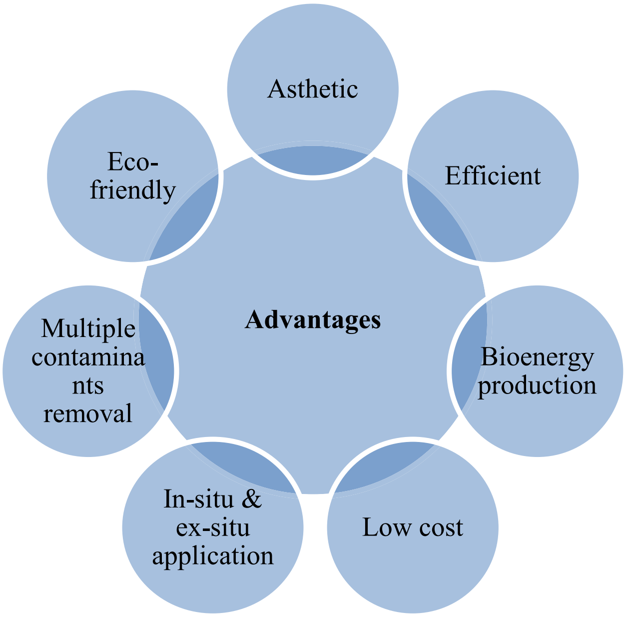


Fig. 4 Advantages of phytoremediation technique

progress and innovation in phytoremediation are still on the peak of interest among the researchers.

Phytoremediation techniques and mechanism of heavy metal alleviation

Being a green technique, phytoremediation can remove many types of contaminants such as heavy metals and organic pollutants from the water and soil without generating byproducts (Nejad et al. 2018). It can be achieved by using plants, grasses, microorganisms, and shrubs as in this process contaminants can be degraded, accumulated, or stabilized (Rajkumar et al. 2012; Cameselle and Gouveia 2019; Shah and Daverey 2020). Mainly these mechanisms have been reported to achieve the process of phytoremediation, which includes rhizospheric biological degradation, phyto-stabilization, phyto-accumulation or phyto-extraction, rhizofiltration, phyto-volatilization and phyto-degradation or phyto-transformation (Erakhrumen and Agbontalor 2007; Patra et al. 2020; Ansari et al. 2020; Al-Thani and Yasseen 2020). These mechanisms have already been discussed in detail in Table 4 that contains the names of the plants reported for phytoremediation of toxic metals present in soil and water near industries.

Steliga and Kluk (2020) found the potential of a phytostabilizer grass, i.e., *Festuca arundinacea* Schreb. for the removal of cadmium, nickel, and lead in an order of Cd < Ni < Pb. These metals were retained by the roots of the plant because the metal transport was not possible from the root to the stem. It was also found to remove the hydrocarbons (in between 49.9 and 60.1%) from the soil which were added by petroleum products due to phytostimulation process of rhizospheric microbes of the plant. Similar studies have also been reported by Sun et al. (2011) and Lou et al. 2017) to improve the soil health through phytoremediation process. Manjate et al. (2020) recognized the role of microplastics in the phytoremediation of cadmium and copper using *P. australis* plant. However, significant quantities of metals were removed (for example, copper 1 mg/g and cadmium 70 μg/g). The cadmium uptake by *Phragmites australis* (Cav.) Steud was governed by temperature, hydrogen ion concentration, redox potential, concentration of competing ions, and organic content of soil (Rocha et al. 2014). *Rhizofiltration*, *phytostabilization*, *phytoextraction*, *phytovolatilization*, *phytostimulation*, and *phytotransformation* are the widely used phytoremediation techniques of heavy metal remediation (Ghosh and Singh 2005; Akpor and Muchie 2010). An overview of these approaches is depicted in Fig. 5.

These techniques are frequently being used to alleviate heavy metal contaminations along with some other inorganic pollutants (for example, nitrate, phosphate, etc.) as well as organic contaminations from the soil and water environments (Ghosh and Singh 2005; Akpor and Muchie 2010; Olguín and Sánchez-Galván 2012). An excellent explanation of the mechanism of heavy metal trapping of some important phytoremediation techniques is depicted in Fig. 6.

