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PHYTOSTABILIZATION OF METALLIFEROUS MINE WASTE

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ABSTRACT

Metalliferous mine wastes including tailings and mill wastes are the major sources of pollution from mining activity. Mine tailing are composed of mostly fine grained material, lack nutrients and contains no organic matter to promote growth of vegetation canopy. Biotoxicity in mine tailings is primarily due to low pH and toxic metal concentrations. There is also chance of release of these metals during rain, resulting in metal leaching and acid mine drainage which impacts local streams and water ways. Most of the conventional remediation methods of mine tailings are expensive and environmental destructive. In recent years, scientists and engineers are working on use of microorganisms/biomass or live plants which can be implemented insitu to remediate tailings and mill wastes. Phytostabilization is one such emerging eco-friendly alternative phytotechnology, uses plants to immobilize environmental toxins, with aim of restoring the environmental status of a polluted soil useable for private or public applications. Phytostabilization focuses on establishing a vegetative canopy of metallophytes to immobilize metals within the mine tailings itself into a less soluble form thus making soil productive. This study includes characteristics and environmental impacts of mine tailings, basic concept of phytostabilization along with case studies and recent research.

INTRODUCTION

Metalliferous mining activities have deleterious effects on the environment due to exploration and beneficiation of minerals and metals. In the mining activities, once the minerals are processed and recovered from the ore the remaining rock becomes another form of mining waste called tailings. Tailings are usually stored above ground in containment areas or ponds (impoundments). About 90% of processed material is dumped in these impoundments. Mass of mine tailings is about 18 billion m3/year, which is expected to double in the next 20-30 years (Aswathanarayana, 2003). Mine wastes/tailings often contains substantial amount of various essential and non-essential metals. Metal concentration of As, Cd, Cu, Mn, Pb and Zn may range from as low as 1g/kg to greater than 50g/kg in mine tailings (Bradshaw *et al.* 1978). Non essential metals are toxic at low concentration whereas essential metals are toxic at higher concen-

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trations (Frerot *et al.* 2006)

Mine tailings are composed of mostly silt or sand sized particles, low in nutrients and organic matter supportive of biological growth (Das and Maiti, 2006). Further the biotoxicity of tailings is enhanced due to presence of low pH and metal content which increases the bioavailability of phytotoxic metal concentration (Stevenson and Cole, 1999). As a result, most tailings disposal sites are devoid of vegetation and have a stressed heterotrophic microbial community (Mendez and Maier, 2008; Mendez and Maer, 2007). There is also chance of release of metal contaminants during rain, results to metal leaching and formation of acid mine drainage which can impact local streams and waterways (USEPA, 2004). Metals may be transferred and accumulated in the bodies of animals or human beings through food chain, which will probably cause DNA damage and carcinogenic effects by their mutagenic ability (Knasmuller *et al.* 1998; Pal and Rai, 2010). Hence, it is very important to remediate the mine tailing wastes.

Conventional technologies for remediation of mine tailings have focused on physical and chemical techniques. Physical techniques entails landfilling with an innocuous material, generally waste rock from mining operations, gravel top soil from an adjacent mining site, or a clay capping, to reduce wind and water erosion. Chemical treatment aims to prevent wind and water erosion using various chemicals or resinous adhesives to form a crust over the tailings, are often temporary in nature (Tordoff *et al.* 2000). These conventional technologies meant to stabilize the toxic mine wastes in the substrate are destructive and expensive (Frerot *et al.* 2007). Most of the conventional technology are either extremely costly or entails isolation of the waste sites (Berti and Cunningham, 2000; Sheoran *et al*. 2008a, b). An emerging remediation technology, phytostabilization, has the potential to be cost effective with minimum inputs to stabilize the contaminants in a safer form in the soil by revegetation alone (Ford and Walker, 2003). Phytostabilization involves the use of plants for the formation of a vegetative cap where sequestration (binding and sorption) processes immobilize metals within the rhizosphere but not in the plant tissue. Consequently the metal bioavailability is reduced to the plants thus reducing the exposure to other tropic levels of the ecosystem (Munshower, 1994; Cunningham *et al*. 1995; Wong, 2003). The green vegetative canopy cover serves to reduce eolian dispersion while plant roots help to prevent water erosion and leaching. Thus, phytostabilization is an environment friendly biotechnology wherein a vegetative canopy is created for the long-term stabilization of the metalliferous mine wastes (Mendez and Maier, 2008b; Kavamura and Esposito, 2010).

