# Chapter 15
# Phytoremediation Application: Plants as Biosorbent for Metal Removal in Soil and Water

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**Abstract** Phytoremediation for metal-contaminated soils was started about 40 years ago, and the phytoremediation for organic pollutants is more recent. Phytoremediation has gained extensive attention and much progress in remediation of inorganic and organic contaminants and as the means for enhanced phytoremediation. Phytoremediation of various inorganic pollutants such as Cd, Cr, Pb, Cu, Zn, Co, Ni, Se, Cs, and As has been extensively studied. This is mainly based on the use of natural hyperaccumulator plants with exceptional metal-accumulating capacity, which can take up metals to concentrations at least an order of magnitude greater than the normal plants growing in the same environment. These plants have several beneficial characteristics such as the ability to accumulate metals in their shoots and an exceptionally high tolerance to heavy metals.

**Keywords** Phytoremediation • Heavy metal contamination • Hyperaccumulator plants • Phytoextraction • Phytostabilization • Phytovolatilization • Rhizofiltration

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## 15.1 Introduction

Phytoremediation for metal-contaminated soils was started about 40 years ago, and the phytoremediation for organic pollutants is more recent. Phytoremediation has gained extensive attention and much progress in remediation of inorganic and organic contaminants and as the means for enhanced phytoremediation. Phytoremediation of various inorganic pollutants such as Cd, Cr, Pb, Cu, Zn, Co, Ni, Se, Cs, and As has been extensively studied. This is mainly based on the use of natural hyperaccumulator plants with exceptional metal-accumulating capacity, which can take up metals to concentrations at least an order of magnitude greater than the normal plants growing in the same environment. These plants have several beneficial characteristics such as the ability to accumulate metals in their shoots and an exceptionally high tolerance to heavy metals.

At present, there are totally more than 400 species of hyperaccumulator plants for As, Cd, Mn, Ni, Zn, etc. Phytoremediation is a general term including several processes, in function of the plant-soil-atmosphere interactions. For heavy metal-contaminated soil, four processes of phytoremediation are recognized: phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration. The first two mechanisms are the most reliable. The different forms of phytoremediation require different general plant characteristics for optimum effectiveness [1].

## 15.2 Definition and Concept

Phytoremediation can be defined as the process, which uses green plants for the relief, transfer, stabilization, or degradation of pollutants from soil, sediments, surface waters, and groundwater. Some plant roots can absorb and immobilize metal pollutants, while other plant species have the ability of metabolizing or accumulating organic and nutrient contaminants [2]. Multifarious relationships and interactions between plants, microbes, soils, and contaminants make these numerous phytoremediation processes possible. The term phytoremediation, from the Greek phyto, means “plant”, and the Latin suffix remedium, “able to cure” or “restore”. It can be used for a wide range of organic and inorganic contaminants [2]. Phytoremediation processes are most effective where contaminants are present at low to medium levels, as high contaminant levels can inhibit plant and microbial growth and activity [3]. Mechanisms involved in the uptake, translocation, and storage of micronutrients are the same involved to translocate and storage heavy metals [1].

Phytoremediation is considered an economical and environmentally friendly method of exploiting plants to extract contaminants from soil [4]. This process is relatively cost-effective compared with other remediation techniques. However, a thorough economic analysis for this process is unavailable. Most phytoremediation studies are directed at the biological, biochemical, and agronomic processes [5]. An economic outlook, instead of simple estimates of the cost advantages of phytoremediation over other techniques, has not been reported.

## 15.3 Advantages and Limitations of Phytoremediation Mechanisms

Phytoremediation, like other remediation technologies, has a range of both advantages and disadvantages. The most positive aspect of using phytoremediation is as follow: (1) more cost-effective; (2) more environmentally friendly; (3) applicable to a wide range of toxic metals, and (4) more aesthetically pleasing method. On the other hand, phytoremediation presents some limitations. It is a lengthy process, thus it may take several years or longer to clean up a site and it is only applicable to surface soils [6].