Chromium [especially Cr(VI)] is one of the most toxic metals for every type of living organisms including human beings and plants (Mohanty and Patra 2020; Steliga and Kluk 2020). According to Mohanty et al. (2012), phytoremediation is a green approach to remove toxic metals by employing plant materials. Many studies have been carried out to remove toxic metals from the environment such as *Lonicera japonica* Thunb. (Liu et al. 2009), which is a hyperaccumulator of cadmium. Similarly, *B. pilosa* L. was used for antimony removal (Qi et al. 2011). Moreover, in situ chromium removal through hyperaccumulator weed plants has been claimed as an innovative technique (Mohanty and Patra 2020). *Festuca arundinacea* Schreb. was found to have extraordinary capacity for the phytoremediation of metal-contaminated soil sites. The reason of this remarkable capacity is due to fast growth of the plant and greater proportion of biomass as well as used for multiple metals such as Cd, Cu, Pb, and Zn (Zhou et al. 2016; Wang et al. 2019; Zhu et al. 2020). However, *Sedum alfredii* H. and *Brassica juncea* L. were found better for the cadmium remediation (Huang et al. 2017). Some important features of the various techniques of phytoremediation are discussed such as:

Rhizofiltration can be carried out using both terrestrial and aquatic plant roots which should have the capability to eliminate the contaminants from the soil and water. Many types of metals (for example, lead, cadmium, copper, nickel, zinc, and chromium) can be eliminated by their roots (Chaudhry et al. 1998; Akpor and Muchie 2010) both in situ as well as ex situ places. Hyper accumulator plants can also be used in this

Table 4 Name of hyperaccumulator plants for the remediation of toxic metals from the soil and water

Toxic metal	Plant	Medium	Uptake of heavy metal (mg/kg)	References
As	*Pteris vittata* L.	Soil and water	8331	Kalve et al. (2011)
	Pteris ryukyuensis Tagawa	Soil	3647	Srivastava et al. (2006)
	Pteris quadriaurita Retz.		2900	
	Pteris biaurita L.		2000	
	Pteris cretica L.		1800	
	Eleocharis acicularis (L.) Roem. & Schult.	Water	1470	Sakakibara et al. (2011)
	Sedum alfredi Hance	–	9000	Xiong et al. (2004)
	Prosopis laevigata (Humb. & Bonpl. ex Willd.) M.C.Johnst.	–	8176	Buendía-González et al. (2010)
	Arabis gemmifera (Matsum.) Makino	–	5600	Kubota and Takenaka (2003)
	Salsola kali L.	Water	2075	de la Rosa et al. (2004)
	Azolla pinnata R.Br.	Water	740	Rai (2008)
	Deschampsia cespitosa (L.) P. Beauv.	Water	236.2	Kucharski et al. (2005)
	Corrigiola telephiifolia Pourr.	Soil	2110	Garcia-Salgado et al. (2012)
Ni	*Alyssum bertolonii* Desv. synonym of *Odontarrhena bertolonii* (Desv.) Jord. & Fourr.	Soil	10,900	Li et al. (2003)
	Alyssum caricum T.R.Dudley & Hub.-Mor. synonym of *Odontarrhena carica* (T.R.Dudley & Hub.-Mor.) Španiel, Al-Shehbaz, D.A.German & Marhold		12,500	
	Alyssum corsicum Rob. ex Gren. & Godr. synonym of *Odontarrhena robertiana* (Bernard ex Gren. & Godr.) Španiel, Al-Shehbaz, D.A.German & Marhold		18,100	
	Alyssum pterocarpum T.R.Dudley synonym of *Odontarrhena pterocarpa* (T.R.Dudley) Španiel, Al-Shehbaz, D.A.German & Marhold		13,500	
	Alyssum heldreichii Hausskn. synonym of *Odontarrhena heldreichii* (Hausskn.) Španiel, Al-Shehbaz, D.A.German & Marhold	Soil	11,800	Bani et al. (2010)
	Alyssum markgrafii O.E.Schulz synonym of *Odontarrhena chalcidica* (Janka) Španiel, Al-Shehbaz, D.A.German & Marhold		19,100	
	Alyssum murale M.Bieb. synonym of *Odontarrhena alpestris* (L.) Ledeb.		4730–20,100	
	Alyssum serpyllifolium Desf.	Soil	10,000	Prasad (2005)
	Isatis pinnatiloba P.H.Davis	Soil	1441	Altinozlu et al. (2012)
Cd	*Phytolacca americana* L.	Soil	10,700	Peng et al. (2008)
	Sedum alfredi Hance		9000	Xiong et al. (2004)
	Prosopis laevigata (Humb. & Bonpl. ex Willd.) M.C.Johnst.	Soil	8176	Buendía-González et al. (2010)
	Arabis gemmifera (Matsum.) Makino synonym of *Arabidopsis halleri subsp. gemmifera* (Matsum.) O'Kane & Al-Shehbaz	–	5600	Kubota and Takenaka (2003)
	Salsola kali L.	Water	2075	de la Rosa et al. (2004)
	Azolla pinnata R.Br.	Water	740	Rai (2008)
	Deschampsia cespitosa (L.) P.Beauv.	Soil	236.2	Kucharski et al. (2005)
	Rorippa globosa (Turcz. ex Fisch. & C.A.Mey.)	Soil	> 100	Wei et al. (2008)
	Thlaspi caerulescens J.Presl & C.Presl synonym of *Noccaea caerulescens* (J.Presl & C.Presl) F.K.Mey.	Soil	263	Lombi et al. (2001)
	Azolla pinnata R.Br.	Water	740	Rai (2008)
	Pteris vittata L.	Water and soil	20,675	Kalve et al. (2011)

