Phytostabilization of Heavy Metals: Understanding of Principles and Practices

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1 Introduction

The use of green plants in the restoration of contaminated sites is generally termed as phytoremediation, a technique that evolved during the last decades of the twentieth century (Salt et al. 1995). Even though the term "phytoremediation" was coined in the earlier 1990s, the concept of using plants to clean up contaminated environments dates back to 300 years. The first plant species documented for the bioaccumulation of heavy metals were *Thlaspi caerulescens* and *Viola calaminaria*, and the credit for this goes to Baumann (1885) at the end of the nineteenth century. Later in 1935, Byers reported that plants coming under the genus *Astragalus* are capable of accumulating up to 0.6% Se in the tissue. One decade later, Minguzzi and Vergnano (1948) identified some plants which are able to accumulate nickel (Ni) in shoots. Later on, Rascio (1977) reported the potential of *Thlaspi caerulescens* toward zinc (Zn) accumulation and tolerance.

The idea of using plants to remove metals from contaminated soil was further developed by Utsunomiya (1980) and Chaney (1983), and the first field trial on Zn and cadmium (Cd) phytoextraction was conducted by Baker et al. (1991). Following Baker till date, there were enormous reports on the heavy metal remediation technique using a number of plants (Salt et al. 1995; Clemens 2001; Suresh and Ravishankar 2004; Lone et al. 2008; Lutts and Lefévre 2015; Devi et al. 2016). These findings throw light to several similar studies, and now a number of plants have been identified as metal tolerators or as metal accumulators.

Phytoremediation in its sense is a very broad technique including several kinds of remediation alternatives (rhizofiltration, phytoaccumulation, phytoexcretion, phytostabilization, and phytovolatilization), and plants should be selected as per the requirement of the site. When an area is only slightly contaminated, plants with a

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strong ability to take up metals from soils can be utilized. These accumulated metals can either be stored inside the plant tissue, a process termed phytoaccumulation, or may exclude from the tissue, processes termed phytoexcretion and phytovolatilization. However, when dealing with more heavily polluted sites, like sites for the disposal of mine tailings, plants that do not transport the metals to the shoots, but instead bind them in the root or the rhizosphere, are preferred. This approach is termed phytostabilization (Wong 2003; Zeng et al. 2018).

Phytostabilization is a less invasive, low-cost phytotechnology which uses green plants to stabilize the toxic metal ions within the root or near the rhizosphere. It is now widely accepted as a means to decontaminate and restore the physical, chemical, and biological characteristics of the contaminated soils (Bolan et al. 2003; Kumpiene et al. 2008). Phytostabilization is not actually physically removing the contaminants from the soil, but rather causes the deactivation and immobilization of the potential ions, thereby preventing the further movement of the same to the food chain. The term phytostabilization thus refers to the use of pollutant-tolerant plants for mechanical stabilization of polluted land in order to prevent bulk erosion, reduce airborne transport, and leach pollutants (Fitz and Wenzel 2002; Boisson et al. 2016). It is mostly used for the remediation of soil, sediment, and sludges (USEPA 2000) and depends on roots' ability to limit contaminant mobility and bioavailability in the soil. The main objectives of phytostabilization have been summarized by Vassilev et al. (2004) as follows:

(i) To change the trace element speciation in the soil aiming to reduce the solubility and exchangeable fraction of these elements
(ii) To stabilize the vegetation cover and limit trace element uptake by crops
(iii) To reduce the direct exposure of soil-heterotrophic living organisms to pollutants
(iv) To enhance biodiversity by limiting the metal mobility

2 Phytostabilization Criteria

Phytostabilization can be applied to fields with varying level of contamination and also with different soil texture, i.e., features like soil pH, salinity, and metal levels, and contaminant types may vary from field to field. Thus, phytostabilization efficiency can be enhanced only through the careful selection of the appropriate plant species and also of the applied amendments particular to the field selected (Berti and Cunningham 2000). There are thus two major components in the phytostabilization process to be considered: the plant itself and the amendments added to the system.

2.1 Selection Criteria of Plants for Phytoremediation

For the effective phytostabilization process, selection of plant is a crucial step, and some important criteria must be considered before selection. Plants characterized as suitable candidates for phytostabilization must be native to the contaminated area and be tolerant to other stress factors like drought, salt, and metal and also must limit the metal accumulation to the shoot (Mendez and Maier 2008). In other words, plants that over-accumulate toxic trace metals in their roots, excluding or limiting translocation to shoots, can be regarded as efficient phytostabilizers (McGrath et al. 2002; Maestri et al. 2010). Moreover, it was suggested that plant species with high bioconcentration factor or BCF_{root} (>1) and low translocation factor or TFs (<1) could be considered as a potential candidate for the phytostabilization (Yoon et al. 2006; Meng et al. 2013; Shackira and Puthur 2017). Additionally plants used for phytostabilization need to exhibit tolerance to multiple metals and metalloids present in the sediments (Fitz and Wenzel 2002).