Prior to phytoremediation field trials, extensive research was performed in laboratories and greenhouses. Some of this work explored the effects of plants on removal of contaminants from spiked soil and soil excavated from contaminated sites. Many of these experiments provided valuable insights into the types and specific mechanisms of phytoremediation of organic contaminants [7]. Some organic compounds can be transported across plant membranes. Of these, the low molecular weight compounds can often be removed from the soil and released through leaves via evapotranspiration processes (phytovolatilization). Some of the non-volatile compounds can be degraded or rendered non-toxic via enzymatic modification and sequestration in plants (phytodegradation, phytoextraction). Other compounds are stable in the plants and can be removed along with the biomass for sequestration or incineration.

## 15.4 Basics of Phytoremediation Process

The discovery of metal-accumulating properties in certain plants leads to the development of phytoremediation technology. Research in the field of phytoremediation is aiming to develop innovative, economical, and environmentally compatible approaches to remove heavy metals from the environment. Even apart from the metal hyperaccumulating property of the plants, the presence of ground cover with plants helps to shield people from direct contact with the soil and prevents the blowing of contaminated dust around the neighbourhood [8].

## 15.5 Types of Phytoremediation Technologies

Depending upon the process by which plants are removing or reducing the toxic effect of contaminants from the soil, phytoremediation technology can be broadly classified as follows [9].

### *15.5.1 Phytoextraction*

This is the process of using pollutant-accumulating plants to remove metals or organics from soil by concentrating them in harvestable plant parts.

### *15.5.2 Phytotransformation*

This is the partial or total degradation of complex organic molecules by their incorporation into plant tissues.

### *15.5.3 Phytostimulation*

In this process, the release of plant exudates or enzymes into the root zone stimulates the microbial and fungal degradation of organic pollutants.

### *15.5.4 Phytostabilization*

This is a method that uses plants to reduce mobility of contaminants (both organic and metallic contaminants) by preventing erosion, leaching, or runoff and to reduce bioavailability of pollutants in the environment, thereby preventing their migration to groundwater or their entry into the food chain [10].

### *15.5.5 Phytovolatilization*

This is the technique of using plants to volatilize pollutants or metabolites. This technology can be used for volatile organic carbons (VOCs) and for the few inorganics that can exist in volatile forms such as selenium and mercury [10].

### *15.5.6 Rhizo-Filtration*

This is the use of plant roots to absorb or adsorb pollutants, mainly metals, but also organic pollutants, from water and aqueous waste streams.

### *15.5.7 Pump and Tree*

This method is the use of trees to evaporate water and simultaneously to extract pollutants from the soil [11].

### *15.5.8 Hydraulic Control*

It is the controlling of water table and soil field capacity by plant canopies [12].

## 15.6 Plant Selection Considerations

Plant species for phytoremediation are selected based on their root depth, the nature of the contaminants and the soil, and regional climate. The root depth directly impacts the depth of soil that can be remediated. It varies greatly among different types of plants and can also vary significantly for one species depending on local conditions such as soil structure, depth of a hard pan, soil fertility, cropping pressure, contaminant concentration, or other conditions [13].

The cleaning depths are approximately phytoremediation. It has been reported that for phytoremediation, grasses are the most commonly evaluated plants [14]. They have been more preferable in use for phytoremediation because compared to trees and shrubs, herbaceous plants, especially grasses, have characteristics of rapid growth, large amount of biomass, strong resistance, effective stabilization to soils, and ability to remediate different types of soils [2]. They are pioneers and usually are adapted to adverse conditions such as low soil nutrient content, stress environment, and shallow soils [15]. The large surface area of their fibrous roots and their intensive penetration of soil reduce leaching, runoff, and erosion via stabilization of soil and offer advantages for phytoremediation. Wild plants such as grasses can produce closures above ground quickly and reduce dispersion of the dust of tailings [16].

