

Phytoremediation Mechanisms of Heavy Metal Removal: A Step Towards a Green and Sustainable Environment

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11.1 Background

Environmental contamination has been an occurrence over time in history. It has always been noted to have developed as a result of environmental pollution that emanates from both the natural accumulation of these contaminants and some anthropogenic activities within the environment (Ajibade et al., 2021a). It is noted that environmental contamination has become more pronounced within the last two centuries, especially the 20th century. This upsurge is stated to be associated with the rapid population growth, urbanization, industrialization, and mining activities; agricultural practices; as well as wars and various conflicts that induce explosives and chemical warfare agents, as well as their manufacture, usage, and storage (Macek et al., 2004). Different types of organic or inorganic contaminants exist. Some of the organic contaminants include petroleum hydrocarbons (e.g., benzopyrene), linear halogenated hydrocarbons (e.g., trichloroethylene), chlorinated solvents (e.g., polychlorinated benzenes), explosives (e.g., trinitrotoluene), and volatile organic carbons while the inorganic compounds comprise phosphates, nitrates, and metals and metalloids such as chromium (Cr), nickel (Ni), mercury (Hg), lead (Pb), arsenic (As), cadmium (Cd), selenium (Se), silver (Ag), copper (Cu), and zinc (Zn), and nonradioactive or radioactive nuclides, like uranium (U), strontium (Sr), and cesium (Cs) (Chandra and Kumar, 2018). Despite the need to control environmental pollution and its associated health hazards, these wastes are still being dumped on land or discharged into water bodies (e.g., rivers, canals, lakes, streams, etc.). Metal accumulation in various compartments of the environment poses risks to living organisms including humans because living organisms accumulate these metal elements, causing biomagnification processes to occur. This biomagnification process happens when there is an increase in the concentration of the contaminants at successively higher levels in a food chain (Ali et al., 2013; Gomes et al., 2016). This continuous rise in the presence of these elements in the ecosystem results in the increased presence of metallic contaminants in the form of metallic nanoparticles in the environment has been of concern to researchers (Ebbs et al., 2016). Although there are several benefits associated with these chemicals when applied in different fields, such as pharmaceuticals, cosmetics, energy, consumer products, and agriculture (Baker et al., 2014), their associated potential risks and negative effects as a result of their use and to the environment remain unclear (Ruffini-Castiglione and Cremonini, 2009).

Over the years, various physicochemical and biological treatment methods have been used as soil cleanup techniques. However, their costs and inefficiencies as well as the fact that sometimes they result in the transfer of the associated risks to other places, thereby causing the control of the contaminants to surround environmental compartments, has led to some research on the use of more effective biological remediation methods (Macek et al., 2004; Gomes et al., 2016). An effective option is the use of some plants that are capable of transferring, accumulating, and removing these pollutants from the environment or lessening their spread within the environment (Macek et al., 2000). This concept is known as phytoremediation. Phytoremediation is the utilization of plants in conjunction with their related microbes to extract, sequester, and detoxify various types of environmental and emerging contaminants from soils, sediments, air, and water (Rahman et al., 2016; Kumar and Chandra, 2017; Sarwar et al., 2017; Yadav et al., 2018; Patra et al., 2020). It is a plant-based technology that involves the discovery of hyperaccumulating plants (capable of accumulating, translocating, and concentrating metals in their harvestable biomass). It has received increasing attention in recent years (Ajibade et al., 2013; Ajibade and Adewumi, 2017; Patra et al., 2020). Furthermore, it has been proposed that this approach can remove inorganic and organic xenobiotics as well as contaminants found in soil, water, and air (Lasat, 2000; Ryslava et al., 2003). Examples of these pollutants are heavy metals, inorganic fertilizers, trace or radioactive elements, pesticides, and recalcitrant organic compounds like polychlorinated biphenyls (PCBs) or polyaromatic hydrocarbons (PAHs). In 1885, Baumann was the first to hypothesize plant accumulation of high amounts of metals for *Thlaspi caerulescens* and *Viola calaminaria* (Lasat, 2000). The use of metal-hyperaccumulating plants for selective removal and recycling of extreme soil metals was first made known in 1983, gained general acceptance in 1990, and it has been studied over time with suggestions that it is a more promising eco-friendly, practical, and cost-effective technology than the existing physicochemical techniques (Chaney et al., 1997). While there have been numerous review studies on phytoremediation (Ali et al., 2013; Ovečka and Takáč, 2014; Akinbile et al., 2016; Mahar et al., 2016; da Conceição Gomes et al., 2016; Antoniadis et al., 2017; Yadav et al., 2018; Akinbile et al., 2019; Omotade et al., 2019; Ugya et al., 2019; Patra et al., 2020), they somewhat provide scattered information.

Thus, this chapter presents a comprehensive synthesis of all aspects of phytoremediation, including numerous techniques (phytoextraction, phytofiltration/rhizofiltration, phytostabilization, phytovolatilization, phytodegradation/phytotransformation). Additionally, the review highlights factors affecting the mobility, uptake, and accumulation of metals in plants, and challenges associated with phytoremediation in decontaminating soil and water. It further discusses innovative approaches for optimizing phytoremediation technology (chelators, biochar, transgenic plants, metal ions, microbes, etc.) and the use of phytoremediation techniques as tools for ensuring environmental sustainability. Lastly, future trends in phytoremediation were also addressed.

11.2 Phytoremediation: A Green Technology of Bioremediation

The term *phytoremediation* simply means “plant-based action”. It is coined from a Greek word *phyto*, meaning “plant” and Latin word *remedium*, meaning “correct evil or to recover” or “restoring balance” (Erakhrumen and Agbontalor, 2007). The term *phytoremediation* was first mentioned in 1991 (Raskin et al., 1998). Many researchers have defined phytoremediation in various ways that collectively refer to a green technology involving the use of plants for environmental cleanup via pollutant removal. Some researchers define phytoremediation as follows:

Phytoremediation is defined as the use of green plants and their associated rhizospheric microorganisms, soil amendments, and agronomic techniques to remove, degrade, or detoxify harmful environmental pollutants. (Ouyang, 2002; Schwitzguébel, 2002)

Phytoremediation is defined as the use of plants and their associated microbes to extract, sequester, and/or detoxify various kinds of environmental pollution or emerging contaminants

from water, sediments, soils, and air (as magnetic particles lying in the particulate matter). (Rai and Singh, 2015; Rai and Chutia, 2016)

Phytotechnology (phytoremediation technology) has various advantages that make it a promising technology for remediation of hazardous sites. These advantages of phytoremediation can be summarized as follows.

Aesthetics: Phytoremediation is an aesthetically attractive technology (Tangahu et al., 2011). Its major plus is its effectiveness in the reduction of heavy metal ion concentration to a minimal level through its various techniques of degradation of contaminants (Rodriguez et al., 2005) while using low-cost biosorbent materials (Rakhshaei et al., 2009). According to the USEPA (2000), phytoremediation is the cleanest and least expensive approach for the treatment of designated hazardous areas.

Less disruptive: Phytoremediation is considered less disruptive than the conventional physicochemical techniques (Tangahu et al., 2011). In addition to providing on-site treatment, this system is environmentally friendly (e.g., phytoextraction) and conserves the topsoil; hence, leaving the topsoil in a utile state which may be recovered for agricultural use.

Effectiveness in contaminants reduction/removal: Phytoremediation is drawing attention as an innovative technology, basically due to its effectiveness and efficiency in the reduction and removal of contaminants (especially, toxic heavy metals). It is considered a cleanup method for contaminated air, water, and soil (Van Ginneken et al., 2007). Phytoremediation can be applied to treat diversified toxic metals and radionuclides, reduce environmental disorderliness, eliminate waterborne wastes, and secondary air, thus gaining more public acceptance (Liu et al., 2000a). Furthermore, phytoremediation can reduce organic contaminants to CO₂ and H₂O, thereby minimizing environmental toxicity (Mwegoha, 2008). When treating heavy metals in the soil and water, phytoremediation technology translocates them into recyclable metal-rich plant residue (Liu et al., 2000b).

Inexpensiveness: Phytoremediation is a cheap technology for the remediation of contaminated environments (Rakhshaei et al., 2009; Tangahu et al., 2011), mainly suitable for sites of comparatively low contamination (Van Ginneken et al., 2007). It is cheaper and less expensive (even up to 60–80% reduction) than conventional physicochemical methods, since it is solar-energy-driven, and at the same time neither expensive equipment nor highly skilled employees are required for management (Tangahu et al., 2011).

Wide range of application: Phytoremediation is suggested to be efficient in treating a wide range of both organic and inorganic pollutants in various environments such as water, soil, and air (Mwegoha, 2008; Van Ginneken et al., 2007). This equally makes the technology a very promising one compared to the conventional methods.

Environmental friendliness: Phytoremediation is better compared to harsher redressing technologies such as incineration, thermal vapourization, solvent washing, or other soil-washing techniques, which simultaneously destroy the biological components of the soil and equally alter its chemical and physical characteristics and consequently leave a comparatively nonviable solid waste (Tangahu et al., 2011). The utilization of phytoremediation generally improves the soil, resulting in a more functional ecosystem and at about one-tenth of the cost of today's technologies (Hinchman et al., 1995). Tangahu et al. (2011) stated that phytoremediation remains the most environmentally friendly cleanup technology for remediation of contaminated soils; hence, it is regarded as a green technology.

Other advantages and benefits of phytoremediation over conventional methods: requires fewer soil disposal sites, higher public acceptability, does not require excavation and transportation, and the possibility of much larger-scale remediation (Schnoor et al., 1995).

11.3 Techniques and Mechanisms Involved in Phytoremediation and Their Applications

Phytoremediation is an umbrella for many plant-related bioremediations. These include different techniques and mechanisms used by plants in detoxifying and decontaminating soil, sludge, ground-water, sediment, and wastewater. For effectiveness, phytoremediation technology is categorized into

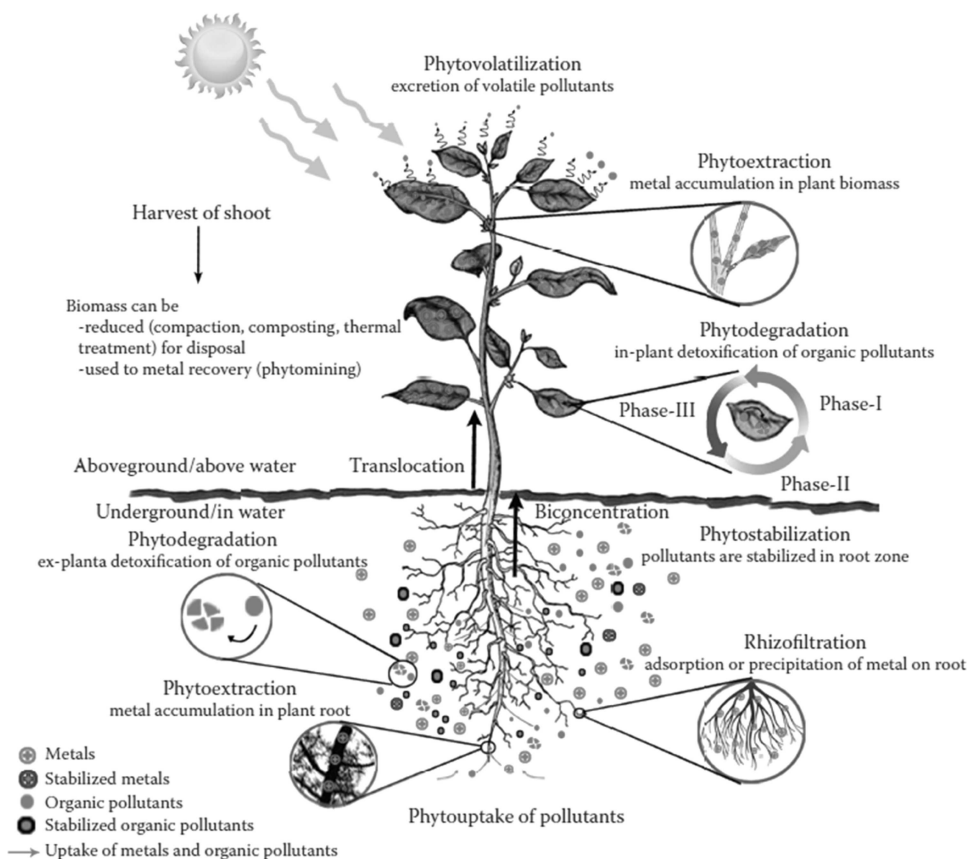


FIGURE 11.1 Graphical representation of various phytoremediation strategies (adapted from Chandra and Kumar, 2018).

phytoextraction, phytofiltration, phytostabilization, phytovolatilization, and phytodegradation, with each category having a different strategy or mechanism of action for redressing pollutants from contaminated soil, sludge, groundwater, surface water, sediment, and wastewater (Alkorta et al., 2004; Chandra and Kumar, 2018), as illustrated in Figure 11.1.

Moreover, the application of these phytoremediation technologies is dependent on some factors such as contaminants, site conditions, degree of cleanup required, and the plant type (Chandra and Kumar, 2018; Rai, 2018). Despite some specific features of plants used in each of these phytoremediation technologies, there are general characteristics that every plant selected for phytoremediation should possess (Sharma et al., 2014). These features are:

1. Ability to grow fast.
2. High tolerance to metals and other contaminants.
3. High resistance to diseases, pests, etc.
4. Easy to cultivate and harvest.
5. Extensive root and shoot system.
6. Unappealing to animals to minimize the transfer of metals and other toxic compounds to a higher trophic level of the terrestrial food chain (Bruce et al., 2003).

Furthermore, Rai (2018) stated that wetland plants could be good candidates for this purpose as they detoxicate soil and groundwater compartments of the environment in the following ways:

1. Altering the physicochemical properties of contaminated soils.
2. Release of root exudates, which increases organic carbon.
3. Improving aeration through the release of oxygen in the root zone, and enhancing porosity in the upper soil zone.
4. Interception and retardation of the mobility of the contaminants.
5. Plant enzymatic conversion of xenobiotics and recalcitrant chemicals, as well as performing co-metabolic microbial.
6. Reducing pollutants' vertical and lateral movement into groundwater by collecting available water and reversing the hydraulic gradient (Singh and Rai, 2016).

11.3.1 Phytoextraction

Phytoextraction is the process by which plants absorb toxic contaminants from soil, sediments, and/or sludge and store or concentrate them in their shoot tissues and harvestable parts of their roots (Garbiscu and Alkorta, 2001). It is also known as phytoaccumulation, phytoabsorption, or phytosequestration. Phytoextraction is the most recognized and used phytoremediation technology for the removal of harmful metal pollutants (Chandra, 2015; Gomes et al., 2016); however, its efficiency when in use is determined by factors like bioavailability of metals, properties of soil, and speciation of metal and plant species that are mainly on shoot metal concentration and biomass (Ali et al., 2013; Li et al., 2010). As illustrated in Figure 11.2, phytoextraction is classified into two categories: induced phytoextraction and continuous phytoextraction.