To meet the complete objectives of phytoremediation (i.e., to decrease water and soil pollution), the selected plants should also be native to the region that needs to be depolluted, grow quickly, and have dense root and shoot systems preventing heavy metal dispersion by water and/or wind erosion (Berti and Cunningham 2000; Freitas et al. 2004; Ali et al. 2013). Besides the plants must possess a large quantity of propagules (Henson et al. 2013) and should preferentially disperse by seeds to allow the implementation of phytostabilization on a large scale (Mench et al. 2006; Bert et al. 2008). It has been also reported that the reclamation methods for phytostabilization require elevated seed production, which usually results in a more continuous vegetation cover (Mendez and Maier 2008; Mench et al. 2010). Finally, species need to have the potential to promote soil development process by a long-term succession in the polluted areas (Mendez and Maier 2008).

To conclude, selection of a plant species for phytostabilization of heavy metals should take into consideration the following features:

(a) Plants should be tolerant to the soil conditions.
(b) Plants must grow quickly to set up a ground cover.
(c) Plants should have dense rooting systems.
(d) Plants must be easy to establish and to maintain under field conditions.
(e) Plants must have a relatively long life or be able to self-propagate (Berti and Cunningham 2000; Mendez and Maier 2008).

2.2 Soil Amendments

The rate of phytostabilization can be amplified when used in combination with certain soil amendments which facilitate trace metal immobilization in the soil, and this remediation strategy is known as aided phytostabilization (Alvarenga et al. 2009). The final aim is to reduce metal mobility in the substrate, and numerous organic and inorganic materials have been used to reduce solubility and bioavailability of heavy metals. These include liming material, phosphate, compost, biosolids, zeolite, and aluminosilicates such as bentonite, fly ash, etc. (Bolan et al. 2003; Kumpiene et al. 2008; Mench et al. 2010). Inclusion of such amendments in the substrate will then improve the nutritional status of the rooting medium, facilitate plant establishment in

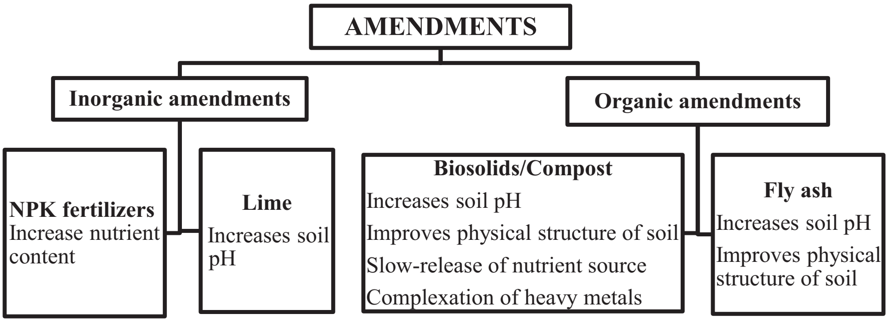

Fig. 1 Various organic and inorganic amendments used for increasing the rate of immobilization of toxic metal ions in the phytostabilization process

a more vigorous manner, supply plant nutrients in a slow-release form, and reduce metal leaching to the belowground level (Kumpiene et al. 2008).

Incorporation of organic additives to the contaminated soils induces numerous changes in the chemical (e.g., pH, organic acids, soil solution composition) and biological (e.g., microbial diversity) properties of soil (Perez-de-Mora et al. 2006; Stanczyk-Mazanek and Sobik-Szoltysek 2010). Amendments added to the soil thus convert the soluble and pre-existing high-soluble solid phase forms to more stable solid phases resulting in a reduced biological availability and plant toxicity of heavy metals. A decrease in the mobile trace element pool in soil promoted by amendments allows the settlement and the growth of vegetation as well as ecosystem restoration on highly contaminated sites (Ruttens et al. 2006). Specific functions of organic and inorganic amendments used in phytostabilization process are listed in Fig. 1.

3 Mechanism Underlying Phytostabilization

During phytostabilization, plants accumulate metals within root tissue or near the rhizosphere and are able to reduce the mobility or bioavailability of metals by stabilizing it in the substrate and/or by accumulating within the root. The higher accumulation of metals in roots may further decrease the mobility of metals in sediment (Nedjimi and Daoud 2009). The basic mechanism underlying phytostabilization depends on various factors like microorganisms present in the rhizosphere, root exudates, cell wall binding of metal ions, chelation of metal ions by metal-binding molecules, and their eventual sequestration into the vacuoles. The basic mechanism underlying phytostabilization includes the trace element mobility in the rhizosphere and is controlled by various soil factors such as pH, organic matter, texture, redox potential, and temperature and also by microbes (Chaignon and Hinsinger 2002). Phytostabilization can occur through the sorption, precipitation, complexation, or metal valence reduction (Ghosh and Singh 2005).