Shrubs and trees produce extensive canopy cover and produce deep roots to prevent erosion in the long term. In addition, shrubs or trees provide high nutrient to the grass while lowering water stress and improve soil physical properties [17]. Many trees can grow on land of marginal quality, have massive root systems, and their above-ground biomass can be harvested with subsequent resprouting without disturbance of the site. However, the cost for planting trees is high and the growth rate is low [18].

To achieve a stable persistent cover, it is important to use a mixed culture and combine grasses, shrubs, and trees in revegetation programs of mining soils because they represent two functional types of plants with different roles in the improvement of mine soils. For a longer duration, as considered for most phytoremediation processes, it cannot be expected to clean up the soil only by one plant species used exclusively in monoculture. Grasses, with their highly developed root system, can stabilize the soils and reduce erosion, while legumes can add nitrogen to the soil, preparing the establishment of other plant species typical of later stages of succession [19].

Perennial grasses develop a large plant biomass in a relatively short time and are recognized as heavy metal-tolerant biosystems, accumulating high levels of these elements. However, the shorter growing period of the seasonal flowering plants is a better option in phytoremediation over perennial plants, as it can be harvested yearly or seasonally, and the area can be replanted with subsequent seasonal flowering plants [20]

For phytoremediation, it is better to use plant species adapted to the climatic and soil conditions of the area to be de-polluted [18]. Use of indigenous plant species is generally favored because they show tolerance to imposed stress conditions, require less maintenance, and present fewer environmental and human risks than non-native or genetically altered species [17]. However, particular non-native plant may work best remediation of specific contaminant and can be safely used under circumstances where the possibility of invasive behavior has been eliminated [21].

## 15.7 Heavy Metal Removal by Phytoremediation

### *15.7.1 Heavy Metals in Soil*

Heavy metals are the major environmental contaminants and pose a severe threat to human and animal health by their long-term persistence in the environment. The remediation of soils contaminated by heavy metals is a cost-intensive and technically complex procedure. Conventional remediation technologies are based on biological, physical, and chemical methods, which may be used in conjunction with one another to reduce the contamination to a safe and acceptable level. In spite of being efficient, these methods are expensive, time-consuming, and environmentally destructive [22].

### *15.7.2 Sources of Metal Pollution*

Geological and anthropogenic activities are sources of heavy metal contamination. Sources of anthropogenic metal contamination include industrial effluents, fuel production, mining, smelting processes, military operations, utilization of agricultural chemicals, small-scale industries (including battery production, metal products, metal smelting, and cable coating industries), brick kilns, and coal combustion [23]. One of the prominent sources contributing to increased load of soil contamination is disposal of municipal wastage. These wastes are either dumped on roadsides or used as landfills, while sewage is used for irrigation. These wastes, although useful as a source of nutrients, are also sources of carcinogens and toxic metals. Other sources can include unsafe or excess application of (sometimes banned) pesticides, fungicides, and fertilizers [23]. Additional potential sources of heavy metals include irrigation water contaminated by sewage and industrial effluent leading to contaminated soils and vegetables [24].

### *15.7.3 Metal Toxicity*

All plants have the ability to accumulate "essential" metals (Ca, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Se, V, and Zn) from the soil solution. Plants need different concentrations for growth and development. This ability also allows plants to accumulate other "non-essential" metals (Al, As, Au, Cd, Cr, Hg, Pb, Pd, Pt, Sb, Te, Tl, and U), which have no known biological function [25]. Moreover, metals cannot be broken down, and when concentrations inside the plant cells accumulate above threshold or optimal levels, it can cause direct toxicity by damaging cell structure (due to oxidative stress caused by reactive oxygen species) and inhibit a number of cytoplasmic enzymes. In addition, it can cause indirect toxic effects by replacing essential nutrients at cation exchange sites in plants [26].