CHARACTERISTICS OF MINE TAILINGS AND ENVIRONMENTAL IMPACT

Mine tailings are the materials remaining after extraction and beneficiation of ores. Mine tailings are typically characterized by shales, cobbles and pebbles, which have a very low water holding capacity. In addition to low pH and elevated metal concentration at mine tailings, other adverse factors includes absence of topsoil, periodic sheet erosion, drought, surface mobility, compaction and absence of soil forming fine ingredients. Mine tailings are devoid of soil organic matter and essential nutrients supportive of biological growth such as nitrogen (N), phosphorus (P) and Potash (K), hence inhibiting soil forming processes and plant growth. Toxicity of metals in mine tailings can also adversely affect the number, diversity and activity of soil organisms, inhibiting soil organic matter decomposition and N mineralization processes. The original soil of mined sites is usually lost or damaged, with only skeletal material. There is change in soil texture, loss of structure; and low availability of soil moisture; uncertain structure and unstable slopes due to hilly terrain (Ernst, 2005; Sheoran *et al.* 2008a).

Disposal of mine wastes historically involved either returning the materials to the mining site; dumping into the ocean, a stream, or lake; or placing them into a receiving pond. Today, surface containment of tailings within embankments (tailing impoundment) remains a commonly used approach. In 1995 it was estimated that on an annual basis over 700 million kg of metals in mine tailings were disposed on land (Warhurst, 2000). The tailings impoundments effects on cultural significance, visual acceptance and above all health and safety of all concerned. The tailings impoundments may affect the ground water condition as metal contents from tailings may damage the quality of ground water. This can change the surface water hydrology, drainage patterns and diverse the natural water channels. The tailing impoundments deforestate the cultivated land, forest or grazing land, thus destruct the green belt and change the cultural and heritage land into destruct land i.e. overall loss of production. It also causes of change in living hood of people and increases social tension and other problems. Thus exposure of mine tailings eventually leads to the loss of biodiversity, amenity and economic wealth (Bradshaw, 1997; Li, 2005).

PHYTOSTABILIZATION OF MINE WASTES

Growth of metallicolous plants

Phytostabilization of metalliferous mine wastes requires indigenous native metallicolous plants for immobilization of heavy metals in the tailings substrate. Metal tolerant plant species with a high bio-concentration factor (metal concentration ratio of plant roots to soil) and low translocation factor (metal concentration ratio of plant shoots to roots) have the potential for phytostabilization. These native species can spread easily in these environments because of lack of competitors (Conesa *et al.* 2007). Metal bioavailability responsible for toxicity (hence toxicity) will decrease as plants facilitate the precipitation of metals to less soluble forms, for example, metal sulfides or metal carbonates, complex metals with organic products, sorb metals onto root surfaces and accumulate metals into root tissues (Cunningham *et al.* 1995; Wong, 2003). Furthermore, the presence of plants in mine tailings enhances the heterotrophic microbial community, which may, in turn, promote plant growth and participate in metal stabilization (Glick, 2003; Mendez *et al.* 2007; Mummey *et al.* 2002). The ultimate objective for successful phytostabilization is the long term succession of the plant community in mine tailings to promote soil development processes, microbial diversity and finally, to restore soil ecosystem functions to a state of self-sustainability. The mechanism of phytostabilization is given in Figure 1.

Phytostabilization of metal mine wastes requires establishing a diverse plant community by introducing metal tolerant plant species that survives and grows quickly and have dense root and shoot system (Berti and Cunningham, 2000; Frerot *et al.* 2006). The characteristics of plants for phytostabilization are given in Table 1. Metallicolous plant species for phytostabilization ideally should be native to the local flora of the area in which the mine tailings are found, as they have evolved survival mechanisms appropriate to the harsh climate of their own environment and also fulfills the environmental guidelines. The use of native plants avoids introduction of non-native and potentially invasive species that may disturb regional biodiversity hence the surrounding ecosystem function and services (Gonzalez and Gonalez-Chavez, 2006; Chaney *et al.* 2007; Rosario *et al.* 2007).

