Phytoremediation: A Novel Approach for Utilization of Iron-ore Wastes

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1 Introduction

Large amounts of toxic contaminants are being released to the environment around the globe from rapid urbanization and industrialization. Among such contaminants are industrial wastes and ore tailings that result from worldwide mining activities. In mining operations, during the processing of low-grade ores, significant quantities of wastes or tailings are produced. The overburden material (also known as "waste"), generated during surface mining of minerals, causes serious environmental hazards if surrounding flora and fauna are not properly protected. It has been roughly estimated that for every ton of metal extracted from ores, roughly 2–12 t of overburden materials are being removed.

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During the mining and processing of sulphide ores, large quantities of overburden and wastes are generated. The waste-containing metal sulphides of Cu, Pb, Zn, Cd, etc. undergo oxidation and form sulphuric acid. Therefore, wastes resulting from the mining of sulphide ore deposits are highly acidic and are toxic to the aquatic environment. When metal sulphides react with sulphuric acid, high concentrations of toxic heavy metal ions (e.g. Cu, Zn, Pb and Cd) are released into the environment in acidic mine drainage water and may devastate the local environment. Usually, the acidic waste water generated has a pH of <3, and a soluble metal content as high as 1,800 mg/L. Other chemicals that are used in waste water concentration processes of sulphide ores, such as flotation reagents, grinding aids and flocculants, may contribute to the toxicity of tailing water when released as effluents to local water bodies.

Surface runoff (Arnaez et al. 2004; Kandel et al. 2004) from erosion, tailings carryover or other waste also poses a significant environmental risk. Explosives, such as ammonium nitrate or trinitrotoluene (TNT) used during blasting of ores, are also subject to surface runoff. Contamination of surface water may also occur from transport of mined-ore material or heavy metal ions from mining machinery maintenance and repair. In addition, significant levels of suspended particulate material (SPM) may contaminate air, which results from mining activities such as blasting, transportation, ore crushing, ore beneficiation and disposal of tailings. Significant releases of metal-containing (including mercury) dusts may result from drying of the ore concentrate. All of the aforementioned wastes are present in thousands of unvegetated and exposed tailing piles throughout the world; such waste is a definite and persistent source of contamination and exposure for nearby communities.

India has large reserves of metal-bearing ore and occupies the sixth position in the world for iron-ore reserves. Therefore, India is an important iron-ore producer and exporter. However, approximately 10–15% of the iron ore mined in India is unutilized, even now, and is discarded as tailings. The tailing wastes that are called ultrafines or slimes, mainly those ore solids having a diameter of less than 150 μm, are not regarded to be useful and hence are discarded. In India, approximately 10–12 million tons of such mined ore is lost as tailings. The safe disposal or utilization of such vast mineral wealth in the form of ultrafines or slimes has remained as a major unsolved and challenging task for the Indian iron-ore industry. Inevitably, the proportion of iron-ore wastes generated will steadily increase, because the demand for iron ores will increase. Such a view is confirmed by the number of steel plants that have been planned for future construction in the state of Orissa and other parts of India. The total production of iron ore in India is expected to exceed 400 million tons within the next decade. Therefore, dealing with the environmental consequences of such enormous quantities of tailings will be a Herculean task. It is therefore imperative that state-of-the-art iron-ore mining and processing technologies be adopted to address and implement effective utilization of tailings.

Another challenge is addressing the panoply of legacy mining waste sites that now accentuate or may contribute in the future to local environmental damage or health consequences of nearby residents. Such sites must be restored for sustainable development, or, at least, secured to prevent off-site contaminant movement.

Dealing with metal toxicity at such waste sites is a major concern. The wastes and tailings from many mines contain ~1–50 g/kg of toxic and heavy metal ions, e.g., As, Cd, Cu, Mn, Fe, Pb and Zn (Boulet and Larocque 1998; Bradshaw et al. 1978; Walder and Chavez 1995). Moreover, waste piles of tailings normally contain no organic matter or macronutrients, and usually exhibit an acidic pH, although some tailings may be alkaline (Johnson and Bradshaw 1977; Krzaklewski and Pietrzykowski 2002). Therefore, tailings-waste areas normally lack soil structure and tend to support severely stressed heterotrophic microbial communities (Mendez et al. 2007; Southam and Beveridge 1992).

There has been an increasing interest in the possibility of using vegetation to remediate contaminated mining sites, such as those described above, through plant-based technology known as phytoremediation. It is our intent in this review to address phytoremediation and associated processes as they apply to iron-ore wastes and mining sites. We will show that phytoremediation is cost-effective and feasible because plants are able to slowly absorb toxins into their tissues and thereby help clean toxins from waste sites. In addition, phytostabilization, the use of plants for in situ stabilization of tailings and metal contaminants, is a feasible alternative to more costly remediation practices (Mendez and Maier 2008). Phytostabilization promotes the conversion of tailings into useful soil material capable of sustaining normal ecological plant succession. Such use of plants to slow or prevent leaching of toxic components or erosion processes actually works better than some traditional methodologies (Dong et al. 2007; Krzaklewski and Pietrzykowski 2002; Wong et al. 1998; Ye et al. 2002). The main benefit of phytostabilization technology is that wastes need not be moved, transported or otherwise disposed of. Rather, one simply introduces the appropriate plant species and gives them time to work.