### *15.7.4 Soil Metal Groups*

Metals are natural components in soil. Based on their role on physiological activities, they can be divided in two groups: (1) Essential heavy metals (Fe, Mn, Cu, Zn, and Ni) which are micronutrients necessary for vital physiological and biochemical functions of plant growth. They are constituents of many enzymes and other proteins and all plants have the ability to accumulate them from soil solution, (2) Non-essential metals (Cd, Pb, As, Hg, and Cr) have unknown biological or physiological function and consequently are non-essential for plant growth [27]. Both groups are toxic to plants, animals, and humans above certain concentrations specific to each element. High contents of both essential and non-essential heavy metals in the soil may inhibit plant growth and can lead to toxicity symptoms in most plants [28].

However, some plant species have the ability to grow and develop in metalliferous soils such as near to mining sites. Such plants can be used to clean up heavy metal-contaminated sites. Willow (*Salix viminalis* L.), maize (*Zea mays* L.), Indian mustard (*Brassica juncea* L.), and sunflower (*Helianthus annuus* L.) have been found to be highly tolerant to heavy metals. Vetiver grass (*Vetiveria zizanioides*) showed tolerance to Pb and Zn and it can be used for revegetating Pb/Zn mine tailings. Populus species are examples of plants widely used to remediate heavy metal-contaminated soils [29].

### 15.7.5 Heavy Metals

Heavy metals are natural constituents of the earth's crust. Their principal characteristics are an atomic density greater than 5 g $cm^{-3}$ and an atomic number >20. The most common heavy metal contaminants are Cd, Cr, Cu, Hg, Pb, and Zn. From the geochemical point of view, trace elements are metals whose percentage in rock composition does not exceed 0.1%. The occurrence of heavy metals in soils can be the result of two main sources:

Natural source: Heavy metals occur naturally in the soil environment from the pedogenetic processes of weathering of parent materials at levels that are regarded as trace (<1000 mg $kg^{-1}$) and rarely toxic [30].

Anthropogenic sources: Human activities, such as mining, smelting, electroplating, energy and fuel production, power transmission, intensive agriculture, sludge dumping, and melting operations, are the main contributor to heavy metal contamination. Heavy metals in the soil from anthropogenic sources tend to be more mobile, hence bioavailable than pedogenic, or lithogenic ones. The industry of mining and processing metals is a major source of farmland heavy metal contamination [31].

### 15.7.6 Heavy Metal Phytoavailability

Bioavailability and phytoavailability are terms used to describe the degree to which contaminants are available for absorption or uptake by living organisms that are exposed to them. Plants respond only to the fraction that is "phytoavailable" to them [32]. For heavy metal phytoremediation (and phytoextraction in particular), bioavailability of metals in contaminated soils is a crucial factor regulating heavy metal uptake by plant roots. However, metal phytoavailability is a complex phenomenon that is dependent on a cascade of related factors [33].

#### 15.7.6.1 Soil pH

Soil pH directly influences the phytoavailability of metals as soil acidity determines the metal solubility and its ability to move in the soil solution. Metal cations are the most mobile under acidic conditions, while anions tend to be absorbed to oxide minerals in this pH range [18].

#### 15.7.6.2 Soil Texture

Texture reflects the particle size distribution of the soil and thus the content of fine particles like oxides and clay [34]. Particle size distribution can influence the level of metal contamination in a soil. Fine particles (<100 μm) are more reactive and have a higher surface area than coarser material.

#### 15.7.6.3 Soil Organic Matter

Soil organic matter is frequently reported to have a dominant role in controlling the behavior of trace metals in the soil. The organic matter is one of the factors that may reduce the ability of metals to be phytotoxic in the soil due to metal-organic complexation [35].

#### 15.7.6.4 Redox Potential

The redox potential is one of the most soil properties that affect changes in metal speciation. Redox potential in soil is established by oxidation-reduction reactions resulting from microbial activity [36].

#### 15.7.6.5 Root Zone

Plant root can influence heavy metal phytoavailability by modifying the soil properties in the rhizosphere. The plant enzymes exuded from the roots should play a key role in the transformation and chemical speciation of heavy metals in soils, which facilitate their uptake by plant [37].