Table 4 (continued)

Toxic metal	Plant	Medium	Uptake of heavy metal (mg/kg)	References
	Eleocharis acicularis (L.) Roem. & Schult.	Water	11,200	Sakakibara et al. (2011)
	Thlaspi calaminare (Lej.) Lej. & Courtois synonym of *Noccaea caerulescens subsp. calaminaris* (Lej.) Holub	Soil	10,000	Sheoran et al. (2009)
	Deschampsia cespitosa (L.) P.Beauv.	Soil	966.5–3614	Kucharski et al. (2005)
Hg	*Achillea millefolium* L.	Soil	18.275	Wang et al. (2012)
	Marrubium vulgare L.	Soil	13.8	Rodriguez et al. (2003)
	Rumex induratus Boiss. & Reut.		6.45	Rodriguez et al. (2003)
	Silene vulgaris (Moench) Garcke	Soil	4.25	Pérez-Sanz et al. (2012)
	Festuca rubra L.	Soil	3.17	Rodriguez et al. (2003)
	Poa pratensis L. *Helianthus tuberosus* L.	Soil	2.74 1.89	Sas-Nowosielska et al. (2008)
	Armoracia rusticana G.Gaertn., B.Mey. &		0.97	
	Juncus maritimus Lam.	–	0.315	Zheng et al. (2011)
	Cicer arietinum L.	Soil	0.2	Wang et al. (2012)
	Eleocharis acicularis (L.) Roem. & Schult.	Water and soil	20,200	Sakakibara et al. (2011)
	Aeollanthus biformifolius De Wild. is a synonym of *Aeollanthus subacaulis var. linearis* (Burkill) Ryding	Soil	13,700	Chaney et al. (2010)
	Ipomoea alpina Rendle *is a synonym of Ipomoea linosepala subsp. alpina* (Rendle) Lejoly & Lisowski	–	12,300	Mitch (2002)
	Haumaniastrum katangense (S.Moore) P.A.Duvign. & Plancke	Soil	8356	Sheoran et al. (2009)
	Pteris vittata L.	Soil	91.975	Wang et al. (2012)
Cr	*Pteris vittata* L.	Soil and water	20,675	Kalve et al. (2011)
Pb	*Medicago sativa* L. *Brassica juncea* (L.) Czern.	Soil	43,300 10,300	Koptsik (2014)
	Brassica nigra (L.) W.D.J.Koch		9400	
	Helianthus annuus L.		5600	
	Betula occidentalis Hook.		1000	
	Euphorbia cheiradenia Boiss. & Hohen.	Soil	1138	Chehregani and Malayeri (2007)
	Deschampsia cespitosa (L.) P.Beauv.	Soil	966.5	Kucharski et al. (2005)
	Euphorbia cheiradenia Boiss. & Hohen	Soil	1138	Chehregani and Malayeri (2007)