Induced phytoremediation is the use of high biomass metal-accumulating plants in which their metal accumulation capability is accelerated by the addition of chemicals like ethylenediaminetetraacetic acid (EDTA), ethylenediaminedisuccinic acid (EDDS), nitrilotriacetic acid (NTA), etc. (Saifullah et al., 2009). Continuous phytoextraction on the other hand involves the use of hyperaccumulators naturally for the decontamination of sites and accumulation of contaminating metals (McGrath et al., 2002).

Interestingly, some plants for phytoextraction have been described to possess a special characteristic known as phytoexcretion (Kadukova and Kavuličova, 2011). For instance, Mediterranean halophytic shrubs or trees, *Tamarix smyrnensis*, has been suggested to be able to use salt glands for the removal of excess salt from the soil. Similarly, in a situation where metals are available in the soil, the salt glands become the excretion point of these metals in the form of non-toxic crystals; this technique is referred to as phytoexcretion (Kadukova and Kalogerakis, 2007; Manousaki et al., 2008). According to UNEP (2016), approximately >400 plants have extreme affinity for metal absorption and some of these plants have been reported in recent studies for remediating heavy metals. They include *Jatropha curcas* (Marrugo-Negrete et al., 2015), *Stanleya pinnata* (Bañuelos et al., 2015), *Brassica juncea* (Kathal et al., 2016), *Pisum sativum* (Tariq and Ashraf, 2016), *Puccinellia frigida* (Rámila et al., 2016), *Brassica napus* (Dhiman et al., 2016), *Helianthus annuus* (Farid et al., 2017), *Salix viminalis* (Mleczek et al., 2018), *Coronopus didymus* (Sidhu et al., 2018), *Melilotus officinalis* and *Amaranthus retroflexus*

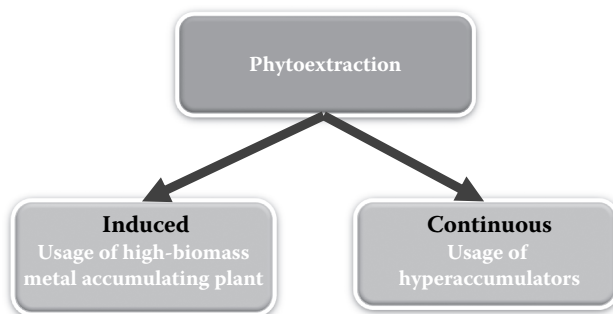


FIGURE 11.2 Phytoextraction classification.

(Ghazaryan et al., 2019), *Allium schoenoprasum* (Eisazadeh et al., 2019), *Amaranthus hypochondriacus* (Sun et al., 2020), *Vetiveria zizanioides* (Pentyala and Eapen, 2020), and *Corchorus capsularis* (Saleem et al., 2020). However, in conjunction with the previously described mechanism, the special characteristics of plants used in phytoextraction include:

- a. Presence of profuse root system.
- b. Tolerance to high metal contents.
- c. Exhibit rapid growth rate, (3) production of high biomass.
- d. Have the ability to accumulate metals in harvestable parts.
- e. Adaptation to extreme weather events (Ali et al., 2013; Yadav et al., 2018).

11.3.2 Phytofiltration (Rhizofiltration)

Rhizofiltration is a root zone phytoremediation strategy, also called phytofiltration, caulofiltration, and blastofiltration, in which terrestrial and aquatic plants are used for removing pollutants, mainly heavy metals in wastewater (Yadav et al., 2018). Contaminants are absorbed, adsorption, concentrated, and precipitated during this process by terrestrial and aquatic plants from polluted sites, usually aqueous sources such as wetlands and wastewater. It involves a series of physical and biochemical processes such as surface absorption of metal onto the plant roots, intracellular absorption, vacuole deposition, translocation to the shoot, or heavy metal precipitation by the action of plant exudates (Ajibade et al., 2013; Kumar and Chandra, 2017). Depending on the nature of the toxic metals, rhizofiltration can be accompanied by other phytoremediation processes such as phytoextraction, phytostabilization, and phytovolatilization. However, the effectiveness of rhizofiltration is dependent on the ability of plant roots to absorb, accumulate, and precipitate contaminants (Akinbile and Yusoff, 2012; Rahman et al., 2016; Bora and Sarma, 2020). Hence, the ideal plants to be used for rhizofiltration must: (1) Have the ability to grow rapidly; (2) produce a good quantity of roots; (3) have roots with large surface area; (4) ability to grow under submerged environments; and (5) can absorb, tolerate, and precipitate toxic metals over a lengthy duration of time (Rahman et al., 2016; Kumar and Chandra, 2017; Bora and Sarma, 2020). In addition, several terrestrial, aquatic, and wetland plants have been discovered and tested for their phytofiltration capacities to remediate heavy metals and some of these plant species include *Micranthemum umbrosum* and *Warnstorfia fluitans* (Islam et al., 2015), *Phragmites australis* and *Typha latifolia* (Kumari and Tripathi, 2015), *Typha domingensis* (Vymazal, 2016), *Salix matsudana* (Tang et al., 2017), *Micranthemum umbrosum* (Islam et al., 2017), *Pistia stratiotes* (Galal et al., 2018), *Warnstorfia fluitans* (Sandhi et al., 2018), *Potamogeton pusillus* (Griboff et al., 2018), *Nymphaea tetragona* (Li et al., 2019), and *Monosoleum tenerum* (Sut-Lohmann et al., 2020). Rhizofiltration is an effective and cost-efficient phytoremediation strategy; however, the use of aquatic plants has been reported to have limited capacity for rhizofiltration due to their small size, slow-growing, and high-water-content roots, which is responsible for their inability to dry, compost, and incinerate rapidly compared to terrestrial plants that have long and effective fibrous root systems and large root surface area for metal sorption (Dushenkov et al., 1995).

11.3.3 Phytostabilization

Phytostabilization, also called phytoimmobilization, is another phytoremediation strategy where contaminants such as heavy metals in the soil are immobilized to reduce their mobility and bioavailability in the environment by the use of certain plant species through absorption and accumulation by their roots, adsorption on their root surfaces, or precipitation within the root zone and physical stabilization of soil (Rahman et al., 2016). Unlike phytoextraction, phytostabilization deals with the sequestering of heavy metals within the rhizosphere (Figure 11.1), thus hindering their leaching into the groundwater and absorption by the plant tissues, therefore reducing metal risks to human health and the environment (Kumar and Chandra, 2017; Yadav et al., 2018). Phytostabilization is used mainly for immobilizing heavy metals such as Pb, As, Cd, Cr, Cu, and Zn. However, some organic contaminants and their

metabolic by-products have the tendency to be attracted or attached to plant parts such as lignins, which can be related to phytostabilization in terms of phytolignification with a long history of application in removing organic contaminants. In addition, microorganisms such as bacteria and mycorrhiza present in the rhizosphere of these plants play an important role in overcoming phytotoxicity (Mastretta et al., 2006). One major difference between phytolignification and phytostabilization is that phytostabilization of heavy metals generally occurs in the soil, whereas phytolignification of organic contaminants occurs above the ground level (Kumar and Chandra, 2017). Consequently, the characteristic features of plants used in phytostabilization include: (1) must be tolerant to soil conditions, (2) have rapid growth rate, (3) have dense root systems, (4) easy to grow and maintain, and (5) have a relatively long life or able to self-propagate (Berti and Cunningham, 2000). Metal-tolerant plants species commonly and recently used in the phytostabilization of heavy metals include *Brassica juncea*, *Typha domingensis*, *Phragmites australis*, *Lupinus luteus*, *Miscanthus sinensis*, *Rose plant*, *Epilobium dodonaei*, *Iris sibirica*, *Hordeum vulgare*, *Vicia villosa*, *Helichrysum microphyllum*, *Atriplex nummularia*, *Salix L.*, *Agrostis* spp. and *Festuca* spp., and *Helianthus petiolaris* (Mahar et al., 2016; Randelović et al., 2016; Ma et al., 2017; Katoh et al., 2017; Bacchetta et al., 2018; Eissa 2019; Ilić et al., 2020; Saran et al., 2020). Macrophytes such as *Vossia cuspidata*, *Arundo donax*, *Zannichellia peltate*, *Apium nodiflorum*, *Nasturtium officinale*, *Typha domingensis*, and have also been recently identified and studied for phytostabilization of heavy metals in the aquatic environment (Galal et al., 2017; Bonanno and Vymazal, 2017).

11.3.4 Phytovolatilization

Phytovolatilization is the release of volatile contaminants via plant transpiration into the atmosphere (Figure 11.1). It is the process whereby organic contaminants are absorbed by plants from the soil and chemically converted into less toxic and volatile compounds and subsequent release into the atmosphere (Ali et al., 2013). Phytovolatilization is a complex phytoremediation strategy driven by biophysical mechanisms of mass transport of highly volatile contaminants through plants (Kumar and Chandra, 2017). Organic contaminants and toxic metals such as Hg, Se, and As are converted into non-toxic forms and released into the atmosphere via roots, shoots, and leaves of plants (Pivetz, 2001; Berken et al., 2002). For instance, the phytovolatilization of Se in plants occurs through a series of metabolic processes whereby several organic and inorganic species of Se such as selenate, selenite, and Se-Met are absorbed and converted into less toxic and volatile compounds (Berken et al., 2002). The volatilization of Se as methyl selenate is recommended as the main process of removal of Se from contaminated soil, while Indian mustard (*Brassica juncea*) is well reported in studies to be the most effective plant for accumulation and volatilization of Se coupled with its rapid growth rate (Berken et al., 2002; Banuelos et al., 2005). Limmer and Burken (2016) categorized phytovolatilization into two types: direct and indirect phytovolatilization. Direct phytovolatilization involves plants absorbing volatile pollutants from polluted locations and releasing them into the atmosphere through their stems, trunks, and leaves through transpiration, while indirect phytovolatilization involves volatile contaminant flux from the subsurface due to the activities of the plant roots (Limmer and Burken, 2016). The removal of heavy metals via ohytovolatilization is less effective because the contaminant must (1) be absorbed by plant roots, (2) move via the xylem to the leaves, (3) be metabolised into volatile forms, and (4) volatilize into the atmosphere (Mueller et al., 1999). Another serious disadvantage of phytovolatilization is the tendency of the volatilized contaminants to be precipitated back into the environment during rainfall (Hussein et al., 2007).

11.3.5 Phytodegradation/Phytotransformation

Phytodegradation, also termed *phytotransformation*, involves the degradation or breakdown of contaminants, mainly organic contaminants, through various plant metabolic processes or via the degrading effects of enzymes produced by the plants on the organic contaminants (Vishnoi and Srivastava, 2008; Ali et al., 2013). Plants are capable of producing enzymes that can facilitate and speed up the degradation of organic contaminants. Some of these enzymes include dehalogenase for degrading chlorinated compounds, peroxidase for transforming phenolic compounds, nitrilase for degrading

cyanated aromatic compounds, nitroreductase for transforming explosives and nitrated compounds, and phosphatase for the degradation of organophosphate pesticides (Jabeen et al., 2009). Phytodegradation depends on the direct uptake of contaminants from the contaminated sites and the accumulation in the vegetation. This direct uptake of contaminants into the plant tissues through the root system depends on the uptake efficiency, transpiration rate, and the concentration of the contaminant in the contaminated sites. Also, the uptake efficiency depends on chemical speciation, physicochemical features, and plant properties, while the transpiration rate depends on the environmental conditions and plant characteristics such as nature, and the leaves' surface area (Kumar and Chandra, 2017). Recent studies have focused on the phytodegradation of organic compounds; for example, *Cyperus alternifolius* was employed for degrading and removal of ethanolamines from wastewater (Dolphen and Thiravetyan, 2015) and *Armoracia rusticana*'s ability to degrade benzophenone within its tissues has also been discovered (Chen et al., 2016).

11.4 Phytoremediation of Heavy Metals Using Aquatic Macrophytes

Heavy metals enter into the environment through natural sources such as volcanic eruption, erosion, mineralization (Ali et al., 2013), and man-made sources (Table 11.1). In contrast to organic contaminants, heavy metals and metalloids persist longer in the environment because of their non-biodegradability property (Ahmadpour et al., 2012). While some metals, namely Fe, Co, Mn, Mo, and Zn, are vital for human physiological and biochemical functions in small concentrations, metals like Pb, Cd, Hg, and Pu are detrimental even in their lowest concentrations (Table 11.2) (Tchounwou et al., 2012; Kumar et al., 2017). Several aquatic macrophytes have been suggested to be effective in phytoremediation of both inorganic and organic contaminants. In phytoremediation of inorganic contaminants, water hyacinth (*Eichhornia crassipes*) has been reported to be efficient in enhancing water quality parameters and it is affirmed as an adequate accumulator of Cd and Zinc (Zn) (Valadi et al., 2019; Ansari et al., 2020). Saha et al. (2017) suggested that plants can equally be employed in the remediation of water polluted with toxic hexavalent chromium (CrVI), while *Lemna minor* has been reported to be able to degrade soluble lead (Pb), nickel (Ni) (Axtell et al., 2003) as well as Cr (VI) (Uysal, 2013). Similarly, *Wolffia globosa* has also been found to have a significant concentration of trace metals in the roots and leaves of and *Najas marina* (Baldantoni et al., 2004). Bennicelli et al.

TABLE 11.1

Natural and anthropogenic sources of heavy metal(loid)s in recent studies

Sources	Test Medium	Heavy Metal(loid)s	References
Natural			
Lithogenic	Coal power soil	As, Pb, and Cd	Zhang et al., 2020a
	Agricultural soils	Fe, Cr, V, Cu, Ni, and Mn	Yuanan et al., 2020
Atmospheric deposition	Yangtze sediments	Cd	Han et al., 2017
Anthropogenic			
Coal mining	Coal power soil	Cu, Mn, and Zn	Zhang et al., 2020a
Vehicle emissions	Agricultural soils	Cd and Pb	Yuanan et al., 2020
Mining activities	Gold mining area	As, Cr, Pb, and Hg	Adewumi, 2020
Pesticides and fertilizers	Farm soil	As and Cd	Zhang et al., 2020b
Fertilizer application	Lake sediment	Cu and Cd	Dai et al., 2018
Shipping activities	Surface water	Cu and Cr	Ismail et al., 2016
Petroleum spills	Pipeline vandalised area	Ni and V	Ogunlaja et al., 2019
Wastewater irrigation	Cropland soils	As	Dong et al., 2019
Metal smelting	Pb/Zn smelter soil	Pb, Zn, Cd, and Cu	Fan et al., 2019

TABLE 11.2

Hazardous effect of heavy metals on human health

Metals	Effects	Reference
Cd	Nausea, muscular weakness, vomiting, dyspnea, and abdominal cramps; in extreme exposure, leads to pulmonary edema or death.	Duruibe et al., 2007; Sobha et al., 2007; Lalor, 2008
Zn	Diarrhea, vomiting, icterus, anemia, bloody urine, kidney or liver failure.	Duruibe et al., 2007; Jaiswal et al., 2018
Cu	Gastrointestinal and skin irritation, hepatic and renal damage, widespread capillary and central nervous system damage.	Argun et al., 2007; Stern et al., 2007; Chambers et al., 2010
Pb	Cardiovascular malfunction, gastrointestinal problems, haemoglobin synthesis inhibition, neurological disorders, and resulting in death.	Kazemipour et al., 2008; Odum, 2016
Cr	Strong oxidizing agent, soluble in alkaline and mildly acidic water, corrosive, and potentially carcinogenic and toxic to humans.	Shaffer et al., 2001; Jeyasingh and Philip, 2005; Huang et al., 2009
Hg	Gastrointestinal disorders like corrosive hematochezia and esophagitis, congenital malformation, and spontaneous abortion.	Duruibe et al., 2007
As	Causes protein coagulation, Guillian-Barre syndrome, and increased exposure lead to death.	Duruibe et al., 2007; Jaiswal et al., 2018

(2004), in their studies using *Azolla caroliniana* (a small water fern), stated that the plants can decontaminate waters contaminated by mercury (Hg) and Cr.