Soil substrate

Mine wastes are generally low in nutrients, organic matter and high phytotoxic metal concentration which affect plant establishment and growth. Phytostabilization also involves the use of soil substrate amendments to promote the formation of insoluble metal complexes that reduces their biological availability thus preventing the entry of metals into food web (Adriano *et al.* 2004; Frerot *et al.* 2006).

Finally, the establishment of vegetative growth on mine tailings sites almost always requires inputs in terms of compost or nutrient amendments to mitigate the initial toxicity of the tailings (Kavamura and Esposito, 2010). Levels of organic matter incorporated in the soil are directly correlated with soil fertility and sustainability of the ecosystems. Examples of organic amendments used are vermicompost, cow manure, goat manure, biosolids etc (Sheoran *et al.* 2010). Therefore the inclusion of these amendments generally improves soil structure, water-holding capacity, cation exchange capacity, and nutrient contents with restoration of soil ecosystem (Munshower, 1994; Tordoff *et al.* 2000; Whiting *et al.* 2004). In addition, organic amendments reduces toxicity by decreasing metal bioavailability in mine tailings, provide a slow-release fertilizer, and serve as microbial inoculums (Jordon *et al.* 2002). The carbon (C) to nitrogen (N) ratio of the organic amendment should range from 12:1 to 20:1 to prevent high rates of organic matter decomposition and nitrogen consumption by the microbial community, thus impeding long term plant establishment (Van Rensburg and Morgenthal, 2004).

Increase in pH by conventional methods like addition of lime also decreases metal solubility thus also toxicity, but it is again a temporary solution for mining wastes that are actively generating acid. Although lime amendment is not expensive but perpetual addition to even active and also abandoned mines proves to be expensive. Thus self perpetuating sustainable vegetative cap is needed for successful phytostabilization (Schippers *et al.* 2000; Schroeder *et al.* 2005; Mains *et al.* 2006). Biosoilds, preferably anaerobically digested, are also used because of higher nitrogen content and a greater enhancement of plant growth as tested in a copper mine tailings site as reported by McNearny, (1998). However, Munshower, (1994) reported that biosolids may contain phytotoxic levels of metals, depending on the source of the material and its application is generally not desirable in ecologically sensitive areas. Piha and others in 1995 restricted the application of inorganic fertilizers, as native harsh vegetation used for phytostabilization of particular mine tailings tends to be adapted to low nutrients and tends to respond differently to fertilizer inputs. For vegetation it is very useful to choose plants spontaneously colonized and adapted to polluted mining sites successfully. These plants should be able to self propagate once planted without any additional inputs.

Furthermore if organic nutrients are added, phosphorus fertilizers may be applied to alleviate phosphate deficiency occurred due to the formation of insoluble-metal-phosphates (Mains *et al.* 2006). Although it was reported that addition of phosphate may increase arsenic uptake into plants as phosphates behave chemically similar to arsenate. Thus in absence of additional organic fertilizers continuous addition of lime may be needed to be added to maintain alkaline pH (Munshower, 1994).