Note: International Plant Names Index (http://www.ipni.org) has been used to verify the name of plants. [Accessed on August 14, 2020]

category of phytoremediation. Usually, sunflower (*Helianthus annuus* L.), Indian mustard (*Brassica juncea* L.), tobacco (*Nicotiana tabacum* L.), rye (*Secale cereal* L.), spinach (*Spinacia oleracea* L.), and corn (*Zea mays* L.) are found enough for their great metal alleviation property (Raskin and Ensley 2000; Lasat 2000; Akpor and Muchie 2010).

Phytoextraction is also termed as phytoaccumulation as it removes soil contaminants with no significant change in soil fertility and textures (Ghosh and Singh 2005; Prasad et al. 2006). Mostly, contaminants accumulate into the biomass of the plants. However, it is good for the area where concentration of toxic metals was observed to be comparatively low (Rulkens et al. 1998). The efficiency of the *Phytoextraction* approach relies on the natural competence of the vegetation (Salt et al. 1997; Teuchies et al. 2013).

Different plants may have dissimilar capacities of uptaking pollutants, and commonly, zinc, copper, lead, chromium, and nickel are reported to have been accumulated by the hyperaccumulator plants (Lasat 2000; Akpor and Muchie 2010; Patra et al. 2020). Further, *phytoextraction* has been categorized into natural phytoextraction (Henry 2000) and phytochelatin-assisted phytoextraction (Cobbett 2000; Ghosh and Singh 2005; Akpor and Muchie 2010).

The *phytofiltration* process is somehow similar to the process of *rhizofiltration*. However, *rhizofiltration* may be a part of it as this process takes place only in the *Rhizosphere* zone of