On the other hand, many free-floating macrophytes have also been reported to show reasonable phytoremediation potential for organic contaminants. For instance, *Salvinia*, *Lemna*, *Eichhornia*, and *Pistia* have been proposed to be effective in removing organic pollutants from water (Bhaskaran et al., 2013). *Chara vulgaris*, *Lemna minor*, *Myriophyllum spicatum*, and *Potamogeton perfoliatus* were also reported to remove alkylbenzene sulfonate (Liu and Wu, 2018; Zhou et al., 2018; Liu et al., 2019). Moreover, *Lemna minor* has been reported to have the capacity to enhance the quality of blue and textile dyes-polluted water (Ekperusi et al., 2019; Neag et al., 2018). It has been reported that *Lemna gibba* is used in phytoremediation of several biochemical processes: biochemical oxygen demand (BOD), total suspended solids, ammonium nitrate and phosphate, ammonia, and total nitrogen (Ekperusi et al., 2019).

11.5 Factors Affecting the Mobility, Absorption, and Accumulation in Plants

Several factors affect the solubility and bioavailability of heavy metals to plants and one of these determining factors is the soil physicochemical properties such as soil pH, electrical conductivity, soil texture, organic matters, cation exchange capacity, clay content, loading rate, and redox potential (Yadav et al., 2018; Patra et al., 2020). It is generally understood that heavy metals in soil with a high clay content, organic matter, or soil pH are less mobile and bioavailable to the plant. Another important factor responsible for the differences in metal mobility and uptake by plants is soil temperature. Plant roots in the soil absorb heavy metals after their solubility and mobilization. However, their mobility in the soil depends on the following: (1) Diffusion of heavy metals along the concentration gradient due to their uptake and depletion around the root vicinity, (2) root interception due to the displacement of soil volume by the roots, and (3) the bulk soil solution to water potential gradient flow of heavy metals (Marschner, 1995). Heavy metal absorption occurs by both roots and leaves and hence increases with increasing metal concentrations in the surrounding environment. However, there is no linear relationship between the increasing concentration of heavy metals in the external environment with the uptake of metals. This is because the metals bound in the plant tissue cause saturation, which is ruled by the metal uptake rate. Also, the efficiency of metal uptake by plants is highest at their low concentration in the external environment. When the accumulation of heavy metals occurs in the vascular system of plants, most of these metals are

insoluble and restricted from moving freely, therefore forming sulphate, phosphate, or carbonate precipitates (Raskin et al., 1998). Generally, when metal ions are absorbed by root symplasm, their mobility to the xylem depends on three procedures: (1) metal sequestration into the root symplasm, (2) symplastic transport into the stele, and (3) release of metals into the xylem (Shah et al., 2010).

The membrane transport proteins mediate the movement of metal ions into the xylem. However, the competition between the transport of essential and non-essential metals using these transmembrane carriers exist. For instance, Cr (III) is taken up by plants in passive processes compared with Cr (VI) transport, which is mediated by sulphate carriers. Nevertheless, the affinity for Cr (VI) is low. In a barley seedlings experiment, inhibitors such as dinitrophenol and sodium azide inhibit the uptake of Cr (VI) as compared to Cr (III), which they did not (Skeffington et al., 1976). Shewry and Peterson (1974) reported group VI anions such as SO_4^{2-} as inhibitors to chromate uptake while Cr (VI) transport is stimulated by Ca^{2+} . Hence, the transportation of the inhibited chromate is due to the chemical similarities and competitiveness of these inhibitors, while the stimulated transport of Cr (VI) by Ca^{2+} occurred because of its important role in the uptake and transport of metals in the plants (Zayed and Terry, 2003; Montes-Holguin et al., 2006). Metals such as B, Cd, Mn, Mo, Se, and Zn are readily absorbed and transported within plant tissues, whereas other metals such as Al, Ag, Cr, Fe, Hg, and Pb are bound strongly to the soil components and plant roots, thus with less mobility (Chaney, 1983a, b). Nevertheless, at some concentrations, all these metals can be translocated within the plant system, even at a concentration gradient. For instance, essential metals such as Zn^{2+} , Cu^{2+} , and Ni^{2+} and nonessential Cd^{2+} have been shown using kinetic data as they compete for their transport through the same transmembrane carrier (Crowley et al., 1991). Other significant factors that influence the uptake mechanisms and efficiency of the various phytotechnologies employed in toxic metal removal from the soil, sludge, and wastewater include bioavailability of the metal, environmental condition, plant species, root zone, chemical properties of the contaminant, properties of the medium, and chelating agent added (Sheoran et al., 2016).

11.6 Challenges Associated with Phytoremediation in Decontaminating Soil/Water

Phytoremediation has been identified to be an efficient contaminant removal technology; however, some challenges or drawbacks have been reported to hinder its efficiency (Ramamurthy and Memarian, 2012; Mahar et al., 2016), especially in the removal of toxic metals from both soil and water environments. A few of these challenges include inadequate metal phytoavailability, biomass, low growth rate, and unable to target metal hyperaccumulators. As a result of these challenges, phytoremediation will take a long period to attain the desired remediation goal (Saxena et al., 2019); thus, leading to an increase in cost for treatment, safety, and accompanied liability of risks, because the longer time the more the cost when assessing the economic practicability at the field (Conesa et al., 2012; Mahar et al., 2016). The enhancement of the phytoremediation technology, such as the use of synthetic chelators for higher metal accumulation by plants, can also add challenges like an additional cost, unwanted environmental issues such as interruption of the physical and chemical properties of soils through mineral components dissolution, soil microorganisms and plant toxicity, and groundwater undesirable leaching, which makes chelate-assisted phytoremediation technology almost unfeasible (Saxena et al., 2019). Vangronsveld et al. (2009) also stated that most European countries have banned several of these metal mobilizing amendments (e.g., EDTA). Also, plants' growth when phytoremediation is taking place equally results in alteration in pH and increase in organic acids, thus, creating room for metals to be more bioaccessible to the food chain prior to their remediated process (Gerhardt et al., 2016), hence bringing up some environmental challenges that can negate some of the merits associated with phytoremediation (Saxena et al., 2019). Since these contaminants are accumulated in plants, there is the likelihood of consequent occurrence such that their toxic forms could be re-discharged or discharge into the soil through leaf debris. Furthermore, phytostabilized metals are not eliminated from the soil, and changing soil conditions may result in re-discharge of contaminants into the environment, necessitating long-term field monitoring to avoid future land-use changes (Gerhardt et al., 2016). Using genetically modified plants to improve phytoremediation

may likewise lead to a higher cost of phytoremediation because of the huge maintenance required for contaminated sites, and government-required field application policies in terms of monitoring and dumping biomass (Stephenson and Black, 2014). Phytoremediation technology is still faced with the problem of inadequate research funding from both public and private sector agencies.

In addition to the explanation of the challenges of phytotechnology, Mahar et al. (2016), in their study, summarily stated the challenges of phytoremediation technology as follows:

- i. A prolonged period is required for soil remediation.
- ii. Reduced efficiency of phytoextraction of some hyperaccumulator as a result of degraded biomass and sulky growth rate.
- iii. Proper and careful disposal of the polluted biomass is required as they are equally toxic after phytoextraction.
- iv. On the occasion of attack from pests and diseases especially in tropical and sub-tropical regions, the efficiency and effectiveness of the hyperaccumulators are negatively influenced.
- v. Difficulty in mobilizing tightly bound metal ions from the soil when there is limited bioavailability of the contaminants.
- vi. Careful selection of plant species is required to avoid the introduction of hyperaccumulators that could be invasive to other indigenous floral diversity.
- vii. Agronomic practices and soil amendments negatively influence the mobility of contaminants.
- viii. Climate and weather condition influences.
- ix. Due to unsustainable plant growth in soils of high contamination, phytoremediation applies primarily in areas of low to moderate metal pollution levels.
- x. When biomass is mishandled, there could be a transfer of the accumulated metal contaminants into the food chain.

11.7 Significance of Plant Root Nature in Phytoremediation/Phytomining

Biotechnology is gradually transmuting global agriculture while adding new traits to crop plants at an immense level of advancement (Gleba et al., 1999). Besides the conventional benefits of plants such as the provision of food, fibre, medicines, and construction materials, biotechnology has disclosed peculiar uses of plants that have been gaining attention from the general public as well as the scientific community globally; these “value-added” uses are phytoremediation (Salt et al., 1998) and molecular farming (phyto-manufacturing), which is the use of plants for the production of valuable organic molecules and recombinant proteins (Nawrath et al., 1995; Franken et al., 1997).

Apart from root crops, plant roots are relatively less studied than the shoots (Gleba et al., 1999). However, this trend is taking a new paradigm due to the emerging biotechnologies (phytotechnologies) described that tap the ability of plants to transport important molecules into and out of their roots. These root-based technologies mainly include phytoextraction and rhizofiltration. Plant roots form large underground networks that serve as solar-energy-driven pumps that extract and concentrate essential elements and compounds from soil and water. For instance, in phytoextraction of metals, the roots of hyperaccumulators transport and concentrate the toxic metals from the soil into harvestable shoots above the ground (Kumar et al., 1995; Vassil et al., 1998). Hydroponically grown plant roots absorb, precipitate, and concentrate toxic metals from contaminated effluents through rhizofiltration (Dushenkov et al., 1995). Furthermore, Agostini et al. (2013) affirm that in organic contaminant removal, plant roots stimulate accelerated decontamination through the discharge of root exudates and oxido-reductive enzymes, such as peroxidases (Px) and laccases.

11.8 Innovative Approaches for Optimizing Phytoremediation of Heavy Metals

Phytoremediation has been noted to be a promising technology for environmental remediation and sustainability. Various traditional phytoremediation techniques as discussed in an earlier section have been suggested to be good in tackling the heavy metal problems in environments. However, some drawbacks associated with these traditional techniques have limited them from being applied on a large scale (Sarwar et al., 2017). These observed challenges associated with the traditional phytoremediation techniques prompted researchers to modify these techniques for improved results, reduced limitations, as well as promote large-scale application of phytoremediation. The improvement approaches in use for optimizing phytoremediation of heavy metals are explained.

11.8.1 Chelators (Chemical-Assisted Phytoremediation)

This is the strategy in which plants' heavy metal uptake potential is promoted and enhance the bioavailability of heavy metals by the addition of biodegradable physicochemical factors such as chelating agents and micronutrients, as well as by stimulating the heavy-metal-uptake capacity of the microbial community in and around the plant (Tangahu et al., 2011). This chelate-assisted phytoremediation technology is also referred to as induced phytoextraction. It is a difficult task to select hyperaccumulator plant species that are effective and efficient for the phytoremediation of heavy metals. However, Baker et al. (1994) suggested the adoption of the shoot-to-root metal concentration ratio to determine whether a plant can be considered as a hyperaccumulator. They concluded that if the ratio is greater than 1.0, it shows that the shoot stores more metal than the root of such plant species; hence, the plant species can be employed as a hyperaccumulator and as a matter of fact could be applied for phytoextraction. Non-hyperaccumulator plants that produce more aboveground biomass but have lower heavy metal extraction potential can equally be modified chemically to suit phytoremediation of heavy metals (Sarwar et al., 2017). Some synthetic chelating agents that have been used in phytoremediation include ethylene diamine tetra-acetic acid (EDTA), diethylene triamine penta-acetic acid (DTPA), and ethylene glycol tetra-acetic acid (AGTA) (Saifullah et al., 2009; Pereira et al., 2010), and nitrilotriacetic acid (NTA) (Tangahu et al., 2011). Furthermore, researchers noticed some inefficiency adaptation issues associated with heavy metal phytoremediation of some plant species, such as stunted growth and low biomass production. This led to the application of some chemicals that would help in improving the capacity of metal plants to work effectively in phytoremediation of heavy metals and at the same time cope with heavy metal stress (Sarwar et al., 2015; Popova et al., 2012). An example of such chemicals with a widespread phenolic compound and has been used is salicylic acid (He et al., 2010; Sarwar et al., 2017).

Besides the advantages of this approach, its most pronounced disadvantage is the high cost of these synthetic chelating agents. Hence, low-molecular-weight organic acids, examples of which are oxalic, citric, acetic, and malic, are used to serve as alternatives and can be effectively used as chelating agents of heavy metals. These organic acids can form metal complexes of low to moderate stability (Sarwar et al., 2017). Another advantage of using these organic acids is that they are more biodegradable in soil than synthetic chelating agents with minimum environmental contamination risks (Souza et al., 2013).

11.8.2 Biochar

Biochar is a carboniferous permeable material that could be produced from the pyrolysis of organic feedstocks such as plant materials, organic manures, and sludges (Paz-Ferreiro et al., 2014). Wood biochar (charcoal) is the most common biochar that has been in use. Biochar is suggested to be a resourceful material for improving traditional phytoremediation techniques due to its specific physicochemical properties (Ajibade et al., 2021c). These properties of biochar include high (alkaline) pH, large surface area for sorption of metals, high carbon content, and its ability to increase the bioavailability of metals in the rhizospheric region, which places it among good heavy metal remediators (Sarwar et al., 2017; Patra et al., 2020). Biochar is also resourceful in phytoremediation of plants as it enhances the biomass (Liu et al., 2013), and this increased plant biomass is possible as a result of high

nutrients, water-holding capacity, and cation exchange capacity in biochar (Ahmad et al., 2016; Fellet et al., 2014; Liu et al., 2013). Elad et al. (2012) further affirm that biochar also helps in improving the activity of essential microbes in soil as well as suppressing the action of pathogenic microbes.