The plants to be cropped for phytostabilisation must be able to limit metal accumulation to rhizosphere zone only i.e root tissue only.Root exudation of organic ligands is considered one of the most important strategies by which plants can exclude metals (such as Al, Cd, and Pb) by chelating them in the rhizosphere or in the apoplastic space and thus preventing their entry into the symplast (Hill *et al.* 2002; Watanabe and Oski, 2002). These mechanisms permit some metal-tolerant species to restrict uptake and translocation of metals, maintaining a low shoot metal concentration over a wide range of substrate/soil concentrations (metal excluders) (Baker, 1981). High citrate exudation from roots has been found in Al-excluder plants such as Al-resistant cultivars of *Phaseolus vulgaris* (Miyasaka *et al.* 1991), *Paraserianthes falcataria, Acacia mangium* (Osawa *et al.* 1997), *Fagopyrum esculentum* (Ma *et al.* 1997) and *Brachiaria brizantha* (Ishikawa, 2000), and differential Al tolerance among genotypes of *Triticum aestivum* was related to the efflux of malate (Pellet *et al.* 1996). Higher concentrations of organic acids have also been found in the root exudates of plants exposed to trace metals other than Al. Qin *et al.* (2007) found that Cu exposure induced root exudation of oxalate, malate and formate, and that Zn induced exudation of formate from Populus. However, no direct evidence of the involvement of these organic acid anions in trace metal exclusion and tolerance was reported. In contrast, the release of oxalate was found to be responsible for differential Pb tolerance among rice varieties (Yang *et al.* 2000). The oxalate content in root exudates of tolerant varieties of *Oryza sativa* increased upon Pb exposure, whereas the opposite was observed for sensitive varieties. Exudation of oxalate was suggested to reduce Pb bioavailability and increase resistance in tolerant varieties. Exposure to Ni induced greater exudation of histidine & citrate from the non-hyperaccumulator Thlaspi arvense than the hyperaccumulator *Thlaspi caerulescens* suggesting exudation of both compounds may be part of a nickel exclusion mechanism rather than being involved in Ni hyperaccumulation (Salt *et al.* 2000; Kidd *et al.* 2009).

Role of Microbial Community

Trace metals in mine spoils are well known to affect microbial growth and survival, community diversity and structure, enzymatic activity and microbial mediated edaphic processes (C and N mineralization, decomposition). Microorganisms have to cope with high concentrations of different trace metals in various kinds of habitats, from naturally metal-rich soils (such as ultramafic/serpentine soils) to anthropogenically created metal contaminated soils (Kavamura and Esposito, 2010; Tremaroli *et al.* 2009). Inoculation of Indian mustard (*Brassica juncea*) and canola (*Brassica campestris*) seeds with PGPR (plant growth promoting rhizobacteria) strain Kluyvera ascorbata SUD165, which produces siderophores and contains 1-aminocyclopropane-1-carboxylate (ACC) deaminase, protected the plants against Ni, Pb, and Zn toxicity (Burd *et al.* 1998).

Microorganisms have developed complex internal mechanisms of metal resistance; exclusion by intra and extracellular sequestration by chelating compounds; sorption by structural components of the cell membrane (metal binding functional groups such as carboxyls, thiols, phosphoryls, amines/imidazoles); active efflux transport systems which excrete toxic or over-concentration metals; enzymatic detoxification; and, reducing the sensitivity of cellular targets to metal ions (Nies, 2003). The large surface area of bacteria permits efficient interaction with mobile metal fraction of the soil. These mechanisms appear to be plasmid mediated and are highly specific to a particular cation or anion. In addition to these internal metal-resistance mechanisms, microorganisms can also interact directly with the trace metals to reduce their toxicity and/or influence their bioavailability; metal dissolution by bacterial production of strong acids such as H_2SO_4 (*Thiobacillus*); production of organic acids that chelate metals to form metal-organic molecules; production of ammonia or organic bases resulting in metal hydroxide precipitates; extracellular metal precipitation (e.g. with sulphate reducing bacteria); production of extracellular polysaccharides that can chelate the heavy metals; fixation of Fe and Mn on the cell surface in the form of hydroxides or some other insoluble metal salts; biotransformation via biomethylation, volatilization, oxidation or reduction (Chen and Cutright, 2003). Chen and Cutright (2003) demonstrated that a rhizosphere microbial consortium, able to resist high levels of trace metals, significantly reduced the bioavailability of metals by altering the pH of its surrounding from 4.5 to near neutral. Inoculation of *Brassica napus* with metal-resistant PGPR containing ACC deaminase stimulated growth of plants cultivated in Cd-contaminated soil (Belimovothe *et al.* 2001). In addition, various N_2-fixing and indol acetic acid (IAA), ethylene and auxin producing PGPR immobilized Cd (24-68% of soluble Cd from soil suspension) and promoted growth and nutrient uptake by *Hordium vulgare* in the presence of toxic Cd concentrations (Pishchik *et al.* 2002). Mycorrhizal colonization can improve metal resistance of plants growing in metal polluted soil (Hindebrandt *et al.* 2007). Multiple mechanisms can contribute to this protection: immobilization of metals in the soil reduced metal uptake, lower root to shoot metal transfer and better P nutrition are among the responsible processes (Yang *et al.* 2009). Recently, these mechanisms have specially been reviewed for the role of arbusculur mycorrhiza (AM) colonization in uranium accumulation in plants and their significance in the phytostabilization of radio-contaminated soils (Dupre de Boulis *et al.* 2008).