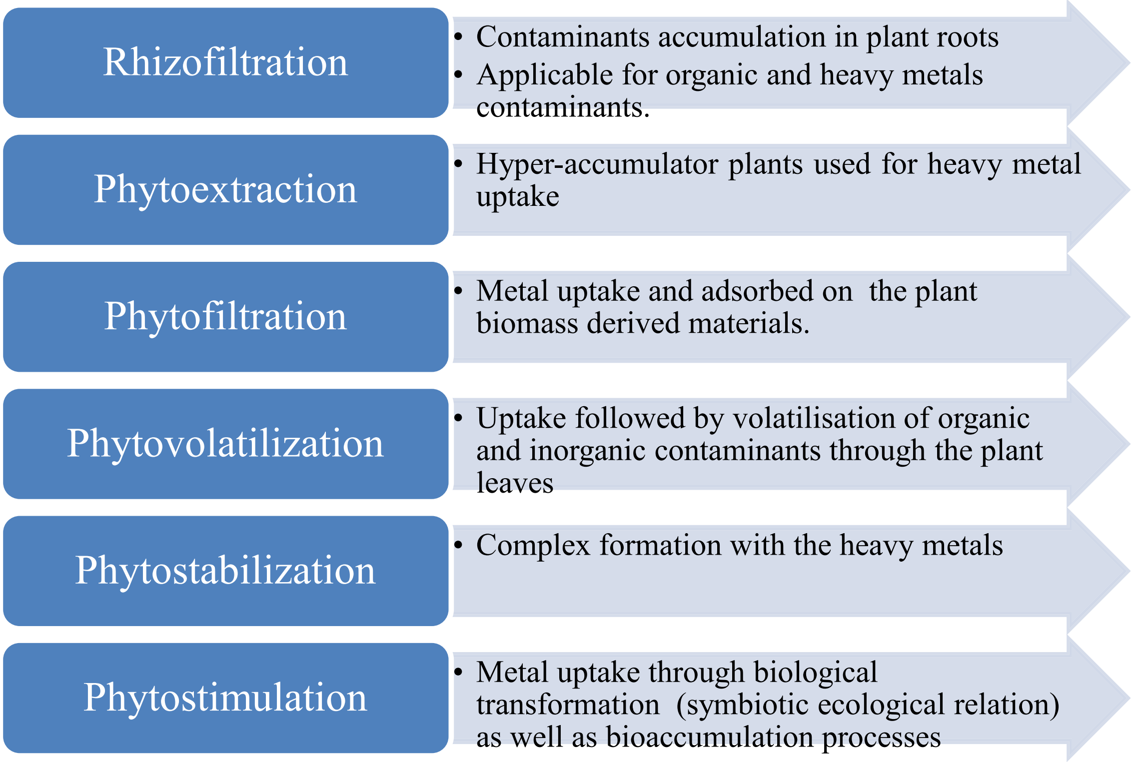


Fig. 5 Overview of phytoremediation and mechanism of heavy metal uptake

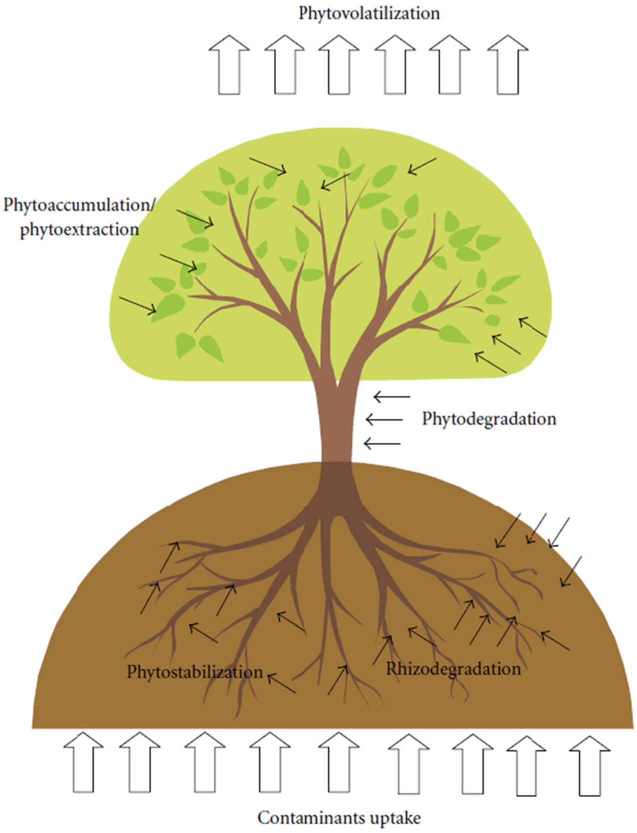


Fig. 6 Mechanism of heavy metals uptake through phytoremediation (adapted from Tangahu et al. 2011)

plants (Akpor and Muchie 2010) and seedlings (or blastofiltration) can also remove heavy metals either through absorption and/or adsorption process (Alkorta et al. 2004; Gardea-Torresdey et al. 2004; Olguín and Sánchez-Galván 2012).

In *phytovolatilization*, plants attract the metallic contaminants from the soil and/or water and release them into the atmosphere through the leaves after converting them into volatile nature. It has been found very effective in the volatilization of mercury metal after changing into a less harmful form of mercury (Henry 2000). An isotope of hydrogen, i.e., tritium (3H, radioactive in nature), is also removed by using this technique (Dushenkov 2003).

Phytostabilization can remove heavy metals from a variety of mediums such as sludge, soil, and sediments. It is a potential approach for rapid immobilization of metallic contaminants of water (both groundwater as well as surface water) (Ghosh and Singh 2005).