11.8.3 Genetic Engineering: Utilization of Transgenic Plants

As a way of enhancing the efficiency and effectiveness of the phytoremediation technology in the decontamination of heavy metals and other toxic contaminants, researchers have tried the application of some advanced technologies. One of these advances made is the utilization of transgenic plants. Transgenic plants in phytoremediation are plants that have been genetically modified for enhanced uptake and degradation of contaminants. The formation of transgenic plants is part of genetic strategies for phytoremediation which have improved the removal or detoxification of toxic metals in the environment due to their increased ability in metal uptake, accumulation, and tolerance to toxicity (Fasani et al., 2018). Currently, using transgenic plants is considered a promising option, despite several anatomical constraints that pose threats to the development of hybrid plants with increased phytoremediation capability (Yadav et al., 2018). Transgenic plants can be developed through a direct DNA method transfer of genes or simple dipping of *Agrobacterium tumefaciens* mediated transformation (Seth, 2012). An example is the inoculation of *Theobroma cacao* with an *Agrobacterium* suspension (Fister et al., 2016). Generally, the use of transgenic plants has been successfully used to phytoextract metals such as Cd, Pb, and Cu, and metalloids such as As and Se in the aboveground biomass (Sarwar et al., 2017; Yadav et al., 2018). It involves the use of metal transporters, improved production of sulphur-metabolizing enzymes such as phytochelations, and metal-detoxifying chelators-metallothioneins (Kotrba et al., 2009). Examples of transgenic plants developed for metal tolerance and phytoremediation are listed in Table 11.3.

Furthermore, Kärenlampi et al. (2000) found that transgenic plants with higher glutathione synthase or phytochelatin synthase show enhanced cadmium (Cd) accumulation. Transgenic plants bearing foreign genes for proteins translocating metals within membranes have equally been developed (Krämer and Chardonay, 2001). Though transgenic plants developed with genes, and huge resistance to certain heavy metals was a result of coding different forms of metallothionein (mammalian, yeast, insect and human) (Kärenlampi et al., 2000), hence the achievement of improved accumulation was not possible

TABLE 11.3

Transgenic plants developed for metal tolerance and phytoremediation

S/N	Transgenic Plants	Plant and Bacteria Source	DNA Method Transfer of Genes for Metals Tolerance and Phytoremediation	References
1	<i>V. sativa</i> homologue of Caffeoyle-CoA Omethyltransferase	<i>Vicia sativa</i>	sCCoAOMT gene transfer for Cd tolerance and accumulation	Xia et al., 2018
2	Metallothionein	<i>Sedum plumbizincicola</i>	SpMTI gene transfer for Cd hyperaccumulation and hypertolerance	Peng et al., 2017
3	Ubiquitin (Ub)-conjugating enzyme	<i>Arabidopsis thaliana</i>	NtUBC1 gene transfer for Cd tolerance and accumulation	Bahmani et al., 2017
4	g-Glutamylcysteine synthetase-glutathione	<i>Streptococcus thermophils synthetase</i>	StGCS-GS gene transfer for Cd, Zn, and Cu accumulation	Liu et al., 2015
5	Glutathione synthase GS and γ -glutamylcysteine synthase ECS	<i>Escherichia coli</i>	γ -ECS gene transfer for Cd, Cr, As, Pb, and Zn tolerance and accumulation	Reisinger et al., 2008
6	Acyl-CoA-binding protein	<i>Arabidopsis thaliana</i>	ACBP1 gene transfer for Pb tolerance and accumulation	Xiao et al., 2008

(Liu et al., 2000b). Dietz and Schnoor (2001), however, stated that metals cannot be enzymatically degraded like organic contaminants; hence, they suggested a special improvement in genetic engineering for phytoremediation of heavy metals. Generally, using transgenic plants in phytoremediation has helped to reduce and address environmental contamination in recent years; however, there are still many challenges to overcome in this area (Yau and Stewart, 2013). One of the major challenges is that most of the research studies in the development and use of transgenic plants are carried out in controlled settings, instead of the physical environment (Abhilash et al., 2009; Bhargava et al., 2012). There is also a need for proper risk evaluation about the application of transgenic plants in phytoremediation of metals and their exposure to humans and wildlife to lead to a safer genetically modification of crops and wider opportunities for their usage (Wolfenbarger and Phifer, 2000; Davison, 2005; Sarwar et al., 2017).

11.8.4 Microbes

Soil microbes carry out some activities in the soil and within the rhizosperic region of plants that are beneficial to plants in their uptake of nutrients. This relationship between soil microorganisms and plants leads to its inclusion among the strategies that enhance the capability of plants in the phytoremediation of heavy metals. The relationship between some soil microbes and plant roots could be a symbiotic or free-living relationship (Sarwar et al., 2017). The primary component of living organism's component within the root zone has been recognized as mycorrhizal fungi (Sarwar et al., 2017), and they are found in many forms with most higher plants such as arbuscular mycorrhizas, ericaceous mycorrhizas, orchid mycorrhizas, and ectomycorrhizas with arbuscular mycorrhizal fungi (AMF) having the most frequent connections with terrestrial plant roots (Sheng and Xia, 2006). The relationship between fungi and plant roots are very important for enhancing the bioavailability of plant nutrients (Ca, N, P, Zn, Co, K, S, Ni, and Cu) via a wide range of hyphal network (Zaidi et al., 2006; Sheng and Xia, 2006). Similarly, these fungal interactions can change the chemical composition of root secretion and soil pH, hence increasing heavy metal bioavailability in the soil (Sarwar et al., 2017). For instance, an application of *Ixeris denticulate*, *Kummerowia striata*, and *Echinochloa crusgalli* mixed with AMF inoculums, showed an increased uptake and accumulation of Pb (Chen et al., 2003).

Some bacteria, such as plant-growth-promoting bacteria (PGPR) are another beneficial group of microorganisms for plants in tackling heavy metal contamination (Seth, 2012). They are similarly classified as symbiotic bacteria and free-living rhizobacteria (Liao et al., 2003). These bacteria enhance plant development through a variety of ways, including reduced ethylene synthesis under stress, nitrogen fixation, and particular enzyme activity (Glick et al., 1998). These organisms not only improve heavy metal absorption and accumulation, but they also reduce the impact of the toxicity and heavy metal stress in the plant (Sarwar et al., 2017; Farwell et al., 2007); hence, the application of the right microbial inoculum can help plant species effectively remove heavy metals from the soil.

11.8.5 Exogenous Phytohormones

Exogenous phytohormones are applied as supplementary enhancers to plants. They are primarily applied to enhance plant biomass, fitness, and stress tolerance for better phytoremediation efficiency (DalCorso et al., 2019). For instance, cytokinins have been suggested to be effective both in enhancing plant growth and increasing phytoextraction capacity (Aderholt et al., 2017); however, auxins showed contradictory results (Vamerali et al., 2011). Although the use of gibberellins or some commercial growth regulator mixes reduced metal buildup in plant tissues, the increase in plant biomass as a result of their application increased metal extraction per plant (Hadi et al., 2010).

11.8.6 Electro Kinetic-Enhanced Phytoremediation

This is a new strategy that has been proposed to overcome some of the limitations such as the long time and limited treatment depths that are associated with traditional phytoremediation (DalCorso et al., 2019). This technique applies the combination of plants and a physicochemical treatment, in other

words, low-intensity electric fields, to the metal-polluted soil, favouring metal mobilization and bioavailability (Cameselle and Gouveia, 2019). Also, a reasonably high Pb, As, and Cs phytoextraction has been obtained by direct current (DC) electric field used with inert affordable graphite electrodes, because of the modification of soil pH and metal solubility from the electric field (Mao et al., 2016). This technology is fascinating as the application of a solar-cell-powered electric field has been tested in a real-scale field test for the phytoremediation of a metal-polluted electronic waste recycling centre by *Eucalyptus globulus*, and it showed an increased plant growth and metal accumulation (DalCorso et al., 2019). Even though the main power supply systems are more effective in metal transportation and containment, nevertheless the cost effectiveness of solar cells suggests that this technique is more sustainable (Luo et al., 2018).

11.8.7 Nanoparticles

Nanoparticles have equally been identified as effective in assisting materials for the phytoremediation of metals. Due to their unique characteristic, absorption capacity, or redox catalytic activity, many kinds of nanomaterials have been employed to remediate metal-polluted substrates (Mueller and Nowack, 2010). Liang et al. (2017) suggested that a combination of plants and nanoparticles can be used to improve the efficacy of phytostabilization by absorbing metal ions. Their combination can also be employed in phytoextraction to enhance plant fitness and stress tolerance as well as increase metal bioavailability (Moameri and Khalaki, 2017; Singh and Lee, 2016).

11.9 Phytoremediation as a Tool for Environmental Sustainability

The generation of environmental pollutants and toxic wastes has grown rapidly over the last two decades due to increasing global industrialization, urbanization, and population (Kumar and Chandra, 2017). These environmental pollutants and toxins include a wide range of organics such as dyes, phenolic compounds, humic substances, petroleum, pharmaceuticals, surfactants, and pesticides; and inorganic contaminants such as salts, heavy metals, and metalloids. These toxic wastes are generally discharged into water bodies or dumped on land with little or no treatment despite the need for pollution control and thus pose a great danger to public health, habitats, and the environment (Gupta et al., 2015; Yadav et al., 2017, 2018). Compared to other conventional methods for wastewater treatment (Table 11.4), phytoremediation has provided a more realistic, sustainable, cost-effective, and aesthetic approach for the remediation of toxic pollutants from the ecosystem to ensure environmental sustainability and preservation (Ajibade et al., 2021b; Rahbar et al., 2016; Vymazal and Březinová, 2016; Rezanian et al., 2016). The use of phytoremediation as a tool for environmental sustainability can be dated to centuries ago, especially in the use of the plant for wastewater treatment (Raskin et al., 1998). The word *phytoremediation* was coined from two Greek words “phyto” which means “plant” and “remedium” which also means “to clear or restore”. Given that phytoremediation is dependent on the usage of plants to extract, sequester, and detoxify contaminants, phytoremediation is globally known as an ecological, economical, and environmentally friendly alternative to conventional methods (Chandra et al., 2015). Several researchers have reported on the remediation capability of plants in different ecosystems i.e., terrestrial or aquatic environments (see section 3). Physically, plants have roots, stems, and leaves which, through different biophysical and biochemical processes including adsorption, translocation, mineralization, and transformation, can remediate contaminants.

11.10 Future Trends in Phytoremediation

Heavy metal contamination is a serious environmental and health problem due to its potential transfer via the food chain. However, phytoremediation strategies have proven to be a pertinent tool in decontaminating and removing of heavy metals from contaminated sites. Currently, phytoremediation is experiencing several new

TABLE 11.4

Conventional techniques for wastewater treatment

Techniques	Merits	Demerits	References
Electro-Chemical Treatments			
Electro-Coagulation (EC)	Small-scale, simple, and productive technology. Easy to operate and require less maintenance. No secondary pollution and can be used to remove a wide range of pollutants. Less sludge generation and generated sludges settle faster. Dewatering is very easy.	Poor systematic reactor design and electrode reliability. The use of electricity may be expensive. High conductivity of wastewater suspension. Loss of efficiency due to the formation of an impermeable oxide film on the electrode.	Emamjomeh and Sivakumar, 2009; Azimi et al., 2017; Syam Babu et al., 2019
Electro-Flotation (EF)	Simplicity in design, operation, and environmental compatibility. Low running cost. Good adaptability with small and compact units. Apply in a wide range of industries such as treatment of oil from oil-water emulsions, sewage and pit waters, groundwater disinfection, colloidal and suspended particles, juice and food processing effluents. Use for removing heavy metal pollutants at a very dilute solution (concentrations < 50 mgm ⁻³).	Power consumption may be high. Electrode dependency. Current density, pH, and electrode types affect EF operation.	Chen, 2004; Azimi et al., 2017; Kolesnikov et al., 2019
Electro-Deposition (ED)	Most efficient method among other electrochemical processes. No further reagents are needed. No sludge is produced. Highly selective and low cost.	Faces conventional aqueous solution problems such as the release of hydrogen gas, low thermal stability, and narrow electrochemical window. Physical parameters such as temperature, pH, and the presence of complexing and chelating agents affect the efficiency of ED.	Azimi et al., 2017
Physico-Chemical Treatments			
Chemical Precipitation	Simple, easily automated method. Wide application in removing different heavy metals.	High chemical consumption. High sludge production. Require constant monitoring and controlling, and generated effluent may cause further environmental pollution.	Azimi et al., 2017; Crini and Lichtfouse, 2019
Ion Exchange	Highly efficient, low cost, and less sludge production. Highly selective and excellent recovery for metal ions.	Physical parameters such as pH, anions, temperature, adsorbent and sorbate, and contact time affects its operation.	Crini and Lichtfouse, 2019; Shahedi et al., 2020
Adsorption	Simple and highly effective. Requires low treatment time.	Limited regeneration, costly, and efficiency depends on the adsorbent.	Crini and Lichtfouse, 2019
Membrane Filtration	Highly efficient and simple separation method. No chemical is required. No pollution loads and lower energy consumption compared with other	High cost of maintenance and operation. Low anti-compacting ability. Specific for some processes. Membrane clogging.	Azimi et al., 2017; Crini and Lichtfouse, 2019

(Continued)

TABLE 11.4 (Continued)

Conventional techniques for wastewater treatment

Techniques	Merits	Demerits	References
Photocatalysis	conventional methods. Wide application in food and beverage industries, biotechnology, water filtration. Uses non-toxic materials as catalysts. Simple design, low-cost operation, high stability, and high removal efficiency. Wide apply in photosplitting and decomposition of water to produce hydrogen gas, disinfection of microorganisms, degradation of organic compounds, selective oxidation, manufacturing liquid chemical fuels and removing pollutants including heavy metals.	Recombination of electrode or hole. Production of unwanted by-product. Absorption of visible light.	Azimi et al., 2017

dimensions of research and applications in heavy metal removal and to ensure further understanding and additional gains in this area, further studies are needed in creating a new approach in the development of higher gene expression in plants and manipulation of metal transporters and their cellular organs to ensure safe partitioning of metals in areas where other cellular activities are not disturbed, development of plants with metal-tolerant capabilities and capable of repelling herbivores from their consumption to prevent the transfer of metals via the food web, and the development of transgenic plants with improved plant-microbe interactions or rhizosphere microbial functions. Also, most studies on transgenic plants in phytoremediation are limited to laboratory settings; hence, the need for open-field efficiency testing. There is a need for transgenic research in phytoremediation to focus on mixed contamination problems.

11.11 Conclusion

The environment is a great factor both as an aspect of the ecosystem and as an object of academic research. The significance of the environment and the need for its sustainability have led to the collaborative efforts of various experts such as scientists, engineers, environmentalists, health personnel, and even rural community groups in advocating for green engineering. The contamination of the environment by some polluting elements including heavy metals, which human activities are the major contributors for, in turn, made the environment unfavourable for both man and other living organisms. This chapter has expressly explicated the phytoremediation technology and its techniques and mechanisms (viz. phytoextraction, phytofiltration or rhizofiltration, phytostabilization, phytovolatilization, phytodegradation or phytotransformation) for the remediation of heavy-metal-contaminated environments. The advantages of the phytoremediation technology over traditional decontamination methods were explained, and its limitations were equally highlighted. Factors affecting the mobility, uptake, and accumulation of heavy metals in plants were discussed and some innovative approaches for improving heavy metal phytoremediation were equally discussed. Finally, possible future trends in phytoremediation for a more effective decontamination of heavy-metal-contaminated environments, by which the environmental and health problems associated with these heavy metals and other contaminants due to their potential transfer via the food chain, could be curbed were suggested. Hence, phytoremediation technology can be instrumental in the promotion of public health quality and environmental sustainability.