## 15.8 Phytoremediation Technologies in Removing Soil Metals

### *15.8.1 Phytoextraction*

This technology involves the extraction of metals by plant roots and the translocation thereof to shoots. The roots and shoots are subsequently harvested to remove the contaminants from the soil. Salt et al. [38] reported that the costs involved in phytoextraction would be more than ten times less per hectare compared to conventional soil remediation techniques. Phytoextraction also has environmental benefits because it is considered a low impact technology. Furthermore, during the phytoextraction procedure, plants cover the soil and erosion and leaching will thus be reduced. With successive cropping and harvesting, the levels of contaminants in the soil can be reduced [39].

### *15.8.2 Phytostabilization*

Also referred to as in-place inactivation, it is primarily used for the remediation of soil, sediment, and sludges. It is the use of plant roots to limit contaminant mobility and bioavailability in the soil. The plants' primary purposes are to (1) decrease the amount of water percolating through the soil matrix, which may result in the formation of a hazardous leachate, (2) act as a barrier to prevent direct contact with the contaminated soil, and (3) prevent soil erosion and the distribution of the toxic metal to other areas [8].

Phytostabilization can occur through the sorption, precipitation, complexation, or metal valence reduction. It is useful for the treatment of lead (Pb) as well as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn). Some of the advantages associated with this technology are that the disposal of hazardous material/biomass is not required and it is very effective when rapid immobilization is needed to preserve ground and surface waters. The presence of plants also reduces soil erosion and decreases the amount of water available in the system [21].

Phytostabilization has been used to treat contaminated land areas affected by mining activities and Superfund sites. The experiment on phytostabilization by Jadia and Fulekar [40] was conducted in a greenhouse, using sorghum (fibrous root grass) to remediate soil contaminated by heavy metals and the developed vermicompost was amended in contaminated soil as a natural fertilizer. They reported that growth was adversely affected by heavy metals at the higher concentration of 40 and 50 ppm, while lower concentrations (5–20 ppm) stimulated shoot growth and increased plant biomass. Further, heavy metals were efficiently taken up mainly by roots of sorghum plant at all the evaluated concentrations of 5, 10, 20, 40, and 50 ppm. The order of uptake of heavy metals was: Zn > Cu > Cd > Ni > Pb. The large surface area of fibrous roots of sorghum and intensive penetration of roots into the soil reduces leaching via stabilization of soil and is capable of immobilizing and concentrating heavy metals in the roots.

### *15.8.3 Rhizofiltration*

This technique is primarily used to remediate extracted groundwater, surface water, and wastewater with low contaminant concentrations [41]. It is defined as the use of plants, both terrestrial and aquatic, to absorb, concentrate, and precipitate contaminants from polluted aqueous sources in their roots. Rhizofiltration can be used for Pb, Cd, Cu, Ni, Zn, and Cr, which are primarily retained within the roots [21]. Sunflower, Indian mustard, tobacco, rye, spinach, and corn have been studied for their ability to remove lead from water, with sunflower having the greatest ability. Indian mustard has a bioaccumulation coefficient of 563 for lead and has also proven to be effective in removing a wide concentration range of lead (4–500 mg $L^{-1}$) [8]. The advantages associated with rhizofiltration are the ability to use both terrestrial and aquatic plants for either in situ or ex situ applications. Another advantage is that contaminants do not have to be translocated to the shoots.

An experiment on rhizofilteration by Karkhanis et al. [42] was conducted in a greenhouse with duckweed and water hyacinth (*Eichornia crassipes*) to remediate aquatic environment contaminated by coal ash containing heavy metals. Rhizofilteration of coal ash started from 0, 5, 10, 20, 30, 40%. Simultaneously, the physicochemical parameters of leachate have been analyzed and studied to understand the leachability. The results showed that pistia has high potential capacity of uptake of the heavy metals (Zn, Cr, and Cu) and duckweed also showed good potential for uptake of these metals next to pistia. Rhizofiltration of Zn and Cu in case of water hyacinth was lower as compared to pistia and duckweed. This research shows that pistia/duckweed/water hyacinth can be good accumulators of heavy metals in aquatic environment [43].