Phytostimulation is a process in which some natural matter is secreted by plants from the roots or else as food for the microorganisms living in symbiotic ecological relation to them. These microbes get stimulated and degrade the contaminants present in soil or water. This process can also be referred to as biological degradation of pollutants through the symbiotic ecological relationship of plants and microorganisms (Lasat 2000; Meers and Tack 2004; Akpor and Muchie 2010).

Immobilization of metallic chemicals can also be achieved by retarding mobility and their biological accessibility in soils (Li et al. 2014a, b). Many advantages have been observed when immobilizations of heavy metals are achieved in combination with another material such as better adsorption potential, easy operation, and protection of adsorptive capacities etc. (Ni et al. 2012; Sukumar et al. 2014; Qin et al. 2020). Recently, several studies have been reported to immobilize heavy metals present in soil and water using modified algae (Mwangi and Ngila 2012), activated carbon (Gilmour et al. 2013), zeolite (Wen et al. 2016), peat (Kim et al. 2017), clay (Zang et al. 2017), synthesized magnetic biochar (Son et al. 2018), waste fish scale (Pal and Maiti 2020), etc.

Mwangi and Ngila (2012) modified algae using a chemical, i.e., ethylenediamine, which could improve the adsorption potential of algal cells for copper and lead because of the immobilization of the amine group on the surface of algae. Son et al. (2018) synthesized magnetic biochar using a waste of marine algae and achieved significant removal of heavy metals from the water. Fajardo et al. (2019) synthesized two nanoparticles like nZVI and Fe_3O_4 for the stabilization of heavy metals from both soil and water. Results have indicated that nZVI nanoparticle was efficient to improve soil from the metallic contaminations. However, the active period of nZVI was relatively less. nZVI nanoparticles are one of the mostly used materials to reduce the biological availability of heavy metals present in water and soil (Mueller et al. 2012). Huang et al. (2019) remediated heavy metals from the soil contaminated by e-waste processing unit using jointly biochar and phosphate fertilizer. 0.8% fertilizer and 3% biochar were used in combination and found effective to remove 34.8% cadmium, 29.4% copper, 46.6% lead, and 41.0% zinc from the soil. Lago-Vila et al. (2019) stated that the combination of nanoparticles and plants is found very effective in the immobilization of lead present in soil of a firing range area. Immobilization of Pb was achieved through combined application of hydroxyapatite nanoparticles and three plant species, i.e., *Festuca ovina* L., *Lactuca sativa* L., and *Sinapis alba* L. Pal and Maiti (2020) successfully remediated Cd and Pb from the aquatic sediment using a biosorbent generated from the waste fish scale in different proportions. The adsorption capacities of the biosorbents were 89.30 mg/g and 92.65 mg/g for Cd and Pb, respectively. Moreover, it was also observed that 20% biosorbents could reduce 70–80% of heavy metals (Cd and Pb) from the aquatic sediment which was previously available for the plants.

Influencing factors for phytoremediation of heavy metals

The growth rate of plants, selectivity of metals, immunity of plants, species of plants, and harvesting method are vital factors which may affect the efficiency of phytoremediation (Cunningham and Ow 1996; Ghosh and Singh 2005). Further, the effectiveness of phytostabilization could also be attributed to the capability of the root system of the vegetations (Ghosh and Singh 2005). Some geographical indicators are also among the governing factors of phytoremediation of contamination which include altitude, climatic conditions, temperature, humidity, etc. required by the plant species. Moreover, the immunity of plants could also affect the rate of contamination uptake (Akpor and Muchie 2010; Tangahu et al. 2011). The plants which have a shallow root system are not found suitable for the groundwater contaminant remediation (Gardea-Torresdey et al. 2005). Some common factors are shown in Fig. 7.