REFERENCES

- Abhilash, P.C., Jamil, S., & Singh, N. (2009). Transgenic plants for enhanced biodegradation and phytoremediation of organic xenobiotics. *Biotechnology Advances*, 27(4), 474–488.
- Aderholt, M., Vogelien, D.L., Koether, M., & Greipsson, S. (2017). Phytoextraction of contaminated urban soils by *Panicum virgatum* L. enhanced with application of a plant growth regulator (BAP) and citric acid. *Chemosphere*, 175, 85–96.
- Adewumi, A.J. (2020). Contamination, sources and risk assessments of metals in media from Anka artisanal gold mining area, Northwest Nigeria. *Science of The Total Environment*, 718, 137235.
- Agostini, E., Talano, M.A., González, P.S., Oller, A.L., & Medina, M.I. (2013). Application of hairy roots for phytoremediation: what makes them an interesting tool for this purpose? *Applied Microbiology and Biotechnology*, 97, 1017–1030. DOI: 10.1007/s00253-012-4658-z.
- Ahmad, N., Imran, M., Marral, M.R., Mubashir, M., & Butt, B. (2016). Influence of biochar on soil quality and yield related attributes of wheat (*Triticum aestivum* L.). *Journal of Environmental and Agricultural Sciences*, 7, 68–72.
- Ahmadpour, P., Ahmadpour, F., Mahmud, T.M.M., Abdu, A., Soleimani, M., & Tayefeh, F.H. (2012). Phytoremediation of heavy metals: a green technology. *African Journal of Biotechnology*, 11(76), 14036–14043.
- Ajibade, F.O., Adelodun, B., Lasisi, K.H., Fadare, O.O., Ajibade, T.F., Nwogwu, N.A., Sulaymon, I.D., Ugya, A.Y., Wang, H.C., & Wang, A. (2021a). Environmental pollution and their socioeconomic impacts. In A. Kumar, V.K. Singh, P. Singh, & V.K. Mishra (Eds.), *Microbe Mediated Remediation of Environmental Contaminants*. Woodhead Publishing, Elsevier. 10.1016/B978-0-12-821199-1.00025.-0.
- Ajibade, F.O., Nwogwu, N.A., Lasisi, K.H., Ajibade, T.F., Adelodun, B., Guadie, A., Ugya, A.Y., Adewumi, J.R., Wang, H.C., & Wang, A. (2021b). Removal of nitrogen oxyanion (nitrate) in constructed wetlands. In N.A. Oladoja & I.E. Unuabonah (Eds.), *Progress and Prospects in the Management of Oxoanion Polluted Aqua Systems*. The Netherlands: Springer Nature, Netherlands. 10.1007/978-3-030-70757-6_12.
- Ajibade, F.O., Wang, H., Guadie, A.A., Ajibade, T.F., Fang, Y., Sharif, H.M.A., Liu, W., & Wang, A. (2021c). Total nitrogen removal in biochar amended non-aerated vertical flow constructed wetlands for secondary wastewater effluent with low C/N ratio: microbial community structure and dissolved organic carbon release conditions. *Bioresource Technology*, 124430. 10.1016/j.biortech.2020.124430.
- Ajibade, F.O., & Adewumi, J.R. (2017). Performance evaluation of aquatic macrophytes in a constructed wetland for municipal wastewater treatment. *FUTA Journal of Engineering and Engineering Technology*, 11(1), 1–11.
- Ajibade, F.O., Adeniran, K.A., & Egbuna, C.K. (2013). Phytoremediation efficiencies of water hyacinth in removing heavy metals in domestic sewage (A Case Study of University of Ilorin, Nigeria). *The International Journal of Engineering and Science*, 2(12), 16–27.
- Akinbile, C.O., Ikuomola, B.T., Olanrewaju, O.O., & Babalola, T.E. (2019). Assessing the efficacy of *Azolla pinnata* in four different wastewater treatment for agricultural re-use: a case history. *Sustainable Water Resources Management*, 5(3), 1009–1015.
- Akinbile, C.O., Ogunrinde, T.A., Che bt Man, H., & Aziz, H.A. (2016). Phytoremediation of domestic wastewaters in free water surface constructed wetlands using *Azolla pinnata*. *International Journal of Phytoremediation*, 18(1), 54–61.
- Akinbile, C.O., Yusoff, M.S., & Shian, L.M. (2012). Leachate characterization and phytoremediation using water hyacinth (*Eichhornia crassipes*) in Pulau Burung, Malaysia. *Bioremediation Journal*, 16(1), 9–18.
- Akinbile, C.O., & Yusoff, M.S. (2012). Assessing water hyacinth (*Eichhornia crassipes*) and lettuce (*Pistia stratiotes*) effectiveness in aquaculture wastewater treatment. *International Journal of Phytoremediation*, 14(3), 201–211.
- Ali, H., Khan, E., & Sajad, M.A. (2013). Phytoremediation of heavy metals – concepts and applications. *Chemosphere*, 91(7), 869–881. 10.1016/j.chemosphere.2013.01.075.
- Alkorta, I., Hernández-Allica, J., Becerril, J.M., Amezcaga, I., Albizu, I., & Garbisu, C. (2004). Recent findings on the phytoremediation of soils contaminated with environmentally toxic heavy metals and metalloids such as zinc, cadmium, lead, and arsenic. *Reviews in Environmental Science and Biotechnology*, 3(1), 71–90.

- Ansari, A.A., Naeem, M., Gill, S.S., & AlZuaibr, F.M. (2020). Phytoremediation of contaminated waters: an eco-friendly technology based on aquatic macrophytes application. *The Egyptian Journal of Aquatic Research*, 10.1016/j.ejar.2020.03.002.
- Antoniadis, V., Levizou, E., Shaheen, S.M., Ok, Y.S., Sebastian, A., Baum, C.,... & Rinklebe, J. (2017). Trace elements in the soil-plant interface: phytoavailability, translocation, and phytoremediation – a review. *Earth-Science Reviews*, 171, 621–645.
- Argun, M.E., Dursun, S., Ozdemir, C., & Karatas, M. (2007). Heavy metal adsorption by modified oak sawdust: thermodynamics and kinetics. *Journal of Hazardous Materials*, 141(1), 77–85.
- Axtell, N.R., Sternberg, S.P., & Claussen, K. (2003). Lead and nickel removal using *Microspora* and *Lemna minor*. *Bioresource Technology*, 89, 41–48. 10.1016/s0960-8524(03)00034-8.
- Azimi, A., Azari, A., Rezakazemi, M., & Ansarpour, M. (2017). Removal of heavy metals from industrial wastewaters: a review. *ChemBioEng Reviews*, 4(1), 37–59.
- Bacchetta, G., Boi, M.E., Cappai, G., De Giudici, G., Piredda, M., & Porceddu, M. (2018). Metal tolerance capability of *Helichrysum microphyllum* Cambess. subsp. *tyrrhenicum* Bacch., Brullo & Giusso: a candidate for phytostabilization in abandoned mine sites. *Bulletin of Environmental Contamination and Toxicology*, 101(6), 758–765.
- Bahmani, R., Kim, D., Lee, B.D., & Hwang, S. (2017). Over-expression of tobacco UBC1 encoding a ubiquitin-conjugating enzyme increases cadmium tolerance by activating the 20S/26S proteasome and by decreasing Cd accumulation and oxidative stress in tobacco (*Nicotiana tabacum*). *Plant Molecular Biology*, 94(4-5), 433–451.
- Baker, T.J., Tyler, C.R., & Galloway, T.S. (2014). Impacts of metal and metaloxidenanoparticles on marine organisms. *Environmental Pollution*, 186, 257–271. DOI: 10.1016/j.envpol.2013.11.014.
- Baker, A.M., Reeves, R.D., & Hajar, A.M. (1994). Heavy metal accumulation and tolerance in british populations of the metallophyte *Thlaspi caerulescens* J and C Presl (Brassicaceae). *New Phytologist*, 127, 61–68.
- Baldantoni, D., Alfani, A., Di Tommasi, P., Bartoli, G., & De Santo, A.V. (2004). Assessment of macro and microelement accumulation capability of two aquatic plants. *Environmental Pollution*, 130(2), 149–156. doi:10.1016/j.envpol.2003.12.015.
- Bañuelos, G.S., Arroyo, I., Pickering, I.J., Yang, S.I., & Freeman, J.L. (2015). Selenium biofortification of broccoli and carrots grown in soil amended with Se-enriched hyperaccumulator *Stanleya pinnata*. *Food Chemistry*, 166, 603–608.
- Bañuelos, G.S., Lin, Z.-Q., Arroyo, I., & Terry, N. (2005). Selenium volatilization in vegetated agricultural drainage sediment from the San Luis Drain, Central California. *Chemosphere*, 60(9), 1203–1213. doi:10.1016/j.chemosphere.2005.02.033.
- Bennicelli, R., Stepniewska, Z., Banach, A., Szajnoch, K., & Ostrowski, J. (2004). The ability of *Azolla caroliniana* to remove heavy metals (Hg(II), Cr(III), Cr(VI)) from municipal waste water. *Chemosphere*, 55(1), 141–146. doi:10.1016/j.chemosphere.2003.11.01.
- Berken, A., Mulholland, M. M., LeDuc, D. L., & Terry, N. (2002). Genetic Engineering of Plants to Enhance Selenium Phytoremediation. *Critical Reviews in Plant Sciences*, 21(6), 567–582. doi: 10.1080/0735-260291044368.
- Berti, W.R., & Cunningham, S.D. (2000). Phytostabilization of metals. In I. Raskin & B.D. Ensley (Eds.), *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment*, 71–88. New York: Wiley.
- Bhargava, A., Carmona, F.F., Bhargava, M., & Srivastava, S. (2012). Approaches for enhanced phytoextraction of heavy metals. *Journal of Environmental Management*, 105, 103–120.
- Bhaskaran, K., Nadaraja, A.V., Tumbath, S., Shah, L.B., & Veetil, P.G. (2013). Phytoremediation of perchlorate by free floating macrophytes. *Journal of Hazardous Materials*, 260, 901–906. 10.1016/j.jhazmat.2013.06.008.
- Bonanno, G., & Vymazal, J. (2017). Compartmentalization of potentially hazardous elements in macrophytes: insights into capacity and efficiency of accumulation. *Journal of Geochemical Exploration*, 181, 22–30.
- Boonyapookana, B., Upatham, E.S., Kruatrachue, M., Pokethitiyook, P., & Singhakaw, S. (2002). Phytoaccumulation and Phytotoxicity of Cadmium and Chromium in Duckweed *Wolffia globosa*. *International Journal of Phytoremediation*, 4(2), 87–100.

- Bora, M.S., & Sarma, K.P. (2020). Phytoremediation of heavy metals/metalloids by native herbaceous macrophytes of wetlands: current research and perspectives. *Emerging Issues in the Water Environment During Anthropocene*, 261–284. Singapore: Springer.
- Bruce, S.L., Noller, B.N., Grigg, A.H., Mullen, B.F., Mulligan, D.R., Ritchie, P.J.,... & Ng, J.C. (2003). A field study conducted at Kidston gold mine, to evaluate the impact of arsenic and zinc from mine tailing to grazing cattle. *Toxicology Letters*, 137, 23–34.
- Cameselle, C., & Gouveia, S. (2019). Phytoremediation of mixed contaminated soil enhanced with electric current. *Journal of Hazardous Materials*, 361, 95–102.
- Chambers, A., Krewski, D., Birkett, N., Plunkett, L., Hertzberg, R., Danzeisen, R.,... & Jones, P. (2010). An exposure-response curve for copper excess and deficiency. *Journal of Toxicology and Environmental Health, Part B*, 13(7-8), 546–578.
- Chandra, R. (Ed.). (2015). *Advances in Biodegradation and Bioremediation of Industrial Waste*. CRC Press.
- Chandra, R., & Kumar, V. (2018). Phytoremediation: a green sustainable technology for industrial waste management. In R. Chandra, N.K. Dubey, & V. Kumar (Eds.), *Phytoremediation of Environmental Pollutants*, 1–42. Boca Raton: Taylor & Francis Group. 10.1201/9781315161549.
- Chandra, R., Saxena, G., & Kumar, V. 2015. Phytoremediation of environmental pollutants: an ecosustainable green technology to environmental management. R. Chandra (Ed.), *Advances in Biodegradation and Bioremediation of Industrial Waste*, 1–29. Boca Raton, FL: CRC Press.
- Chaney, R.L. (1983a). Potential effects of waste constituents on the food chain. J.F. Parr, P.B. Marsh & J.M. Kla (Eds.), *Land Treatment of Hazardous Wastes*, 152–240. Park Ridge, New Jersey, USA: Noyes Data Corp.
- Chaney, R.L. (1983b). Plant uptake of inorganic waste. J.F. Parr, P.B. Marsh and J.M. Kla. (Eds.), *Land Treatment of Hazardous Wastes*, 50–76. Park Ridge, New Jersey, USA: Noyes Data Corp.
- Chaney, R. L., Malik, M., Li, Y. M., Brown, S. L., Brewer, E. P., Angle, J. S., & Baker, A. J. (1997). Phytoremediation of soil metals. *Current Opinion in Biotechnology*, 8(3), 279–284. doi: 10.1016/S0958-1669(97)80004-3.
- Chen, G. (2004). Electrochemical technologies in wastewater treatment. *Separation and Purification Technology*, 38(1), 11–41.
- Chen, J., Yang, L., Yan, X., Liu, Y., Wang, R., Fan, T.,... & Cao, S. (2016). Zinc-finger transcription factor ZAT6 positively regulates cadmium tolerance through the glutathione-dependent pathway in Arabidopsis. *Plant Physiology*, 171(1), 707–719.
- Chen, B.D., Li, X.L., Tao, H.Q., Christie, P., & Wong, M.H. (2003). The role of arbuscular mycorrhizal in zinc uptake by red clover growing in a calcareous soil spiked with various quantities of zinc. *Chemosphere*, 50, 839–846.
- Conesa, M.H., Evangelou, W.H., Robinson, H.B., & Schulin, R. (2012). A critical view of the current state of phytotechnologies to remediate soils: still a promising tool? *Scientific World Journal*, doi: 10.1100/2012/173829.
- Crini, G., & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters*, 17(1), 145–155.
- Crowley, D.E., Wang, Y.C., Reid, C.P.P., & Szaniszlo, P.J. (1991). Mechanisms of iron acquisition from siderophores by microorganisms and plants. In *Iron Nutrition and Interactions in Plants*, 213–232. Dordrecht: Springer.
- da Conceição Gomes, M.A., Hauser-Davis, R.A., de Souza, A.N., & Vitória, A.P. (2016). Metal phytoremediation: general strategies, genetically modified plants and applications in metal nanoparticle contamination. *Ecotoxicology and Environmental Safety*, 134, 133–147.
- Dai, L., Wang, L., Li, L., Liang, T., Zhang, Y., Ma, C., & Xing, B. (2018). Multivariate geostatistical analysis and source identification of heavy metals in the sediment of Poyang Lake in China. *Science of the Total Environment*, 621, 1433–1444.
- DalCorso, G., Fasani, E., Manara, A., Visioli, G., & Furini, A. (2019). Heavy metal pollutions: state of the art and innovation in phytoremediation. *International Journal of Molecular Sciences*, 20, 3412. doi:10.3390/ijms20143412.
- Davison, J. (2005). Risk mitigation of genetically modified bacteria and plants designed for bioremediation. *Journal of Industrial Microbiology and Biotechnology*, 32(11-12), 639–650.
- Dhiman, S.S., Selvaraj, C., Li, J., Singh, R., Zhao, X., Kim, D.,... & Lee, J.K. (2016). Phytoremediation of