3.1 Role of Microorganisms

Under natural conditions plant roots are exposed to a large number of different microorganisms which play crucial roles in the recycling of plant nutrients, maintenance of soil structure, detoxification of noxious chemicals, and control of plant pests and pathogens (Filip 2002). Association between plant and microbes may be specific or non-specific, i.e., in specific association, plants provide carbon source that helps bacteria to reduce the toxicity of the contaminated soil, and in non-specific association, various metabolic activities of plants increase the growth of microbial community, which then degrades the contaminants entrapped in soil (Kushwaha et al. 2015). Thus, the microorganisms (bacteria and mycorrhiza) living in the rhizosphere of plants not only actively contribute to change the metal speciation, but they can also assist the plant in overcoming phytotoxicity, thereby aiding the revegetation process (van der Lelie et al. 1999).

It has been reported that the addition of bacteria like *Sphingomonas macrogoltabidus*, *Microbacterium liquefaciens*, *M. arabinogalactanolyticum*, *Alyssum murale*, etc. to the soil significantly increased the phytoavailability of heavy metals including Ni by reducing the soil pH, thereby facilitating phytostabilization (Abou-Shanab et al. 2003). Similarly, *Brassica napus* plants were inoculated with different kinds of bacteria like *Pseudomonas chlororaphis*, *Azotobacter vinelandii*, *Bacillus mucilaginosus*, and *Microbacterium lactium* for the increased tolerance toward various heavy metals (Wu et al. 2006; Ma et al. 2009; He et al. 2010). Different *Glomus* spp.-mediated phytostabilizations of heavy metals like Zn and Cd in *Zea mays* L. have been reported earlier by Janeeshma (2015).

3.2 Complexation with Root Exudates

Exudates secreted by roots affect the solubility, mobility, and phytoavailability of metal ions which play crucial role in phytostabilization (Colzi et al. 2012). About 12–40% of the photosynthates transported from the leaves to the roots are released into the rhizosphere during plant development naturally. These exudates may include various kinds of sugars, polysaccharides, organic and amino acids, peptides, and proteins depending upon the plants (Lin et al. 2003; Hinsinger et al. 2006). Root exudates may be grouped into two, high-molecular-weight (e.g., mucilages including polysaccharides, polyuronic acid, and ectoenzymes) and low-molecular-weight (e.g., organic acids, sugars, phenols, and various amino acids including nonprotein amino acids, such as phytosiderophores) compounds. Root exudates play a significant role in the process of phytostabilization by enhancing the accumulation, stabilization, or volatilization of contaminants from soil (Kushwaha et al. 2015).

In addition to the above facts, root exudates constitute an efficient energy sources for microorganisms present in the soil and act as ligands for binding heavy metal ions which ultimately influence the pH of the rhizosphere. The change in soil pH influences the mobilization of metals in soils and their accumulation by plant roots. Thus, roots can indeed modify the trace element mobility by changing soil pH and electrochemical potentials through element sorption in the apoplast or their rhizodeposition/complexation in the rhizosphere (Hinsinger 2001; Lombi et al. 2001; Chaignon and Hinsinger 2002).

Stabilization of toxic metal ions in the rhizosphere by root exudates without uptaking it into the root plays a crucial role in the phytostabilization process. Graminaceous plants secrete an amino acid compound, namely, phytosiderophore which can form a stable complex with iron (Fe), Cd, Zn, and copper (Cu) (Chaignon et al. 2002; Xu et al. 2005). Nair et al. (2008) have also reported the role of siderophores secreted by plant roots in arsenic (As) immobilization, thereby detoxifying the toxicity. Similarly, organic acids like oxalic acid, malic acid, citric acid, etc. secreted by wheat plants prevent the entry of Cd^{2+} into roots (Kushwaha et al. 2015). There are also reports stating that the heavy metals especially Ni- and Zn-chelating histidine molecules along with citrate accumulate in root exudates and help to reduce the uptake of the same inside the cell (Salt et al. 2000; Hall 2002).