CASE STUDIES FOR PHYTOSTABILIZATION OF MINE TAILINGS

Grasses are reported as potential plant species for phytostabilization because of their rapid growth and extensive rooting systems. Roots of grasses are fibrous that can slow erosion and their soil forming tendencies eventually produce a layer of organic soil, stabilize soil, conserve soil moisture and may compete with weedy species. *Lygeum spartum* L. (family Poaceae) has been reported to tolerate extreme conditions of acidity pH less than 5 from Southern Spain (Conesa *et al.* 2006, Conesa *et al.* 2007). Smith and Bradshaw (1979) applied fertilizers and lime at mine wastes containing copper, lead and zinc at UK and stabilized these sites by grasses *Agrostis tenuis* Sibthorp (colonial bentgrass, Poaceae) and *Fistuca rubra* (red fescue, Poaceae). *Vertiveria zizanioides* (Vetiver grass) has been reported by various authors for phytostabilization of mine spoils. It is highly tolerant to extreme soil conditions including prolonged drought, flood, submergence, extreme temperature (-10 to 48 °C), a wide range of soil acidity, alkalinity, salinity, Al, Mn and heavy metals (As, Cd, Cr, Ni, Pb, Zn, Hg, Se and Cu) toxicities in the soil. Also oil products extracted from vetiver roots possess high values in biomedical utilization. By planting vetiver grass in metal contaminated soils, it will fulfill the dual purpose of stabilizing and modifying soil properties suitable for the colonization of other plants, and the same time producing oils with a high commercial value (Dalton *et al.* 1996).

Several plant species (grasses and legumes) has been reported growing on Pb/Zn mine spoils in China. These included *Vetiveria zizanioides*, grass (Shu *et al.* 2000), *Sesbania rostrata*, herb legume (Yang *et al.* 1997) and Leucaena leucocephala, woody legume (Zhang *et al.* 2001). Recently, it has been found that vetiver grass is the best species (in terms of biomass production and coverage) when compared with other three grass species namely *Paspalum notatum, Cynodon dactylcon* and *Imperata cyclindrica* var. major used for revegetating Pb/Zn mine tailings in S. China (Madejon *et al.* 2002). Madejon *et al.* (2002) reported two grass species Bermuda grass (*Cynodon dactylon*) and wild sorghum (*Sorghum halepense*) for stabilization at Pb/Zn mine wastes. Zhou *et al.* (2002) reported some crops such as maize, corn, peanuts and soybean potential for Cu phytostabilization. Yang *et al.* (2003) reported vetiver grass (*Vetiveria zizaniodes*) and two legume species (*Sesbania rostrata* and *Sesbania sesban)* for the phytostabilization of Pb/Zn tailings amended with domestic refuse and/or fertilizer. Frerot *et al.* (2006) demonstrated the importance of using plant mixtures which combined local metallicolous legumes and grass species, for achieving a stable, persistent plant community. They reported that *Festuca arvernensis* decreased Zn concentration from 2885 to 1469 mg/kg, Pb concentration from 1002 to 376 mg/kg, Cd concentration from 19 to 8 mg/kg. They also reported that *Koeleria vallesiana* decreased Zn concentration from 3514 to 2786mg/kg, Pb concentration from 1960 to 1477mg/kg and Cd concentration from 34 to 26 mg/kg. Antosiewicz *et al.* (2008) reported phytostabilization of Arsenic (As) by *Stachys sylvatica*. The leguminous species *Lupinus albus* has been suggested as a good candidate for phytostabilization of Cd and As mine spoils. This is due to several benefits: an improvement in soil properties due to its ability to fix atmospheric-N2, an increase in the pH of acid soils, a decrease in soil $CaCl_2$-extractable Cd and As and the retention of both elements in roots (accumulation was found in the root nodules). King *et al.* (2008) assessed the suitability of four Eucalyptus (E.) species (*E. cladocalyx, E. melliodora, E. polybractea*, and *E. viridis*) for the phytostabilisation of arsenical, sulphidic gold mine tailings. All four species accumulated low As concentrations, the highest being recorded in mature leaves, ranging from 0.29 to 5.14 mg/kg As. *E. cladocalyx* grew significantly taller than other species and concluded that *E. cladocalyx*, in particular is an ideal candidate for the long-term phytostabilisation of As-contaminated land and mine tailings. Martinez-Alcala *et al.* (2009) associated the immobilization of Pb and Zn in the rhizosphere of *Lupinus albus* L. (white lupin) with more oxidant conditions that occurred in the rhizosphere.