### *15.8.4 Phytovolatilization*

This technique involves the use of plants to take up contaminants from the soil, transforming them into volatile forms, and transpiring them into the atmosphere [21]. Mercuric mercury is the primary metal contaminant that this process has been used for. The advantage of this method is that the contaminant, mercuric ion, may be transformed into a less toxic substance (that is, elemental Hg). The disadvantage to this is that the mercury released into the atmosphere is likely to be recycled by precipitation and then redeposited back into lakes and oceans, repeating the production of methyl-mercury by anaerobic bacteria.

## 15.9 Metal Uptake by Plants

This depends on the concentration of soluble and bioavailable fraction of metals in the soil solution. The bioavailable fraction of metal in the soil can be determined by the Potential Bioavailable Sequential Extraction (PBASE) procedure [18]. Even though chemical extraction won't extract metal from the soil in a manner identical to that of a plant root system, it can be used as a reliable method for assessing the bioavailability of metals bound to soil particles [44].

Plants extract and accumulate metals from soil solution. Before the metal can move from the soil solution into the plant, it must pass the surface of the root. This can either be a passive process, with metal ions moving through the porous cell wall of the root cells, or an active process by which metal ions move symplastically through the cells of the root. This latter process requires that the metal ions traverse the plasmalemma, a selectively permeable barrier that surrounds cells [10].

In a polluted soil, the concentration of bioavailable pollutants tends to reduce over time due to physical, chemical, and biological processes. Because of this reason, aged soils are more difficult to phytoremediate [10]. It is known that to enhance metal solubility, plants either excrete organic ligands or lower the soil pH in the rhizosphere. To improve metal solubility in the soil solution, synthetic chelates such as ethylenediaminetetraacetic acid (EDTA), nitrilotriacetic acid (NTA), pyridine-2-6-dicarboxylic acid (PDA), citric acid, nitric acid, hydrochloric acid, and fluorosilicic acid can be used in phytoremediation studies [45]. The addition of excess chelating agents may increase the chances of leaching the metals from the soil to groundwater. If the metal concentration in the soil is near to the phytotoxic levels, addition of lime or organic matter reduces the metal solubility [10].

### 15.9.1 Phytoremediation of As, Cd, Pb, and Zn

Arsenic pollution is one of the major concerns in the world due to its chronic effects on the health of human beings. Recently, it was proposed that phytoremediation could be an effective tool for arsenic clean up [46]. Research in this field has mainly concentrated on arsenic contamination in the aquatic environment. Studies have been done to remove arsenic from contaminated soil and revealed that Chinese brake fern (*Pteris vittata*) is an efficient As accumulator. This plant is not suitable for a region like Oklahoma, where the climate is too dry, even though it can be used with higher metal 20 concentrations. Also, the concentration of Zn affects the growth of *P. vittata*. A study has shown that a concentration of 1242 mg Zn $kg^{-1}$ in soil causes phytotoxicity to the ferns [46]. Cadmium is present in most of the zinc-contaminated sites. Different plants such as indian mustard (*Brassica juncea*), willow clones (*Salix*), alpine penny-cress (*Thlaspi caerulescens*), sunflower (*Helianthus annus*), and corn (*Zea mays*) are able to accumulate Cd. *Brassica juncea* was able to accumulate cadmium from a soil with a concentration of 200 mg Cd $kg^{-1}$ in soil. Experiments showed that *Thlaspi caerulescens* can be a good phytoremediator in a soil with 390 mg Cd $kg^{-1}$. *Helianthus annus* and *Zea mays* were also found as good accumulators in soil with a cadmium concentration of 90 mg $kg^{-1}$ [47].