3.3 Cell Wall Binding

From the soil, heavy metals can enter the plant root cell either by simple passive diffusion through the plasma membrane or by active metal uptake via special metal transporters. There are enormous reports stating that cell wall is recognized as one of the main compartments for heavy metal accumulation in plant roots (e.g., Małecka et al. 2008; Meyers et al. 2009; Konno et al. 2010). Plant cell walls are rich in pectin compounds, which are able to bind divalent and trivalent metal cations, and the main pectin domain in the cell wall responsible for binding metal ion is homogalacturonans (HGA) (Pelloux et al. 2007; Caffall and Mohnen 2009). The physiological advantage of metal binding with the HGA of cell wall is the metabolic inactivation of the absorbed metal ions within the apoplast itself there by reducing the toxicity (Jiang and Wang 2008).

Bringezu et al. (1999) have reported that different heavy metals were accumulated in the epidermal cell walls of heavy metal-tolerant *Silene vulgaris* ssp. *humilis*. Moreover, it has been reported earlier that lead (Pb) can bind efficiently with the carboxyl group of pectin in the cell wall and is considered as the most important reliable interaction by which a plant can tolerate Pb toxicity (Meyers et al. 2008; Jiang and Liu 2010). Moreover, increased content of various metals including Fe, Cu, Zn, and Pb have been observed in the cell walls of *Minuartiaverna* sp. *hercynica* growing on heavy metal-contaminated mine tailings (Solanki and Dhankhar 2011; Kushwaha et al. 2015). Enhanced pectin level in the roots of Cu-tolerant *Silene paradoxa* has resulted in binding of Cu at a higher rate to the root cell wall, thereby restricting Cu accumulation within the roots itself (Colzi et al. 2012).

3.4 Chelation with Metal-Binding Molecules

Metal ions once enter to the cytosol may be sequestered into the vacuole via chelation of metal ions by organic acids, amino acids, peptides, or metalloproteins, thereby providing greater resistance to the toxicity of heavy metals. The two best-characterized heavy metal-binding ligands in plant cells are the phytochelatins (PCs) and metallothioneins (MTs). These include different classes of low-molecular-weight, cysteine-rich peptides or polypeptide molecules which have a high affinity to various heavy metals and are synthesized inside the plant cell (Hall 2002).

The synthesis of PCs in plants is triggered by the presence of heavy metals. Heavy metals induce the activation of an enzyme, namely, phytochelatin synthase, which acts upon a glutathione substrate so as to produce PCs (Cobbett and Goldsbrough 2002; Suresh and Ravishankar 2004). It has been reported earlier that Pb and mercury (Hg) exposure in a halophyte *S. salsa* was found to significantly enhance the mRNA expression of *SsPCS*. *SsPCS* is the second *PCS* gene cloned from a halophyte, and it might contain a different metal sensing capability than the first *PCS* from *Thellungiella halophila* (Cong et al. 2016).

Plant MTs have been classified into Classes I, II, and III based on the arrangement of Cys residues. Most of the plant MTs are Class I proteins containing two smaller Cys-rich domains and a large spacer region devoid of this amino acid. In Class II MTs, Cys residues are distributed in a scattered manner in the entire protein sequence. Class III MTs differ markedly from Class I and II MTs and are enzymatically derived (Usha et al. 2009). Expression analysis of different metallothionein genes was studied by several groups in different plant species. Significant increase in the transcripts of AmMT2 gene in *Avicennia marina* plants was reported by Huang and Wang (2010) in response to Zn, Cu, and Pb. Similarly in *Bruguiera gymnorrhiza*, remarkable increase was found in the transcript level of BgMT2 in response to Zn, Cu, and Pb in leaves (Huang et al. 2011). Chen et al. (2014) studied the metallothionein gene (KoMT2) expression in the leaves of *Kandelia obovata* seedlings exposed to Cd stress and the expression levels of the gene was found to be increased. The overall mechanism underlying phytostabilization has been elucidated in Fig. 2.

4 Pros and Cons of Phytostabilization

Phytostabilization, the approach of using green plants for in situ stabilization/decontamination of metal wastes, is a feasible alternative to other costly remediation practices. As mentioned earlier, plants play an important role in phytostabilization by protecting the soil surface and also by physically stabilizing the soil with dense root systems to prevent erosion. Plant roots also help to minimize water percolation through the soil, further reducing contaminant leaching to the belowground part (Berti and Cunningham 2000). In addition, plant roots can also provide surfaces for sorption