Hemidesmus indicus (sunflower) has also been reported to be fast growing crop favouring stabilization of Pb, Zn, Cd contaminated mined soils (Madejon et al. 2003; Jadia and Fulekar, 2008). Its tough leaves and stems are rarely eaten by animals. The seeds (actively eaten by birds) have very low concentration of potentially toxic elements and represent low risk for the food web. Song *et al*. (2004) reported phytostabilization of tin mine tailings by woody legume *Leucaena leucocephala* of the soil fertilized with garbage compost. Conesa *et al*. (2006) reported two plant species, *Hyparrhenia hirta* and *Zygophyllum fabago* (Syrian beancaper, Zygophyllaceae), that have naturally colonized some parts of mine tailings in South-East Spain, to tolerate high metal concentration of Pb, Zn and Cu in their rhizospheres. Mendez *et al*. (2007) reported the use of halophyte *Atrilpex lentiformis* (quailbush, Chinopodiaceae) along with adequate amount of compost for the phytostabilization of both moderately acidic and extremely acidic Pb/Zn mine tailings in Australia. Nitrogen fixing species (leguminous species) have a dramatic effect on soil fertility through the production of readily decomposable, nutrient rich litter and turnover of fine roots and nodules. Mineralization of N-rich litter from these species allow substantial transfer to companion species and subsequent cycling, thus enabling the development of a self-sustaining ecosystem (Singh et al. 2002). It has also been reported that compared to native non-leguminous species, native leguminous species show greater improvement in soil fertility parameters. Also, native legumes are more efficient in bringing out differences in soil properties than exotic legumes in the short term. In addition to grasses and legumes, some tree species such as *Alnus glutinosa* (black alder), *Acer pseudoplatanus* (sycamore maple), *Fraxinus excelsior* (common ash), *Robinia pseudoacacia* (black locust) and *Salix* spp. (willows) were reported suitable for phytostabilisation of moderately contaminated mine wasteland (Pulford and Watson, 2003; Mertens *et al.* 2007; Brunner *et al*. 2008). Misra *et al.* (2009) reported stabilization of Zn tailings (Zawar Zinc Mine, Udaipur) using *Brassica juncea* (Indian mustard) and amendments made with humus and phosphatic clay, to reduce the bioavailability of heavy metals.

Panfill *et al*. (2005) showed that the grass species *Fistuca rubra* and *Agrostis tenuis* accelerated the weathering of zinc sulfide when grown on contaminated dredged sediment, thus increasing Zn bioavailability in the rhizosphere. However, after two years of plant growth, micrometer sized Mn-Zn black precipitates were observed at the root surface of *Fistuca rubra.* Using electron microscopy and synchrotron-based microanalytical tools, Lanson *et al*. (2008) identified this precipitate as a Zn-rich phylomanganate. These authors proposed that this plant induced Zn biomineralization at the root-soil interface is likely to be a defense mechanism against metal toxicity.