2 Iron-ore Tailings

Iron ore is being beneficiated around the world to meet the raw material requirements of the iron and steel industries. Iron ore has its own peculiar mineralogical characteristics and for optimum product extraction at any site requires tailoring of the metallurgical treatment and specific beneficiation process selected for use. The choice of beneficiation technique depends on the nature of the gangue and its association with the ore structure. The prime function of beneficiation of iron ore in India is to improve the content of extracted iron and reduce the Al–Si content of the finished iron. In India, iron-ore beneficiation proceeds mainly from washing, sizing by classification, jigging and then magnetic separation. The advantage of washing is to impart better handling properties to the ores, particularly the removal of fines, which becomes sticky in the rainy season and may pose problems during transportation to steel plants. In addition, the fines, which are preferentially accumulated with silica- and alumina-bearing minerals, are being removed as washing proceeds, thereby enhancing the quality of the iron ore. A large volume of water is required for iron-ore processing. Before tailings are transported to tailing ponds for impoundment, most water is recovered for recycling by using a dewatering process that utilizes a thickener. After beneficiation, the rejected portion of the iron ore may include coarse and fine particulates in the wash water, and these particulates may form a slurry known as wet tailings. The physical and chemical nature of such wet tailing from beneficiation plants depends on the ore type and beneficiation process used. All washing plants in India utilize ponds for disposal of tailings. Such ponds conserve resources and help control pollution. In the future, when all of the existing rich iron resource is exhausted, extraction of iron from such tailing pond waste may become economically viable.

The typical beneficiation process, as adopted by one of India's magnetite ore processing plants situated at Kudremukh, involved a three-stage crushing operation, followed by spiral classification, magnetic separation and transfer to a flotation column. Unfortunately, this plant generated approximately 29,424 t of solids (as slurry) per day while beneficiating magnetite ore. As a consequence, Indian governmental environmental laws were imposed on it and the plant ceased operation. In contrast, an Indian iron-ore mine belonging to the National Mineral Development Corporation (NMDC) at Bailadila generates tailings of 2,700 t/d, which are disposed of in 7,500 m^3 of water that has a 27–30% solids content. Other characteristics of this waste slurry is that it contains heavy amounts of total dissolved solids (TDS) equal to 250–1,500 ppm; in addition, the slurry has an ore-fine content of 95% and a clay–silica content of 5%.

Laboratory characterization of iron-ore tailings or slimes has indicated that they are largely made up of extremely fine material. More than 60% of the particulates in such slimes have diameters that are <20 μm (Das et al. 1992, 1993). Moreover, the silica and alumina content of the tailings is quite high, which requires both beneficiation and agglomeration treatment prior to their use in steel making. The distribution of particle sizes in tailing slurries is solely dependent on the beneficiation process adopted. The distribution size of particulates is important, because iron-ore particles and associated total suspended solids (TSS) constitute the main water pollutants that require downstream treatment before being discharged. The extent to which iron-ore tailings are produced at different washing plants in India from iron-ore mining activities is presented in Table 1. From the foregoing, it is evident that large quantities of iron-ore slimes are annually produced in India and the iron content of such waste streams varies between 52 and 62.8% Fe. Iron-ore tailings are also contaminated with parts per million levels of heavy metal ions such as Cu, Pb, Zn, Cr, Sn, Mo and U, as well as lower levels of macronutrients. Many of these potentially toxic elements reach and become pollutants of water.

The composition of various inorganic contaminants in a typical set of different slimes is shown in Table 2. Concentrations of toxic heavy metals such as Cu, Fe, Mn, Zn, Cr, Mo, Ni and Co have been found in mine water, as well as in iron tailings. It has also been reported that high concentrations of heavy metals, viz., Cu, Fe, Mn, Zn, Cr, Mo, Ni and Co, are also found in the soils of surrounding localities. The soil concentration of metal ions at such sites varies as follows: Fe (33.2–121.5 g/L), Mn (0.39–1.39 g/L), Cr (57–204 g/L), Co (1.3–4.6 g/L), Cu (25.8–93.0 g/L), Mo

Table 1 Fe content of iron-ore slimes from mining operations produced at different washing plants in India

Washing plants	Production (t/year)	Average Fe content (%)
Daitari	0.3	60.0
Bailadilla-14	1.2	62.8
Bailadilla-5	0.5	61.2
Barsua	0.6	52.5
Kiriburu	1.6	60.4
Donimalai	1.0	57.9
Meghahatuburu	0.6	60.0
Bolani	0.4	59.8
Noamundi	0.75	58.1
Kudremukh[a]	15.0	26.6

[a] No longer in operation
t metric tons
Source: IMMT (Institute of Minerals and Materials Technology), Bhubaneswar, India (unpublished data)