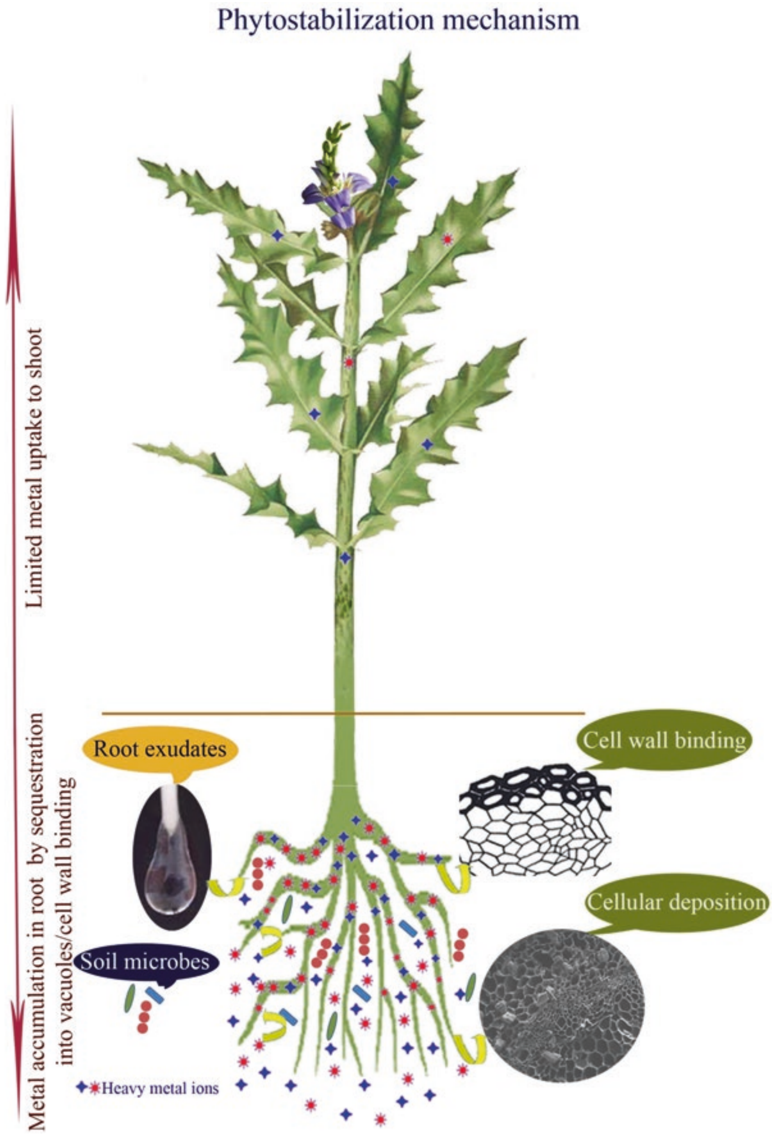

Fig. 2 General mechanisms of phytostabilization of heavy metals

or precipitation of trace metal elements, thereby playing an important role in groundwater protection and reduction of metal dispersion (Ruttens et al. 2006).

Phytostabilization is employed to treat polluted soils involving the establishment of a persistent plant cover that prevents pollution spread by erosion, water percolation, leaching, and wind dispersal of toxic dust (Berti and Cunningham 2000; Wong 2003). Phytostabilization can also diminish the metal bioavailability by their precipitation to less soluble compounds (Wong 2003). Vegetative stabilization improves the chemical

Table 1 Major advantages and limitations of phytostabilization technique

Sl no.	Advantages	Limitations
1	Disposal of polluted biomass is not required	The contaminants remain in place
2	Effective immobilization reduces leaching and bioavailability of toxic metal ions	It is useful at sites with shallow contamination and is not much effective at sites where the contaminants reaches deep in the soil
3	The presence of plants with dense root system reduces soil erosion	The vegetation and soil may require long-term maintenance to prevent rerelease of the contaminants and future leaching
4	Does not destroy or remove soil organic matter, soil microorganisms, and soil texture	Vegetation may require extensive fertilization or soil modification using amendments
5	It has a lower cost and is less disruptive than other more vigorous soil remedial technologies	Contaminant stabilization might be due primarily to the effects of soil amendments, with plants only contributing to stabilization by decreasing the amount of water moving through the soil
6	Revegetation enhances ecosystem restoration and renders the site aesthetically pleasing	The root zone, root exudates, contaminants, and soil amendments must be monitored to prevent an increase in metal solubility and leaching
7	Vegetation provide physical stability to the soil	Plants that accumulate heavy metals in the roots and in the root zone typically are effective at depths of up to 24 inches

and biological properties of the site through an increase in organic matter content, cation exchange capacity, and biological activities (Lutts and Lefévre 2015). Furthermore, this method of using appropriately selected plant species can improve the soil parameters and affect the fertilization methods (Reevers et al. 2007).