There are many plants that can accumulate lead in a very high concentration in its different parts. *Brassica juncea* can be effectively used as a phytoremediator for soils with lead contamination up to 500 mg Pb $kg^{-1}$ of soil. *Helianthus annus* and *Zea mays* have been grown in a soil with a concentration of 16,000 mg Pb $kg^{-1}$ [48]. Research using *Piptatherum miliaceum* (Smilo grass) has shown that this species can be used for remediating the metal contamination in a soil with 300–1500 mg Pb $kg^{-1}$ concentration [49]. *Thlaspi praecox* is able to accumulate a considerable amount of Pb from soil with a concentration of 67,940 mg Pb $kg^{-1}$ [50]. *Hemidesmus indicus* has been shown to remove 65% of the lead effectively from a soil having 10,000 ppm of lead concentration [51]. Most of the superfund sites in US are contaminated with zinc. Studies showed that *Piptatherum miliaceum* (Smilo grass) can be used for 21 phytoremediation in a soil with 100–600 mg Zn $kg^{-1}$ concentration [49]. *Helianthus annus* and *Zea mays* have been grown in soil with a concentration of 75,000 mg Zn $kg^{-1}$ and found to accumulate zinc in their harvestable parts [48].

### 15.9.2 Plants as Biosorbents for Heavy Metals Removal in Waste Water

Wastewater is a mixture of pure water with large number of chemicals (including organic and inorganic) and heavy metals, which can be produced from domestic, industrial and commercial activities, in addition to storm water, surface water, and ground water [52]. Due to the danger of the entry of chemicals into wastewater, it must be treated before the final disposal. Many physical, chemical, and biological methods have been developed for the treatment of wastewater. It is reported that biological methods are more interesting for wastewater treatment and one of the branches of biological method for wastewater treatment is phytoremediation [53]. The concept of this method is based on the using of plants and microorganisms in the same process as to remove the pollutants from environment [54].

Among phytoremediation techniques, artificial wetlands (AW) is known to be as the most effective technology to treat wastewater. The AWs can promote biodiversity via preparation of alarge habitat for a wide number of wildlife such as the reptiles, rodents, fishes, and birds. It should be noted that the selection of suitable species of plants is important for the implementation of phytoremediation [53].

The selected species must contain the following features: (1) high ability to uptake both organic and inorganic pollutants; (2) high ability to grow faster in wastewater; and (3) should be easy to control. It should be also noted that the ability of pollutant removal varies from species to species, plant to plant within a genus [55]. The rate of photosynthetic activity and plant growth have a key role during the implementation of phytoremediation technology for the removal of low to moderate amount of pollutants [56]. In addition to water hyacinth, plants like Water Lettuce (*Pistia stratiotes*), Duckweed (*Water lemna*), Bulrush (*Typha*), Vetiver Grass (*Chrysopogon zizanioides*), and Common Reed (*Phragmites australis*) have been successfully implemented for the treatment of wastewater containing different types of pollutant [57]. Nowadays, human health is being threatened with the release of polluted wastewater in presence of heavy metals into the environment.

Lasat [58] has shown that plants are successful in removing the heavy metals. The use of plants as biosorbents for the removal of heavy metals is considered to be inexpensive, effective, and eco-friendly technology. Phytoremediation can be considered advantageous if the plant is considered to be as solar-driven pump which can concentrate and extract particular type of elements present in the polluted wastewater. The root of the plant helps to absorb the pollutants existing in the wastewater, particularly the heavy metals and will help in improving the quality of water [59].

Water hyacinth has been widely studied in the laboratory at pilot and large scale for the removal of organic matter present in the waste water in comparison to other aquatic plants. Although water hyacinth is known to be a persistent plant all over the world, it is being widely used as a main resource for waste management and agricultural process [60]. Both the field and laboratory studies have shown that water hyacinth is capable of removing large number of pollutants present in the swine wastewater [61]. Duckweed and water hyacinth are being considered for the treatment of dairy and pig manure-based wastewater [59]. The treated wastewater in the presence of water hyacinth for the duration of 25 days resulted in the reduction of solids, calcium, magnesium, and total hardness. Wastewater from duck farm was treated by water hyacinth and resulted in 64, 23, and 21% removal of COD, TP, and TN, respectively [62]. In combination of water hyacinth and duckweed for treating dairy wastewater, it could remove 79% of total nitrogen and 69% of total phosphorus [57].