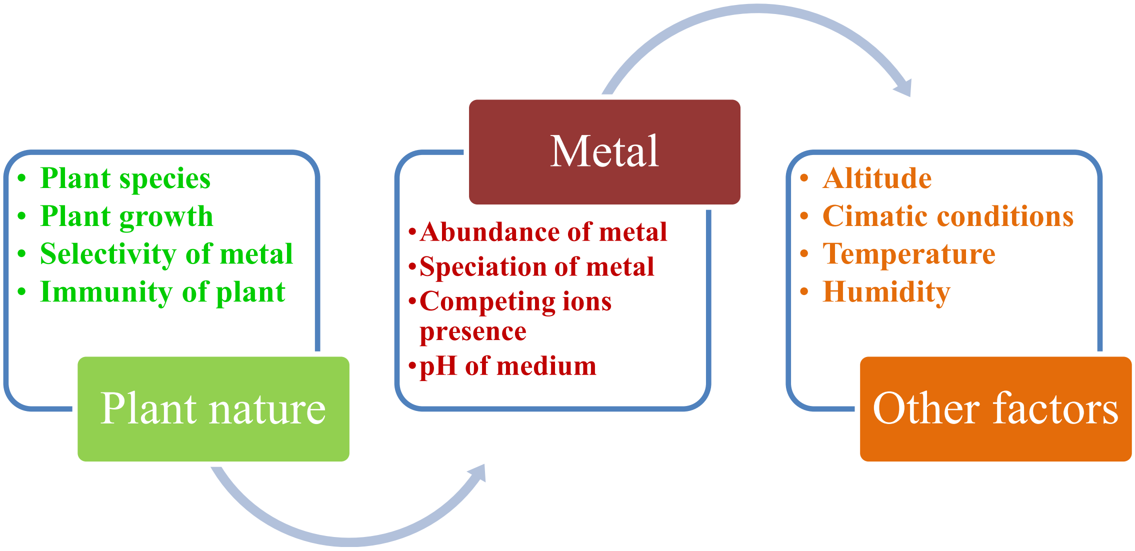


Fig. 7 Influencing factors for phytoremediation of heavy metals

Another example of having a low phytoextraction potential of plants for lead is also reported elsewhere but it can also trap lead metal after adding synthetic chelators in the contaminated soil (USEPA 2000). The uptake mechanism of heavy metals by any plant relies on several chemical factors such as the chemical nature of the metallic species, presence of competing ions, pH of the medium, abundance of metallic species, the selectivity of plants, etc. (Gardea-Torresdey et al. 2004). Therefore, it can be understood that many environmental, climatic, metallic nature as well as nature and species of plants are among the most important factors affecting phytoremediation of heavy metals either from soil or water.

Conclusion

Inappropriate urban and industrial expansions have severely degraded the quality of the environmental system (air, water, and soil), which ultimately cause threats to human health. Developing countries like India and China are at great risk because of an extremely large population. Heavy metals are one of the most toxic chemicals which affect the health of human beings including other creatures as well. Heavy metals are observed as carcinogenic, genotoxic, hepatotoxic, immunotoxic, neurotoxic, reproductive organ disruptor, nephrotoxic, etc. These metals can enter the body mostly through the intake of contaminated drinking water and food items. Therefore, their qualitative as well as quantitative determinations in the environmental and biological system are very crucial while developing remedial measures. However, now, many advanced techniques have been developed for this purpose, such as AAS, ICPs, XRF, NAA, etc. These techniques have the capacity to detect even the trace levels (ppm and/or ppb and/or ppt) of heavy metal presence with high precision and accuracy. However, synchrotron-based XRF technique is observed as widely accepted and accurate for the elemental analysis of samples (for example, environmental, biological, geological, etc.). Further, many researchers have proposed some remedial measures to reduce the problems of heavy metals from the water and soil environment such as phytoremediation, bioremediation, phytoextraction, sorption, phytovolatilization, etc. Phytoextraction and phytovolatilization methods are preferred to decontaminate soil and water environments, respectively, from the toxic metals. Finally, change in human behavior and adoption of the principles of sustainable development can help in the holistic management of all the environmental problems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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