CONCLUSION AND FUTURE SCOPE

Amongst various biotechnological approaches phytostabilization can be a suitable option to manage derelict metalliferous mine soils by reinstating the ecosystem to function and provide services. This technology uses solar energy hence natural resources are conserved and energy costs and expenses are reduced. The plant cover provides the basis for a successional development that leaves the site with a diverse, self-sustaining, vegetative cap that minimizes the eolian dispersion, water erosion and leaching processes. Thus provides improved conditions for natural attenuation, hence is aesthetically pleasing, socially accepted alternative to structural remediation and decontamination technologies. Although metal migration is minimized by phytostabilization, soils are often subject to erosion and still pose an exposure risk to human being and other animals. The addition of various amendments/inputs to soil increases the cost of remediation. It is also limited by the climatic and geological conditions of the mined site to be treated and requires highly technical, expert project

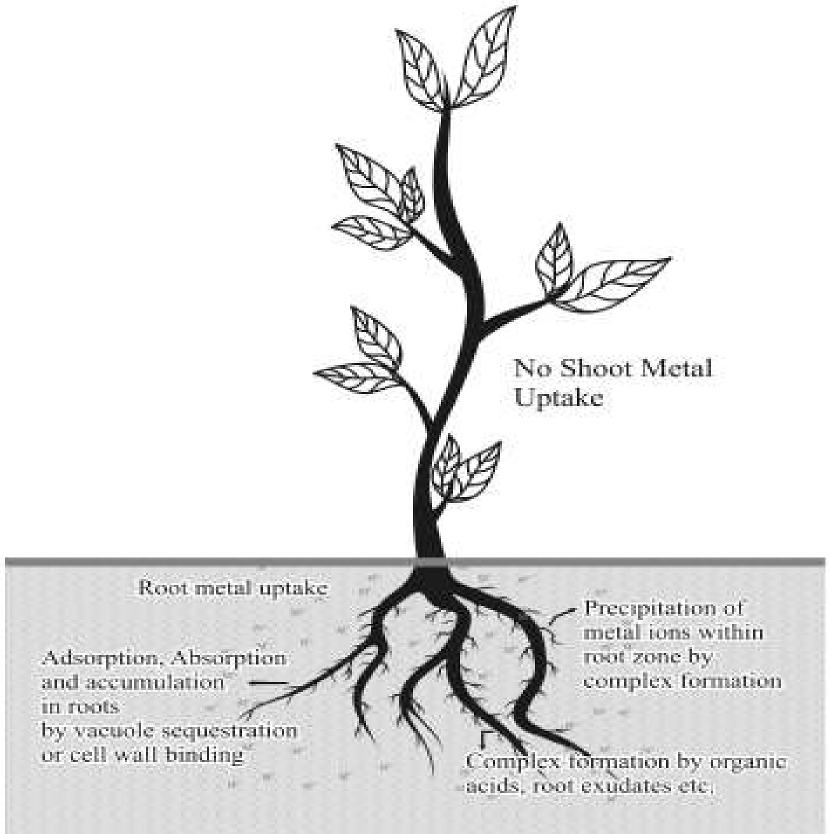

Table 1. Plant characteristics and shoot metal concentration for phytostabilization (after Mendez and Maier, 2008a)

Characteristics	Phytostabilization
Plant characteristics	Large canopy or ground cover; perennial; deeply rooting
Shoot metal concentration (mg/kg)	
As	= 30
Cd	= 10
Cu	= 40
Mn	= 2000
Pb	= 00
Zn	= 500

designers with plenty of field experience that carefully choose the proper species and manage the entire system to maximize the efficiency of stabilization. Thus immobilizing/confining the contaminants in a safer form within the contaminated landscapes itself with many other environmental advantages, offers innovative ecological approach to achieve successful soil remediation.

The future of the technology is still in development and research phase. The majority of the research has been conducted in laboratories under relatively controlled conditions for short periods of time. More extensive research under field conditions for long durations is required for a better understanding of the potential role of phytostabilization of mine wastes. The challenge for phytostabilization is to identify a regional- and climatic-specific native plant that accumulates metals in root zone/rhizosphere and not in shoot tissue with minimum inputs needed in soil substrate in terms of fertilizers as active mining sites are in remote area and abandoned mines are unattended. Role of plant-microbial associations using rhizosphere microbes to increase or decrease metal accumulation by shoot/roots tissues is yet to be fully revealed. On commercial scale public awareness of this technology is necessary to enhance its acceptability as global sustainable technology.

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