- metal-contaminated soils by the hyperaccumulator canola (*Brassica napus* L.) and the use of its biomass for ethanol production. *Fuel*, 183, 107–114.
- Dietz, A.C., & Schnoor, J.L. (2001). Advances in Phytoremediation. *Environmental Health Perspectives*, 109(1), 163–168.
- Dolphen, R., & Thiravetyan, P. (2015). Phytodegradation of Ethanolamines by *Cyperus alternifolius*: effect of Molecular Size. *International Journal of Phytoremediation*, 17(7), 686–692.
- Dong, B., Zhang, R., Gan, Y., Cai, L., Freidenreich, A., Wang, K.,... & Wang, H. (2019). Multiple methods for the identification of heavy metal sources in cropland soils from a resource-based region. *Science of the Total Environment*, 651, 3127–3138.
- Duruibe, J.O., Ogwuegbu, M.O.C., & Ekwurugwu, J.N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences*, 2(5), 112–118.
- Dushenkov, V., Kumar, P.A., Motto, H., & Raskin, I. (1995). Rhizofiltration: the use of plants to remove heavy metals from aqueous streams. *Environmental Science and Technology*, 1239–1245, 1239–1245. doi: 10.1021/es00005a015.
- Ebbs, S.D., Bradfield, S.J., Kumar, P., White, J.C., Musante, C., & Ma, X. (2016). Accumulation of zinc, copper, or cerium in carrot (*Daucus carota*) exposed to metal oxide nanoparticles and metal ions. *Environmental Science: Nano*, 3(1), 114–126. doi: 10.1039/C5EN00161G.
- Eisazadeh, S., Kapourchal, S.A., Homae, M., Noorhosseini, S.A., & Damalas, C.A. (2019). Chive (*Allium schoenoprasum* L.) response as a phytoextraction plant in cadmium-contaminated soils. *Environmental Science and Pollution Research*, 26(1), 152–160.
- Eissa, M.A. (2019). Effect of Compost and Biochar on Heavy Metals Phytostabilization by the Halophytic Plant Old Man Saltbush [*Atriplex Nummularia* Lindl]. *Soil and Sediment Contamination: An International Journal*, 28(2), 135–147.
- Ekperusi, A.O., Sikoki, F.D., & Nwachukwu, E.O. (2019). Application of common duckweed (*Lemna minor*) in phytoremediation of chemicals in the environment: state and future perspective. *Chemosphere*. doi: 10.1016/j.chemosphere.02.025.
- Elad, Y., Cytryn, E., Harel, Y.M., Lew, B., & Graber, E.R. (2012). The biochar effect: plant resistance to biotic stresses. *Phytopathologia Mediterranea*, 50, 335–349.
- Emamjomeh, M.M., & Sivakumar, M. (2009). Review of pollutants removed by electrocoagulation and electrocoagulation/flotation processes. *Journal of Environmental Management*, 90(5), 1663–1679.
- Erakhrumen, A., & Agbontalor, A. (2007). Review phytoremediation: an environmentally sound technology for pollution prevention, control and remediation in developing countries. *Educational Research and Reviews*, 2(7), 151–156.
- Fan, S., Wang, X., Lei, J., Ran, Q., Ren, Y., & Zhou, J. (2019). Spatial distribution and source identification of heavy metals in a typical Pb/Zn smelter in an arid area of northwest China. *Human and Ecological Risk Assessment: An International Journal*, 25(7), 1661–1687.
- Farid, M., Ali, S., Rizwan, M., Ali, Q., Abbas, F., Bukhari, S.A.H.,... & Wu, L. (2017). Citric acid assisted phytoextraction of chromium by sunflower; morpho-physiological and biochemical alterations in plants. *Ecotoxicology and Environmental Safety*, 145, 90–102.
- Farwell, A.J., Vesely, S., Nero, V., Rodriguez, H., McCormack, K., Shah, S.,... Glick, B.R. (2007). Tolerance of transgenic canola plants (*Brassica napus*) amended with plant growth promoting bacteria to flooding stress at a metal contaminated field site. *Environmental Pollution*, 147, 540–545.
- Fasani, E., Manara, A., Martini, F., Furini, A., & DalCorso, G. (2018). The potential of genetic engineering of plants for the remediation of soils contaminated with heavy metals. *Plant, Cell & Environment*, 41(5), 1201–1232. doi: 10.1111/pce.12963.
- Fässler, E., Evangelou, M.W., Robinson, B.H., & Schulin, R. (2010). Effects of indole-3-acetic acid (IAA) on sunflower growth and heavy metal uptake in combination with ethylene diamine disuccinic acid (EDDS). *Chemosphere*, 80, 901–907.
- Fellet, G., Marmiroli, M., & Marchiol, L. (2014). Elements uptake by metal accumulator species grown on mine tailings amended with three types of biochar. *Science of the Total Environment*, 468, 598–608.
- Fister, A.S., Shi, Z., Zhang, Y., Helliwell, E.E., Maximova, S.N., & Guiltinan, M.J. (2016). Protocol: transient expression system for functional genomics in the tropical tree *Theobroma cacao* L. *Plant Methods*, 12(1), 1–13. doi: 10.1186/s13007-016-0119-5.

- Franken, E., Teuschel, U., & Hain, R. (1997). Recombinant proteins from transgenic plants. *Current Opinion in Biotechnology*, 8, 411–416.
- Galal, T.M., Eid, E.M., Dakhil, M.A., & Hassan, L.M. (2018). Bioaccumulation and rhizofiltration potential of *Pistia stratiotes* L. for mitigating water pollution in the Egyptian wetlands. *International Journal of Phytoremediation*, 20(5), 440–447.
- Galal, T.M., Gharib, F.A., Ghazi, S.M., & Mansour, K.H. (2017). Phytostabilization of heavy metals by the emergent macrophyte *Vossia cuspidata* (Roxb.) Griff.: a phytoremediation approach. *International Journal of Phytoremediation*, 19(11), 992–999.
- Garbiscu, C., & Alkorta, I. (2001). Phytoextraction: a cost effective plant based technology for the removal of metals from the environment. *Bioresource Technology*, 77, 229–236.
- Gerhardt, K.E., Gerwing, P.D., & Greenberg, B.M. (2016). Opinion: taking phytoremediation from proven technology to accepted practice. *Plant Science*, 256, 170–185. doi: 10.1016/j.plantsci.2016.11.016.
- Ghazaryan, K.A., Movsesyan, H.S., Minkina, T.M., Sushkova, S.N., & Rajput, V.D. (2019). The identification of phytoextraction potential of *Melilotus officinalis* and *Amaranthus retroflexus* growing on copper-and molybdenum-polluted soils. *Environmental Geochemistry and Health*, 1–9.
- Gleba, D., Borisjuk, N.V., Borisjuk, L.G., Kneer, R., Poulev, A., Skarzhinskaya, M.,... & Raskin, I. (1999). Use of plant roots for phytoremediation and molecular farming. *Proceedings of the National Academy of Sciences*, 96, 5973–5977.
- Glick, B.R., Penrose, D.M., & Li, J. (1998). A model for the lowering of plant ethylene concentrations by plant growth promoting bacteria. *Journal of Theoretical Biology*, 190, 63–68.
- Gomes, M.C., Hauser-Davis, R.A., de Souza, A.N., & Vitória, A.P. (2016). Metal phytoremediation: general strategies, genetically modified plants and applications in metal nanoparticle contamination. *Ecotoxicology and Environmental Safety*, 134, 133–147. doi:10.1016/j.ecoenv.2016.08.024.
- Griboff, J., Wunderlin, D.A., & Monferran, M.V. (2018). Phytofiltration of As³⁺, As⁵⁺, and Hg by the aquatic macrophyte *Potamogeton pusillus* L, and its potential use in the treatment of wastewater. *International Journal of Phytoremediation*, 20(9), 914–921.
- Gupta, N., Yadav, K.K., & Kumar, V. (2015). A review on current status of municipal solid waste management in India. *Journal of Environmental Sciences*, 37, 206–217.
- Hadi, F., Bano, A., & Fuller, M.P. (2010). The improved phytoextraction of lead (Pb) and the growth of maize (*Zea mays* L.): the role of plant growth regulators (GA₃ and IAA) and EDTA alone and in combinations. *Chemosphere*, 80, 457–462.
- Hamon, R., Wundke, J., McLaughlin, M., & Naidu, R. (1997). Availability of zinc and cadmium to different plant species. *Soil Research*, 35(6), 1267–1278.
- Han, D., Cheng, J., Hu, X., Jiang, Z., Mo, L., Xu, H.,... & Wang, H. (2017). Spatial distribution, risk assessment and source identification of heavy metals in sediments of the Yangtze River Estuary, China. *Marine Pollution Bulletin*, 115(1-2), 141–148.
- He, J., Ren, Y., Pan, X., Yan, Y., Zhu, C., & Jiang, D. (2010). Salicylic acid alleviates the toxicity effect of cadmium on germination, seedling growth, and amylase activity of rice. *Journal of Plant Nutrition and Soil Science*, 173, 300–305.
- Hinchman, R.R., Negri, M.C., & Gatliff, E.G. (1995). *Phytoremediation: using green plants to clean up contaminated soil, groundwater, and wastewater*. Retrieved from Argonne National Laboratory Hinchman, Applied Natural Sciences, Inc.: http://www.treemediation.com/Technical/Phytoremediation_1998.pdf.
- Huang, S.H., Bing, P.E.N.G., Yang, Z.H., Chai, L.Y., & Zhou, L.C. (2009). Chromium accumulation, microorganism population and enzyme activities in soils around chromium-containing slag heap of steel alloy factory. *Transactions of Nonferrous Metals Society of China*, 19(1), 241–248.
- Hussein, H.S., Ruiz, O.N., Terry, N., & Daniell, H. (2007). Phytoremediation of mercury and organomercurials in chloroplast transgenic plants: enhanced root uptake, translocation to shoots, and volatilization. *Environmental Science & Technology*, 41(24), 8439–8446.
- Ilić, Z.H., Pajević, S., Borišev, M., & Luković, J. (2020). Assessment of phytostabilization potential of two *Salix* L. clones based on the effects of heavy metals on the root anatomical traits. *Environmental Science and Pollution Research*, 27, 29361–29383. doi: 10.1007/s11356-020-09228-8.
- Islam, M.S., Saito, T., & Kurasaki, M. (2015). Phytofiltration of arsenic and cadmium by using an aquatic

- plant, *Micranthemum umbrosum*: phytotoxicity, uptake kinetics, and mechanism. *Ecotoxicology and Environmental Safety*, 112, 193–200.
- Islam, M.S., Sikder, M.T., & Kurasaki, M. (2017). Potential of *Micranthemum umbrosum* for phytofiltration of organic arsenic species from oxic water environment. *International Journal of Environmental Science and Technology*, 14(2), 285–290.
- Ismail, A., Toriman, M.E., Juahir, H., Zain, S.M., Habir, N.L.A., Retnam, A.,... & Azid, A. (2016). Spatial assessment and source identification of heavy metals pollution in surface water using several chemometric techniques. *Marine Pollution Bulletin*, 106(1-2), 292–300.
- Jabeen, R., Ahmad, A., & Iqbal, M. (2009). Phytoremediation of heavy metals: physiological and molecular mechanisms. *The Botanical Review*, 75(4), 339–364.
- Jaiswal, A., Verma, A., & Jaiswal, P. (2018). Detrimental effects of heavy metals in soil, plants, and aquatic ecosystems and in humans. *Journal of Environmental Pathology, Toxicology and Oncology*, 37(3), 183–197.
- Jeyasingh, J., & Philip, L. (2005). Bioremediation of chromium contaminated soil: optimization of operating parameters under laboratory conditions. *Journal of Hazardous Materials*, 118(1-3), 113–120.
- Kadukova, J., & Kalogerakis, N. (2007). Lead accumulation from non-saline and saline environment by *Tamarix smyrnensis* Bunge. *European Journal of Soil Biology*, 43, 216–223.
- Kadukova, J., & Kavuličova, J. (2011). Phytoremediation of heavy metal contaminated soils – plant stress assessment. In I.A. Golubev (Ed.), *Handbook of Phytoremediation*, 185–222. New York: Nova Science Publishers, Inc.
- Kärenlampi, S., Schat, H., Vangronsveld, J., Verkleij, J.A., van der Lelie, D., Mergeay, M., & Tervahauta, A.I. (2000). Genetic engineering in the improvement of plants for phytoremediation of metal polluted soils. *Environmental Pollution*, 107, 225–231.
- Kathal, R., Malhotra, P., Kumar, L., & Uniyal, P.L. (2016). Phytoextraction of Pb and Ni from the Polluted Soil by *Brassica juncea* L. *Journal of Environmental and Analytical Toxicology*, 6, 394.
- Katoh, M., Risky, E., & Sato, T. (2017). Immobilization of lead migrating from contaminated soil in rhizosphere soil of barley (*Hordeum vulgare* L.) and hairy vetch (*Vicia villosa*) using hydroxyapatite. *International Journal of Environmental Research and Public Health*, 14(10), 1273.
- Kazemipour, M., Ansari, M., Tajrobehkar, S., Majdzadeh, M., & Kermani, H.R. (2008). Removal of lead, cadmium, zinc, and copper from industrial wastewater by carbon developed from walnut, hazelnut, almond, pistachio shell, and apricot stone. *Journal of Hazardous Materials*, 150(2), 322–327.
- Kolesnikov, V.A., Il'in, V.I., & Kolesnikov, A.V. (2019). Electroflotation in wastewater treatment from oil products, dyes, surfactants, ligands, and biological pollutants: a review. *Theoretical Foundations of Chemical Engineering*, 53(2), 251–273.
- Kotrba, P., Najmanova, J., Macek, T., Ruml, T., & Mackova, M. (2009). Genetically modified plants in phytoremediation of heavy metal and metalloids soil and sediment pollution. *Biotechnology Advances*, 27(6), 799–810.
- Krämer, U., & Chardonay, A. (2001). The use of transgenic plants in the bioremediation of soils contaminated with trace elements. *Applied Microbiology and Biotechnology*, 55, 661–672.
- Kumar, B., Smita, K., & Flores, L.C. (2017). Plant mediated detoxification of mercury and lead. *Arabian Journal of Chemistry*, 10, S2335–S2342.
- Kumar, P.A., Dushenkov, V., Motto, H., & Raskin, I. (1995). Phytoextraction: the use of plants to remove heavy metals from soils. *Environmental Science and Technology*, 29, 1232–1238. doi:10.1021/es00005a014.
- Kumar, V., & Chandra, R. (2017). Phytoremediation: a green sustainable technology for industrial waste management. In *Phytoremediation of Environmental Pollutants*, 15–56. Boca Raton: CRC Press.
- Kumari, M., & Tripathi, B.D. (2015). Efficiency of *Phragmites australis* and *Typha latifolia* for heavy metal removal from wastewater. *Ecotoxicology and Environmental Safety*, 112, 80–86.
- Lalor, G.C. (2008). Review of cadmium transfers from soil to humans and its health effects in the Jamaican environment. *Science of the Total Environment*, 400(1-3), 162–172.
- Lasat, M.M. (2000). Phytoextraction of toxic metals: a review of biological mechanisms. *Journal of Environmental Quality*, 31, 109–125.
- Li, C., Wang, M., & Luo, X. (2019). Uptake of uranium from aqueous solution by *Nymphaea tetragona* Georgi: the effect of the accompanying heavy metals. *Applied Radiation and Isotopes*, 150, 157–163.
- Li, J.-T., Liao, B., Lan, C.Y., Ye, Z.H., Baker, A.J., & Shu, W.S. (2010). Cadmium accumulation in a high-