However, this technology does not achieve a complete cleanup of the contaminated soil, but rather changes the mobility of potentially toxic elements by either reducing concentrations in the soil water/matrix or by reducing re-entrainment of toxic particulates following the development of a stable and permanent vegetation cover. Sometimes, the use of soil additives is required for the physical and chemical immobilization of toxic metal ions in the process of phytostabilization. Thus, even though phytostabilization offers a great deal in limiting the bioavailability of metal ions, it cannot be sometimes suggested as a perfect remedial measure especially in the sites where stabilization is not much possible. Major advantages and disadvantages of phytostabilization are listed in Table 1.

5 Phytostabilization: The Most Affable and Affordable Technique

Phytostabilization seems to be a more comprehensive practice since this technique offers an aesthetically pleasing and environmental-friendly approach with an affordable economic feasibility. Remediation of polluted soil through phytostabilization is nowadays being applied by a number of researchers who have estimated the actual cost of the technique implemented in a field to be less as compared to other remediation techniques.

5.1 Cost-Effectiveness of Phytostabilization

Phytostabilization has been recognized as an adaptable, eco-friendly, and cost-effective strategy for the restoration of a functional ecosystem which is highly polluted. In general, the in situ inactivation of metals through phytostabilization may be an economically realistic and cost-effective remediation alternative, especially for vast industrial sites, dredged sediment dumps, and other dumping grounds where due to the huge volumes of material to be treated, excavation or landfilling is impractical and especially cost-inefficient (Vassilev et al. 2004). In general, the economics of any phytoremediation technique like phytostabilization are characterized by two considerations: the potential for application and the cost comparison to conventional treatments. Before going to practice phytostabilization in a larger field, one has to consider the whole system costs that may include the following:

(i) **Design costs:**
- (a) Site characterization
- (b) Work plan and report preparation
- (c) Treatability and pilot testing

(ii) **Installation costs:**
- (a) Site preparation
- (b) Soil preparation (physical modification: tilling, chelating agents, pH control, drainage)
- (c) Infrastructure (irrigation system, fencing)
- (d) Planting (seeds, plants, labor, protection)

(iii) **Operating costs:**
- (a) Maintenance (irrigation water, fertilizer, pH control, chelating agent, drainage water disposal, pesticides, fencing/pest control, replanting)
- (b) Monitoring (soil nutrients, soil pH, soil water, plant nutrient status, plant contaminant status) (EPA 2000; Vassilev et al. 2004)

The actual costs of the phytostabilization process cannot be practically listed accurately and may vary strongly with specific site conditions, contaminant type, plants selected, distance to target level, scale of operation, etc. However, Cunningham et al. (1995) have made an attempt to calculate the actual costs of the process. According to him, for phytostabilization, cropping system costs have been estimated at US\$200–\$10,000/ha, equivalent to US \$0.02–US \$1.00/m^3 of soil, assuming a 1 m root depth (Cunningham et al. 1995). The cost of traditional remediation techniques like physical removal or chemical stabilization of metals ranges from approximately

US$1.50 to US$450 per m^3 of soil entrapped with metal contaminants (Berti and Cunningham 2000; Evans and Willgoose 2000). Moreover, as an emerging remediation technology, phytostabilization can minimize this cost to an estimated US$0.40–26 per m^3 for revegetation (Ford and Walker 2003).

5.2 Practical Applications of Phytostabilization

Phytostabilization can be applied at sites where other regulatory strategies of metal decontamination usually fail and have high environmental risks due to continuous erosion or leaching (Berti and Cunningham 2000). This mechanism can be used to minimize migration of contaminants in soils through absorption and accumulation by the roots, adsorption onto roots, or precipitation within the root zone of plants. Phytostabilization is a management strategy for stabilizing toxic contaminants: its purpose is to establish a vegetation cover that will reduce soil erosion, windblow of contaminated particles, and water pollution by interception of incident precipitation.

Many heavy metals including Pb, As, Cd, chromium (Cr), Cu, Zn, etc. have been efficiently stabilized by phytostabilization technique (Berti and Cunnigham 2000; Alkorta et al. 2010). Phytostabilization is functional in different plant species in order to cover the different metal content in the soil and to conserve a portion of the plant diversity of pristine areas. In order to self-sustain the phytostabilization, the use of different tolerant and native plants species is recommended because they can perform distinct functional roles in the habitat apart from decontamination. An association of several species in polluted area should also increase the soil cover percentage, combining several shoot and root characteristics and then improving erosion control. Even though till date numerous plant species have been reported to be potential candidates for phytostabilization of different kinds of lands, the two most studied sites of phytostabilization are wetlands and mining sites.