Chen et al. [63] demonstrated that 36% of nitrogen and phosphorus could be removed from swine wastewater using water hyacinth. Also reported among the different forms of nitrogen, ammonical nitrogen was found to be removed to a greater extent when compared to other forms of nitrogen.

Ismail et al. [64] showed the efficiency of water hyacinth and water lettuce for the uptake of nitrate, *ortho*-phosphate, nitrite and ammoniacal nitrogen. It was found that water hyacinth exhibited better performance for reducing nitrate in comparison to orthophosphate. Valipour et al. [65] in their latest study showed that the roots of water hyacinth are primarily involved in the transportation, where the shoots resulted in the accumulation of considerable amount of nutrients (N and P) in comparison to the root area.

Liao and Chang [66] ranked the heavy metal removal rate based on the ability of water hyacinth to remove (Cu > Zn > Ni > Pb > Cd) and showed that higher and lower removal efficiency belonged to Cu and Cd, respectively. Xiaomei et al. [67] used water hyacinth for the removal of Zn and Cd from wastewater and also measured the concentration of Cd and Zn absorbed in different parts of water hyacinth (stem, leaves, roots, flowers). It was observed for the presence of 2040 mg $kg^{-1}$ of Cd and 9650 mg $kg^{-1}$ of Zn accumulated in the roots of water hyacinth. According to Shaban et al. [68], to treat 1 L of wastewater contaminated with 1500 mg $L^{-1}$ arsenic requires 30 g of dried water hyacinth root for a period of 24 h estimated chromium(III) removal from the aqueous solution and found the removal rate to be 87.52% with 10 mg Cr/1 solution. Gupta and Balomajumder [69] found that water hyacinth can uptake more than 99% of phenol in a single and twofold solution of Cr and Phenol (at 10 mg $L^{-1}$) in 14 and 11 days, respectively. Padmapriya and Murugesan [70], during their study for the removal of heavy metals in aqueous solution using water hyacinth, found Langmuir and Freundlich models fitted well for the biosorption of all the metal ions.

## 15.10 Fate of Absorbed Metals in Plant

The metals absorbed in a plant can accumulate in various parts of the plant. For an effective phytoremediation process, the metals should be accumulated in a harvestable part of the plant. Brake fern, one of the major plants for arsenic phytoremediation, accumulated almost 95% of arsenic taken up into the aboveground biomass. The arsenic concentration in the brake fern root was the least when compared to the other parts. The highest concentration was reported in old fronds followed by young fronds, fiddle heads, and rhizomes [71]. Arsenate usually enters the plant root through the phosphate uptake system, and to limit the toxicity, the plant chemically reduce As(V) to As(III) in the roots. In the case of Indian mustard, a large portion of absorbed As remains in the root itself and a small amount of arsenic is transported to the shoots; however, the addition of water-soluble As-chelators can increase this fraction [72]. In most plants, the major portion of absorbed Cd remains in the root of the plant and only some is translocated to the shoots [72].

Sunflower accumulates zinc mostly in the stem (437.81 mg Zn $kg^{-1}$ dry weight) and lead in roots (54.53 mg Pb $kg^{-1}$ dry weight). In the case of corn, lead and zinc were accumulated more in leaves (84.52 mg Pb $kg^{-1}$ dry weight) (1967 mg Zn $kg^{-1}$ dry weight) [48]. Hemidesmus indicus 22 accumulates lead in the shoots [51] and Smilo grass accumulates lead in roots and zinc in shoots [49]. Experiments on *Thlaspi praecox* revealed that Zn and Cd accumulate in the shoots and their concentration in the shoots is linearly correlated with total soil Zn and Cd concentrations, thus confirming that the plant can be used for the phytoremediation of soil contaminated with Zn and Cd. At the same time, 80% of the accumulated lead is immobilized in the roots [50].

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