- biomass tropical tree (*Averrhoa carambola*) and its potential for phytoextraction. *Journal of Environmental Quality*, 39(4), 1262–1268.
- Liang, S.X., Jin, Y., Liu, W., Li, X., Shen, S.G., & Ding, L. (2017). Feasibility of Pb phytoextraction using nano-materials assisted ryegrass: results of a one-year field-scale experiment. *Journal of Environmental Management*, 190, 170–175.
- Liao, J.P., Lin, X.G., Cao, Z.H., Shi, Y.Q., & Wong, M.H. (2003). Interactions between arbuscular mycorrhizae and heavy metals under a sand culture experiment. *Chemosphere*, 50, 847–853.
- Limmer, M., & Burken, J. (2016). Phytovolatilization of organic contaminants. *Environmental Science & Technology*, 50(13), 6632–6643.
- Liu, N., & Wu, Z. (2018). Toxic effects of linear alkylbenzenesulfonate on *Chara vulgaris* L. *Environmental Science and Pollution Research*, 4934–4941.
- Liu, Y., Liu, N., Zhou, Y., Wang, F., Zhang, Y., & Wu, Z. (2019). Growth and physiological responses in *Myriophyllum spicatum* L. exposed to linear alkylbenzenesulfonate. *Environmental Toxicology and Chemistry*, 38(9), 2073–2081. doi: 10.1002/etc.4475.
- Liu, D., An, Z., Mao, Z., Ma, L., & Lu, Z. (2015). Enhanced heavy metal tolerance and accumulation by transgenic sugar beets expressing *Streptococcus thermophilus* StGCS-GS in the presence of Cd, Zn and Cu alone or in combination. *PLoS One*, 10(6), e0128824.
- Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., & Paz Ferreira, J. (2013). Biochar's effect on crop productivity and the dependence on experimental conditions a meta-analysis of literature data. *Plant Soil*, 373, 583–594.
- Liu, D., Jiang, W., Liu, C., Xin, C., & Hou, W. (2000a). Uptake and accumulation of lead by roots, hypocotyls and shoots of Indian mustard [*Brassica juncea* (L.)]. *Bioresource Technology*, 71(3), 273–277.
- Liu, J.R., Suh, M.C., & Choi, D. (2000b). Phytoremediation of cadmium contamination: overexpression of metallothionein in transgenic tobacco plants. *Burdesgesundheitsbl Gesundheitsforsch-Gesundheitsschutz*, 2, 126–130.
- Luo, J., Yang, D., Qi, S., Wu, J., & Gu, X.S. (2018). Using solar cell to phytoremediate field-scale metal polluted soil assisted by electric field. *Ecotoxicology and Environmental Safety*, 165, 404–410.
- Ma, N., Wang, W., Gao, J., & Chen, J. (2017). Removal of cadmium in subsurface vertical flow constructed wetlands planted with *Iris sibirica* in the low-temperature season. *Ecological Engineering*, 109, 48–56.
- Macek, T., Pavlikova, D., & Mackova, M. (2004). Phytoremediation metals and Inorganic Pollutants. In A. Singh & O.P. Ward (Eds.), *Applied Bioremediation and Phytoremediation (Vol. 1)*, 135–157. Berlin, Heidelberg, New York: Springer-Verlag.
- Macek, T., Mackova, M., & Kas, J. (2000). Exploitation of plants for the removal of organics in environmental remediation. *Biotechnology Advances*, 18, 23–35.
- Mahar, A., Wang, P., Ali, A., Awasthi, M.K., Lahori, A.H., Wang, Q.,... & Zhang, Z. (2016). Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. *Ecotoxicology and Environmental Safety*, 126, 111–121.
- Manousaki, E., Kadukova, J., Papadantonakis, N., & Kalogerakis, N. (2008). Phytoextraction and phytoexcretion of Cd by the leaves of *Tamarix smyrnensis* growing on contaminated non saline and saline soils. *Environmental Research*, 106(3), 326–332.
- Mao, X., Han, F.X., Shao, X., Guo, K., McComb, J., Arslan, Z., & Zhang, Z. (2016). Electro-kinetic remediation coupled with phytoremediation to remove lead, arsenic and cesium from contaminated paddy soil. *Ecotoxicology and Environmental Safety*, 125, 16–24.
- Marrugo-Negrete, J., Durango-Hernández, J., Pinedo-Hernández, J., Olivero-Verbel, J., & Díez, S. (2015). Phytoremediation of mercury-contaminated soils by *Jatropha curcas*. *Chemosphere*, 127, 58–63.
- Marschner H. (1995). *Mineral Nutrition of Higher Plants*. Cambridge: Academic Press.
- Mastretta, C., Barac, T., Vangronsveld, J., Newman, L., Taghavi, S., & Lelie, D.V.D. (2006). Endophytic bacteria and their potential application to improve the phytoremediation of contaminated environments. *Biotechnology and Genetic Engineering Reviews*, 23(1), 175–188.
- McGrath, S.P., Zhao, F.J., & Lombi, E. (2002). Phytoremediation of metals, metalloids, and radionuclides. *Advances in Agronomy*, 75, 1–56.
- Mleczeck, M., Gąsecka, M., Waliszewska, B., Magdziak, Z., Szostek, M., Rutkowski, P.,... & Niedzielski, P. (2018). *Salix viminalis* L.-A highly effective plant in phytoextraction of elements. *Chemosphere*, 212, 67–78.
- Moameri, M., & Khalaki, M.A. (2017). Capability of *Secale montanum* trusted for phytoremediation of lead

- and cadmium in soils amended with nano-silica and municipal solid waste compost. *Environmental Science and Pollution Research*, 1–8.
- Montes-Holguin, M.O., Peralta-Videa, J.R., Meitzner, G., Martinez-Martinez, A., de la Rosa, G., Castillo-Michel, H.A., & Gardea-Torresdey, J.L. (2006). Biochemical and spectroscopic studies of the response of *Convolvulus arvensis* L. to chromium (III) and chromium (VI) stress. *Environmental Toxicology and Chemistry: An International Journal*, 25(1), 220–226.
- Mueller, N.C., & Nowack, B. (2010). Nanoparticles for remediation: solving big problems with little particles. *Elements*, 6, 395–400.
- Mueller, B., Rock, S., Gowswami, D., & Ensley, D. (1999). Phytoremediation decision tree. *Prepared by Interstate Technology and Regulatory Cooperation Work Group*, 1–36.
- Mwegoha, W.J. (2008). The use of phytoremediation technology for abatement soil and groundwater pollution in Tanzania: opportunities and challenges. *Journal of Sustainable Development in Africa*, 10(1), 140–156.
- Nawrath, C., Poirier, Y., & Somerville, C. (1995). Plant polymers for biodegradable plastics: cellulose, starch and polyhydroxyalkanoates. *Molecular Breeding*, 1, 105–122.
- Neag, E., Malschi, D., & Măicăneanu, A. (2018). Isotherm and kinetic modelling of Toluidine Blue (TB) removal from aqueous solution using *Lemna minor*. *International Journal of Phytoremediation*, 20, 1049–1054. doi: 10.1080/15226514.2018.1460304.
- Odum, H.T. (Ed.). (2016). *Heavy Metals in the Environment: Using Wetlands for their Removal*. 19–344. Boca Raton: CRC Press. doi: 10.1201/9781420032840.
- Ogunlaja, A., Ogunlaja, O.O., Okewole, D.M., & Morenikeji, O.A. (2019). Risk assessment and source identification of heavy metal contamination by multivariate and hazard index analyses of a pipeline vandalised area in Lagos State, Nigeria. *Science of the Total Environment*, 651, 2943–2952.
- Omotade, I.F., Alatise, M.O., Olanrewaju, O.O. Recycling of aquaculture wastewater using charcoal based constructed wetlands. *International Journal of Phytoremediation*, 21 (2019), 399–404. doi: 10.1080/15226514.2018.1537247.
- Ouyang, Y. (2002). Phytoremediation: modelling plant uptake and contaminant transport in the soil-plant-atmosphere continuum. *Journal of Hydrology*, 266, 66–82.
- Ovečka, M., & Takáč, T. (2014). Managing heavy metal toxicity stress in plants: biological and biotechnological tools. *Biotechnology Advances*, 32(1), 73–86.
- Patra, D.K., Pradhan, C., & Patra, H.K. (2020). Toxic metal decontamination by phytoremediation approach: concept, challenges, opportunities and future perspectives. *Environmental Technology & Innovation*, 18, 100672.
- Paz-Ferreiro, J., Lu, H., Fu, S., Méndez, A., & Gascó, G. (2014). Use of phytoremediation and biochar to remediate heavy metal polluted soils: a review. *Solid Earth*, 5, 65–75.
- Peng, J.S., Ding, G., Meng, S., Yi, H.Y., & Gong, J.M. (2017). Enhanced metal tolerance correlates with heterotypic variation in SpMTL, a metallothionein-like protein from the hyperaccumulator *Sedum plumbizincicola*. *Plant, Cell & Environment*, 40(8), 1368–1378.
- Pentyala, V.B., & Eapen, S. (2020). High-efficiency phytoextraction of uranium using *Vetiveria zizanioides* L. Nash. *International Journal of Phytoremediation*, 1–10.
- Pereira, B.F., De-Abreu, C.A., Herpin, U., De-Abreu, M.F., & Berton, R.S. (2010). Phytoremediation of lead by jack beans on a rhodic hapludox amended with EDTA. *Scientia Agricola*, 67, 308–318.
- Pilon-Smits, E.A., Hwang, S., Lytle, C.M., Zhu, Y., Tai, J.C., Bravo, R.C.,... & Terry, N. (1999). Overexpression of ATP sulfurylase in Indian mustard leads to increased selenate uptake, reduction, and tolerance. *Plant Physiology*, 119(1), 123–132.
- Pivet, B.E. (2001). *Phytoremediation of Contaminated Soil and Ground Water at Hazardous Waste Sites*. US Environmental Protection Agency, Office of Research and Development, Office of Solid Waste and Emergency Response.
- Popova, L.P., Maslenskova, L.T., Ivanova, A., & Stoinova, Z. (2012). Role of salicylic acid in alleviating heavy metal stress. In *Environmental Adaptations and Stress Tolerance of Plants in the Era of Climate Change*, 447–466. New York: Springer.
- Rahbar, A., Farjadfard, S., Leili, M., Kafaei, R., Haghshenas, V., & Ramavandi, B. (2016). Experimental data

- of biomaterial derived from *Malva sylvestris* and charcoal tablet powder for Hg²⁺ removal from aqueous solutions. *Data in Brief*, 8, 132–135.
- Rahman, M.A., Reichman, S.M., De Filippis, L., Sany, S.B.T., & Hasegawa, H. (2016). Phytoremediation of toxic metals in soils and wetlands: concepts and applications. In *Environmental Remediation Technologies for Metal-contaminated Soils*, 161–195. Tokyo: Springer.
- Rai, P.K. (2018). *Phytoremediation of Emerging Contaminants in Wetlands*. Boca Raton: Taylor & Francis Group.
- Rai, P.K., & Chutia, B. (2016). Biomagnetic monitoring through *Lantana* leaves in an Indo-Burma hot spot region. *Environmental Skeptics and Critics*, 5(1), 1–11.
- Rai, P.K., & Singh, M.M. (2015). *Lantana camara* invasion in urban forests of an Indo-Burma hotspot region and its ecosustainable management implication through biomonitoring of particulate matter. *Journal of Asia-Pacific Biodiversity*, 8, 375–381.
- Rakhshaei, R., Giasi, M., & Pourahmad, A. (2009). Studying the effect of cell wall's carboxyl-carboxylate ratio change of *Lemna minor* to remove heavy metals from aqueous solution. *Journal of Hazardous Materials*, 163(1), 165–173.
- Ramamurthy, A.S., & Memarian, R. (2012). Phytoremediation of mixed soil contaminants. *Water, Air, & Soil Pollution*, 223, 511–518.
- Rámila, C.D.P., Contreras, S.A., Domenico, C.D., Montenegro, M.A.M., Vega, A., Handford, M., Bonilla, C.A., & Pizarro, G.E. (2016). Boron stress response and accumulation potential of the extremely tolerant species *Puccinellia frigid*. *Journal of Hazardous Materials*, 317, 476–484.
- Randelović, D., Gajić, G., Mutić, J., Pavlović, P., Mihailović, N., & Jovanović, S. (2016). Ecological potential of *Epilobium dodonaei* Vill. for restoration of metalliferous mine wastes. *Ecological Engineering*, 95, 800–810.
- Raskin, I., Salt, D.E., & Smith, R.D. (1998). Phytoremediation. *Plant Molecular Biology*, 49, 643–668.
- Reisinger, S., Schiavon, M., Terry, N., & Pilon-Smits, E.A. (2008). Heavy metal tolerance and accumulation in Indian mustard (*Brassica juncea* L.) expressing bacterial γ -glutamylcysteine synthetase or glutathione synthetase. *International Journal of Phytoremediation*, 10(5), 440–454.
- Rezania, S., Taib, S.M., Din, M.F.M., Dahalan, F.A., & Kamyab, H. (2016). Comprehensive review on phytotechnology: heavy metals removal by diverse aquatic plants species from wastewater. *Journal of Hazardous Materials*, 318, 587–599.
- Rodriguez, L., Lopez-Bellido, F.J., Carnicer, A., Recreo, F., Tallos, A., & Monteagudo, J.M. (2005). Mercury recovery from soils by phytoremediation. In *Book of Environmental Chemistry*, 197–204. Berlin, Germany: Springer.
- Ruffini-Castiglione, M., & Cremonini, R. (2009). Nanoparticles and higher plants. *Caryologia*, 62, 161–165.
- Ryslava, E., Krejčík, Z., Macek, T., Novakova, H., Demnerova, K., & Mackova, M. (2003). Study of PCB degradation in real contaminated soil. *Fresenius Environmental Bulletin*, 12, 296–301.
- Saha, P., Shinde, O., & Sarkar, S. (2017). Phytoremediation of industrial mines wastewater using water hyacinth. *International Journal of Phytoremediation*, 19, 87–96.
- Saifullah, M.E., Qadir, M., de Caritat, P., Tack, F.M., Du Laing, G., & Zia, H. (2009). EDTA-assisted Pb phytoextraction. *Chemosphere*, 74, 1279–1291.
- Saleem, M.H., Fahad, S., Adnan, M., Ali, M., Rana, M.S., Kamran, M.,... & Hussain, R.M. (2020). Foliar application of gibberellic acid endorsed phytoextraction of copper and alleviates oxidative stress in jute (*Corchorus capsularis* L.) plant grown in highly copper-contaminated soil of China. *Environmental Science and Pollution Research*, 1–13.
- Salt, D. E., Smith, R.D., & Raskin, I. (1998). Phytoremediation. *Annual Review of Plant Biology*, 49(1), 643–668.
- Sandhi, A., Landberg, T., & Greger, M. (2018). Phytofiltration of arsenic by aquatic moss (*Warnstorffia fluitans*). *Environmental Pollution*, 237, 1098–1105.
- Saran, A., Fernandez, L., Cora, F., Savio, M., Thijs, S., Vangronsveld, J., & Merini, L.J. (2020). Phytostabilization of Pb and Cd polluted soils using *Helianthus petiolaris* as pioneer aromatic plant species. *International Journal of Phytoremediation*, 22(5), 459–467.
- Sarwar, N., Imran, M., Shaheen, M.R., Ishaque, W., Kamran, M.A., Matloob, A.,... & Hussain, S. (2017). Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. *Chemosphere*, 171, 710–721. doi:10.1016/j.chemosphere.2016.12.116.
- Sarwar, N., Ishaq, W., Farid, G., Shaheen, M.R., Imran, M., Geng, M., & Hussain, S. (2015). Zinc–cadmium