5.2.1 Phytostabilization in Wetlands

In general, the term “wetlands” refers to transition zones between terrestrial and aquatic systems with soil saturated with water for at least part of the year or covered by shallow water along with characteristic wetland plant species (Kalff 2002). Wetlands constitute a highly productive ecosystem and are often situated close to highly populated and industrial areas. As a consequence, large amounts of toxic metal pollutants are entrapped in the salt marsh ecosystems and act as important sinks for heavy metals. Thus wetlands may be regarded as crucial sites for phytostabilization.

As an ecosystem, wetlands are helpful for recovering and cycling nutrients; releasing excess nitrogen; deactivating phosphates; treating wastewater; removing toxins, chemicals, and heavy metals; etc. The extensive rhizosphere of wetland plants provides an enriched culture zone for the microbes involved in degradation. The wetland sediment zone provides reducing conditions that are conducive to the metal removal pathway. The physicochemical properties of wetlands provide many positive attributes for remediating heavy metals. These unique characteristics of wetlands promote various biogeochemical processes that are responsible for the extraordinary capacity of wetlands to retain heavy metals from a diverse range of industrial effluents including municipal, agricultural, refinery, and pulp-mill effluent (Moshiri 1993). Thus, phytostabilization with wetland plants is an eco-friendly, aesthetically pleasing, cost-effective, solar-driven, passive technique that is useful for cleaning up environmental pollutants with low to moderate levels of contamination (USEPA 2001).

Castro et al. (2009) have reported that monocotyledonous halophyte species such as *Triglochin maritima* and *Juncus maritimus* provide higher Hg stabilization than the dicotyledonous species of halophytes such as *Sarcocornia perennis* and *Halimione portulacoides*. Moreover, mangroves with high BCF_{root}, for example, *Kandelia obovata* (Liu et al. 2014), *Avicennia marina* (MacFarlane et al. 2003), *Phragmites australis* (Weis and Weis 2004), *Aegiceras corniculatum* (Wu et al. 2015), etc., are appropriate candidates for phytostabilization, retaining metallic inputs and thereby reducing transport to adjacent estuarine and marine systems. Moreover, the halophytic shrubs recommended for phytostabilization include creosote bush (*Larrea tridentata*) and desert broom (*Baccharis sarothroides*). Recently, Shackira and Puthur (2017) and Shackira et al. (2017) have reported high BCF_{root} (>1) and low TF_{shoot} (<1) in *Acanthus ilicifolius* L. at high Cd and Zn concentrations, suggesting that *Acanthus ilicifolius* is a potential candidate species for Cd and Zn phytostabilization in polluted wetlands.

5.2.2 Phytostabilization in Mine Tailings

Introduction of plants directly at mine tailings has repeatedly been attempted, but has usually failed. This is due to the fact that such impoundments offer a harsh environment with high levels of heavy metals, low levels of macronutrients, and poor substrate structure (Clemensson-Lindell et al. 1992). Extraction of metals by mining results in large volumes of wastes that have to be removed in order to avoid contamination of the environment. The problem arises primarily after extraction of nonferrous base metals like Cu, Pb, and Zn, since these are found in ores with high sulfide content. After the metals have been extracted, approximately 95% of the rock is left as finely grained sand called mine tailings, containing high levels of metal sulfides, among which pyrite (FeS) is most abundant. The acidic drainage water from mine tailings may be a source of heavy metal leakage to various water bodies ultimately entering to the food chain and cause serious threats to the ecosystem (Notter 1993).

The success of the phytostabilization and ecological succession in the mining areas depends on the knowledge of the characteristics of metals and contaminated soils, rhizosphere processes, as well as the rate of uptake, translocation, accumulation, and chelation of metals by the pioneer plants (Mendez and Maier 2008; Abreu and Magalhães 2009). The plant populations (metallophytes) inhabiting the mine sites are usually specific ecotypes which are well adapted to mining conditions as well as drought and nutritional stresses. The ecological behavior of distinct plant species occupying mining areas has been studied by several authors (Freitas et al. 2004; Batista et al. 2007; Anawar et al. 2011; Abreu et al. 2012).

A low coverage by grasses could promote the colonization and establishment of native shrub species, since the facilitation is known to be an important process in harsh environment and enhance the phytostabilization and restoration strategies (Cunningham et al. 1995; Wong 2003; Padilla and Pugnaire 2006; Shackira and Puthur 2017; Shackira et al. 2017). *Cistus ladanifer* L. is one of the spontaneous species considered promising for phytostabilization of mining areas with multi-elemental (e.g., As, Cu, Pb, Zn, etc.) contamination (Alvarenga et al. 2004; Abreu et al. 2011; Anawar et al. 2011; Santos et al. 2012). Halophytes (salt-tolerant plants) are especially valuable in phytostabilization, and *Atriplex* spp. have been reported as pioneer species inhabiting in mine tailings (Jefferson 2004). The use of plants from Fabaceae family and/or other nitrogen-fixing species within the plant community can also be advantageous in the process (Wong 2003; Ahmad et al. 2012). List of plants characterized as potential candidates for phytostabilization of various heavy metals in different soil types are summarized in Table 2.

Table 2 List of plants characterized as potential candidates for phytostabilization of various heavy metals

Plant	Metal	Site of stabilization	References
Agrostis capillaris L.	As	Wetlands	Porter and Peterson (1975), Benson et al. (1981), Symeonidis et al. (1985)
Deschampsia cespitosa (L.) P. Beauv.	As	Wetlands	Cox and Hutchinson (1980, 1981)
Silene vulgaris (Moench) Garcke	As	Wetlands	Paliouris and Hutchinson (1991)
Avicennia marina (Forsk.)	Cu and Cd	Wetlands	MacFarlane et al. (2003)
Phragmites australis (Cav.) Trin. ex Steudel	Cu and Pb	Wetlands	Weis and Weis (2004)
Lolium perenne L.	Cu	Soils	Santibáñez et al. (2008)
Atriplex halimus L.	Cd	Wetlands	Nedjimi and Daoud (2009)
Quercus ilex subsp. *ballota*	Cd	Mine tailings	Domínguez et al. (2009)
Lupinus uncinatus Schldl.	Cd	Soils	Ehsan et al. (2009)
Triglochin maritima L. and *Juncus maritimus* Lam.	Hg	Wetlands	Castro et al. (2009)
Rhizophora mucronata (Lam.)	Cu, Pb, Mn, and Fe	Wetlands	Pahalawattaarachchi et al. (2009)
Microchloa altera (Rendle) Stapf	Cu	Soils	Shutcha et al. (2010)

(continued)

Table 2 (continued)

Plant	Metal	Site of stabilization	References
Haumaniastrum katangense (S. Moore) P.A. Duvign. & Plancke	Cu	Soils	Chipeng et al. (2010)
Typha latifolia L.	Mn, Cr, As, Zn, Co, Cd, Ni	Industrial sludge	Varun et al. (2011)
Arachis pintoi Krapov. & W.C. Gregory	Cu	Mine tailings	Andreazza et al. (2011)
Salix babylonica L.	Cu	Mine tailings	Chen et al. (2012)
Ricinus communis L. cultivar Zibo No. 8	Cd	Soils	Zhang et al. (2014)
Silene vulgaris Garcke (Moench)	Cd	Wetlands	Moreno et al. (2014)
Festuca rubra L.	Zn, Cd	Mine tailings	Galende et al. (2014)
Vigna unguiculata subsp. *sesquipedalis* L.	Cd	Soils	Deivanai and Thulasyammal (2014)
Oenothera glazioviana Micheli	Cu	Mine tailings	Guo et al. (2014)
Kandelia obovata Sheue, Liu & Yong	Cd	Wetlands	Liu et al. (2014)
Aegiceras corniculatum L.	As	Wetlands	Wu et al. (2015)
Andropogon schirensis Hochst.ex A.Rich., *Eragrostis racemosa* (Thunb.) Steud., *Loudetia simplex* (Nees) C. E. Hubb., *Monocymbium ceresiiforme* (Nees) Stapf, and *Hyparrhenia diplandra* (Hack.) Stapf.	Cu	Soils	Boisson et al. (2016)
Lupinus microcarpus Sims	As	Soils	Díaz et al. (2016)
Cistus ladanifer L.	As, Pb, Cu, Zn	Mine tailings	Santos et al. (2016)
Acanthus ilicifolius L.	Cd, Zn	Wetlands	Shackira and Puthur (2017), Shackira et al. (2017)
Osmanthus fragrans Lour., *Ligustrum vicaryi* L., *Cinnamomum camphora* (L.) J. Presl., *Loropetalum chinense* var. *rubrum*, and *Euonymus japonicas cv. Aureo-mar.*	Cd	Soil	Zeng et al. (2018)
Eichhornia crassipes (Mart.) Solms., *Pistia stratiotes* L.	Cd	Water	Sricoth et al. (2018)

6 Future Perspectives

Phytostabilization programs have low installation and maintenance costs compared to other remediation options. Polluted soils which lack green vegetation are considered as susceptible to soil erosion and leaching, and hence to guarantee the successful restoration of degraded ecosystem, the use of potential phytostabilizing species which have tolerance to multiple stress conditions is highly recommended. Moreover, this technology can increase the incomes from nonproductive contaminated soils if associated with species with economic value. Although the technique, phytostabilization, has become more widely accepted nowadays, further research is needed concerning the testing of new amendments and the selection of tolerant plant species for the process.

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