- interactions: impact on wheat physiology and mineral acquisition. *Ecotoxicology and Environmental Safety*, 122, 528–536.
- Saxena, G., Purchase, D., Mulla, S.I., Saratale, G.D., & Bharagava, R.N. (2019). Phytoremediation of heavy metal-contaminated sites: eco-environmental concerns, field studies, sustainability issues and future prospects. *Reviews of Environmental Contamination and Toxicology*, doi: 10.1007/398_2019_24.
- Schnoor, J.L., Licht, L.A., McCutcheon, S.C., Wolfe, N.L., & Carreira, L.H. (1995). Phytoremediation of organic contaminants. *Environmental Science & Technology*, 29, 318–323.
- Schwitzguébel, J.-P. (2002). Hype or hope: the potential of phytoremediation as an emerging green technology. *Federal Facilities Environmental Journal*, 109–125.
- Seth, C.S. (2012). A review on mechanisms of plant tolerance and role of transgenic plants in environmental clean-up. *The Botanical Review*, 78(1), 32–62.
- Shahedi, A., Darban, A.K., Taghipour, F., & Jamshidi-Zanjani, A. (2020). A review on industrial wastewater treatment via electrocoagulation processes. *Current Opinion in Electrochemistry*, 22, 154–169. doi: 10.1016/j.coelec.2020.05.009.
- Shaffer, R.E., Cross, J.O., Rose-Pehrsson, S.L., & Elam, W.T. (2001). Speciation of chromium in simulated soil samples using X-ray absorption spectroscopy and multivariate calibration. *Analytica Chimica Acta*, 442(2), 295–304.
- Shah, F.U.R., Ahmad, N., Masood, K.R., & Peralta-Videa, J.R. (2010). Heavy metal toxicity in plants. *In-Plant Adaptation and Phytoremediation*, 71–97. Dordrecht: Springer.
- Sharma, S., Singh, S., & Manchanda, V.K. (2014). Phytoremediation: role of terrestrial plants and aquatic plants and aquatic macrophytes in the remediation of radionuclides and heavy metal contaminated soil and water. *Environmental Science and Pollution Research*, doi: 10.1007/s11356-014-3635-8.
- Sheng, X.F., & Xia, J.J. (2006). Improvement of rape (*Brassica napus*) plant growth and cadmium uptake by cadmium-resistant bacteria. *Chemosphere*, 64, 1036–1042.
- Sheoran, V., Sheoran, A.S., & Poonia, P. (2016). Factors affecting phytoextraction: a review. *Pedosphere*, 26(2), 148–166.
- Shewry, P.R., & Peterson, P.J. (1974). The uptake and transport of chromium by barley seedlings (*Hordeum vulgare* L.). *Journal of Experimental Botany*, 25(4), 785–797.
- Sidhu, G.P.S., Bali, A.S., Singh, H.P., Batish, D.R., & Kohli, R.K. (2018). Ethylenediamine disuccinic acid-enhanced phytoextraction of nickel from contaminated soils using *Coronopus didymus* (L.) Sm. *Chemosphere*, 205, 234–243.
- Singh, J., & Lee, B.K. (2016). Influence of nano-TiO₂ particles on the bioaccumulation of Cd in soybean plants (*Glycine max*): a possible mechanism for the removal of Cd from the contaminated soil. *Journal of Environmental Management*, 170, 88–96.
- Singh, M.M., & Rai, P.K. (2016). Microcosm investigation of Fe (iron) removal using macrophytes of Ramsar Lake: a phytoremediation approach. *International Journal of Phytoremediation*, 18(12), 1231–1236.
- Skeffington, R.A., Shewry, P.R., & Peterson, P.J. (1976). Chromium uptake and transport in barley seedlings (*Hordeum vulgare* L.). *Planta*, 132(3), 209–214.
- Sobha, K., Poornima, A., Harini, P., & Veeraiah, K. (2007). A study on biochemical changes in the fresh water fish, *Catla catla* (Hamilton) exposed to the heavy metal toxicant cadmium chloride. *Kathmandu University Journal of Science, Engineering and Technology*, 3(2), 1–11.
- Souza, L.A., Piotto, F.A., Nogueiro, R.C., & Azevedo, R.A. (2013). Use of non-hyperaccumulator plant species for the phytoextraction of heavy metals using chelating agents. *Scientia Agricola*, 70, 290–295.
- Stephenson, C., & Black, C.R. (2014). One step forward, two steps back: the evolution of phytoremediation into commercial technologies. *Bioscience Horizons*, 7, 1–15.
- Stern, B.R., Solioz, M., Krewski, D., Aggett, P., Aw, T.C., Baker, S.,... & Keen, C. (2007). Copper and human health: biochemistry, genetics, and strategies for modeling dose-response relationships. *Journal of Toxicology and Environmental Health, Part B*, 10(3), 157–222.
- Sun, S., Zhou, X., Cui, X., Liu, C., Fan, Y., McBride, M.B.,... & Zhuang, P. (2020). Exogenous plant growth regulators improved phytoextraction efficiency by *Amaranthus hypochondriacus* L. in cadmium contaminated soil. *Plant Growth Regulation*, 90(1), 29–40.
- Sut-Lohmann, M., Jonczak, J., & Raab, T. (2020). Phytofiltration of chosen metals by aquarium liverwort (*Monosoleum tenerum*). *Ecotoxicology and Environmental Safety*, 188, 109844.

- Syam Babu, D., Anantha Singh, T.S., Nidheesh, P.V., & Suresh Kumar, M. (2019). Industrial wastewater treatment by electrocoagulation process. *Separation Science and Technology*, 1–33.
- Tang, C., Song, J., Hu, X., Hu, X., Zhao, Y., Li, B.,... & Peng, L. (2017). Exogenous spermidine enhanced Pb tolerance in *Salix matsudana* by promoting Pb accumulation in roots and spermidine, nitric oxide, and antioxidant system levels in leaves. *Ecological Engineering*, 107, 41–48.
- Tangahu, B.V., Abdullah, S.R., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). A Review on Heavy Metals (As, Pb, and Hg) Uptake by Plants through Phytoremediation. *International Journal of Chemical Engineering*. doi:10.1155/2011/939161.
- Tariq, S.R., & Ashraf, A. (2016). Comparative evaluation of phytoremediation of metal contaminated soil of firing range by four different plant species. *Arabian Journal of Chemistry*, 9(6), 806–814.
- Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K., & Sutton, D.J. (2012). Heavy metal toxicity and the environment. In *Molecular, Clinical and Environmental Toxicology*, 133–164. Basel: Springer.
- Ugya, A.Y., Hua, X., & Ma, J. (2019). Phytoremediation as a tool for the remediation of wastewater resulting from dyeing activities. *Applied Ecology and Environmental Research*, 17(2), 3723–3735.
- UNEP. (2016). United Nations Environment Programme. *Phytoremediation: An Environmentally Sound Technology for Pollution Prevention, Control and Remediation, Newsletter and Technical Publications, Freshwater Management Series No. 2*.
- USEPA (Environmental Protection Agency). (2000). *Introduction to Phytoremediation*. Retrieved from National Risk Management Research Laboratory, EPA/600/R-99/107: <http://www.clu-in.org/download/remed/introphyto.pdf>
- Uysal, Y. (2013). Removal of chromium ions from wastewater by duckweed, *Lemna minor* L. by using a pilot system with continuous flow. *Journal of Hazardous Materials*, 263, 486–492. doi: 10.1016/j.jhazmat.2013.10.006.
- Valadi, A.S., Hatamzadeh, A., & Sedaghatthoor, S. (2019). Study of the accumulation of contaminants by *Cyperus alternifolius*, *Lemna minor*, *Eichhornia crassipes*, and *Canna generalis* in some contaminated aquatic environments. *Environmental Science and Pollution Research*, 26, 21340–21350. doi: 10.1007/s11356-019-05203-0.
- Vamerali, T., Bandiera, M., Hartley, W., Carletti, P., & Mosca, G. (2011). Assisted phytoremediation of mixed metal (loid)-polluted pyrite waste: effects of foliar and substrate IBA application on fodder radish. *Chemosphere*, 84, 213–219.
- Van Ginneken, L., Meers, E., Guissson, R., Ruttens, A., Elst, K., Tack, F.M.,... & Dejonghe, W. (2007). Phytoremediation for heavy metal-contaminated soils combined with bioenergy production. *Journal of Environmental Engineering and Landscape Management*, 15(4), 227–236.
- Vangronsveld, J., Herzig, R., Weyens, N., Boulet, J., Adriaensen, K., Ruttens, A.,... & Mench, M. (2009). Phytoremediation of contaminated soils and groundwater: lessons from the field. *Environmental Science and Pollution Research*, 16, 765–794.
- Vassil, A.D., Kapulnik, Y., Raskin, I., & Salt, D.E. (1998). The Role of EDTA in Lead Transport and Accumulation by Indian Mustard. *Plant Physiology*, 117, 447–453. DOI: 10.1104/pp.117.2.447.
- Vishnoi, S.R., & Srivastava, P.N. (2008). Phytoremediation—green for environmental clean. In *Proceedings of Taal2007: the 12th World Lake Conference (Vol. 1016)*, 1021.
- Vymazal, J. (2016). Concentration is not enough to evaluate accumulation of heavy metals and nutrients in plants. *Science of the Total Environment*, 544, 495–498.
- Vymazal, J., & Březinová, T. (2016). Accumulation of heavy metals in aboveground biomass of *Phragmites australis* in horizontal flow constructed wetlands for wastewater treatment: a review. *Chemical Engineering Journal*, 290, 232–242.
- Wolfenbarger, L.L., & Phifer, P.R. (2000). The ecological risks and benefits of genetically engineered plants. *Science*, 290(5499), 2088–2093.
- Xia, Y., Liu, J., Wang, Y., Zhang, X., Shen, Z., & Hu, Z. (2018). Ectopic expression of *Vicia sativa* Caffeoyl-CoA O-methyltransferase (VsCCoAOMT) increases the uptake and tolerance of cadmium in *Arabidopsis*. *Environmental and Experimental Botany*, 145, 47–53.
- Xiao, S., Gao, W., Chen, Q.F., Ramalingam, S., & Chye, M.L. (2008). Overexpression of membrane-associated acyl-CoA-binding protein ACBP1 enhances lead tolerance in *Arabidopsis*. *The Plant Journal*, 54(1), 141–151.

- Yadav, K.K., Gupta, N., Kumar, A., Reece, L.M., Singh, N., Rezaia, S., & Khan, S.A. (2018). Mechanistic understanding and holistic approach of phytoremediation: a review on application and future prospects. *Ecological Engineering*, 120, 274–298.
- Yadav, K.K., Gupta, N., Kumar, V., & Singh, J.K. (2017). Bioremediation of heavy metals from contaminated sites using potential species: a review. *Indian Journal of Environmental Protection*, 37(1), 65.
- Yaseen, D.A., & Scholz, M. (2017). Comparison of experimental ponds for the treatment of dye wastewater under controlled and semi-natural conditions. *Environmental Science and Pollution Research International*, 24, 16031–16040.
- Yau, Y.Y., & Stewart, C.N. (2013). Less is more: strategies to remove marker genes from transgenic plants. *BMc Biotechnology*, 13(1), 36.
- Yuanan, H., He, K., Sun, Z., Chen, G., & Cheng, H. (2020). Quantitative source apportionment of heavy metal (loid) s in the agricultural soils of an industrializing region and associated model uncertainty. *Journal of Hazardous Materials*, 391, 122244.
- Zaidi, S.S., Usmani, B.R., & Singh, M.J. (2006). Significance of *Bacillus subtilis* strain SJ–101 as a bioinoculant for concurrent plant growth promotion and nickel accumulation in *Brassica juncea*. *Chemosphere*, 64, 991–997.
- Zayed, A.M., & Terry, N. (2003). Chromium in the environment: factors affecting biological remediation. *Plant and Soil*, 249(1), 139–156.
- Zhang, Y., Wu, D., Wang, C., Fu, X., & Wu, G. (2020a). Impact of coal power generation on the characteristics and risk of heavy metal pollution in nearby soil. *Ecosystem Health and Sustainability*, 6(1), 1787092.
- Zhang, M., Wang, X., Liu, C., Lu, J., Qin, Y., Mo, Y.,... & Liu, Y. (2020b). Identification of the heavy metal pollution sources in the rhizosphere soil of farmland irrigated by the Yellow River using PMF analysis combined with multiple analysis methods – using Zhongwei city, Ningxia, as an example. *Environmental Science and Pollution Research*, 1–12.
- Zhou, J., Wu, Z., Yu, D., Pang, Y., Cai, H., & Liu, Y. (2018). Toxicity of linear alkylbenzene sulfonate to aquatic plant *Potamogeton perfoliatus* L. *Environmental Science and Pollution Research*, 25, 32303–32311.