Table 2 Detailed chemical composition of different iron-ore slimes

Constituents	1[a]	2	3	4	5	6	7	8
Fe	59.8	61.2	52.5	60.3	57.9	57.8	59.3	26.8
SiO_2	2.30	6.84	7.82	2.96	6.42	4.00	4.1	51.2
AlO_3	4.52	2.81	9.88	4.96	6.28	8.30	4.8	1.82
MnO	0.08	0.8	0.1	0.12	0.08	0.03	0.03	0.08
CaO	0.09	0.11	0.11	0.14	0.12	0.08	0.09	0.11
MgO	0.06	0.05	0.07	0.07	0.05	0.04	0.06	0.06
LOI	7.0	2.34	7.40	5.10	3.90	5.20	5.2	4.05

[a] Location in India: 1 Daitari, 2 Bailadilla, 3 Barsua, 4 Kiriburu, 5 Donimalai, 6 Meghahatuburu, 7 Bolani, 8 Noamundi
[b] *LOI* loss of ignition
Source: IMMT, Bhubaneswar (unpublished data)

(1.08–4.25 g/L) and Zn (15.5–55.9 g/L; Ghosh and Sen 2001). The high levels of these toxic metal ions produce an adverse effect on growth and development of plants, animals and humans. Therefore, it is essential that eco-friendly techniques are developed to reduce potentially damaging exposures to these metals.

3 Environmental Impact and Waste Minimization

In recent decades, intensive research and development efforts have been directed towards finding cost-effective and eco-compatible solutions for minimizing and/or utilizing the waste produced in iron-ore mining operations (Bandopadhyay et al. 2002; Johnson et al. 1992). Recent trends in solid waste management that employ reengineering are strategically designed to maximize utilization of waste stream components (Bandopadhyay et al. 1999, 2002; Johnson et al. 1992; Kumar and Singh 2004; Kumar et al. 2005; U.S.EPA 2003). In addition, the recycling of solid wastes, after removal of harmful contaminants and recovery of valuable components by simple physical beneficiation techniques, is also being utilized to reduce the impact of waste streams (Das et al. 2003; Kumar and Singh 2004).

In addition to reducing the load of toxic components in waste streams, sensitive and robust eco-friendly tools that are capable of detecting the effects of toxic substances in complex aquatic ecosystems are also needed (Gustavson and Waengberg 1995). One such tool that has been employed to explore the relative propensity of waste streams to cause environmental damage is the use of mesocosms. Mesocosms utilize bacteria, phytoplankton and periphytic algae in a model system setting and have been useful for testing of sediment toxicity and contamination. If properly designed, such model systems are sensitive, reliable and require modest investment. Mesocosms are potentially useful in environmental impact assessments for determining the effects of dredging and dumping activities, and subsequent disposal of dredged spoils in the region (Alden et al. 1985; Lewis et al. 2001; Word et al. 1987).

Other tests are designed to determine the toxicity and bioavailability of metals that exist in contaminated dredge spoils, sediments and resuspended sediments in the water column. Such tests are performed in the laboratory, comprise in situ sediment bioassays, or are performed in microcosm-scale systems (Balczon and Pratt 1994; Fichet et al. 1998; Hurk et al. 1997; Togna et al. 2001). One of the most used techniques for determining the environmental risk of pollutants from mining activities is to employ green plants in removal, detoxification or stabilization of mining and processing tailings. This approach is cost-effective and eco-friendly. There are plants uniquely able to tolerate and survive high heavy metal (e.g. Zn, Cd and Ni) concentrations in soils. The details of methods that rely on such plants are described below.

4 Phytoremediation: Sustainable Remediation and Utilization of Iron-ore Tailings

The conventional technologies that are employed to remediate mine tailings generally rely on physical and chemical stabilization processes. Physical stabilization entails covering mine waste with innocuous material, generally waste rock from mining operations, gravel, topsoil from adjacent sites or a clay cap to reduce wind and water erosion. These solutions are often temporary, costly and often inadequate because capping processes are impermanent (Johnson and Bradshaw 1977). Phytoremediation is an emerging alternative approach, which offers prospects for reducing costs and potentially improving the performance of tailings environmental pollution abatement.

Phytoremediation relies on green plants as means to remove polluting substances from the substrates in which they grow and the subsequent transformation of potentially toxic pollutants into harmless ones. Most conventional technologies employed in mining-waste remediation are expensive and may actually reduce soil fertility, subsequently causing negative effects on ecosystems. In contrast, phytoremediation is cost-effective, environmentally friendly and is an aesthetically pleasing alternative that is far more suitable for use in developing countries. Phytoremediation offers an environmentally attractive means for removing toxic metals from hazardous waste sites and contaminants from soil, and achieves success by relying on selected hyperaccumulator plants, and ultimately on solar energy. Phytoremediation works well under the climatic conditions extant in India and has been confirmed through scientific experimentation to work both in ex situ and in situ projects (Blaylock and Huang 2000; Cooper et al. 1999; Ghosh and Singh 2005; Huang et al. 1997). The results of in situ phytoremediation that has been performed generally support the view that reductions of pollutants in waste material are sustainable.

Metal-contaminated soil can be remediated through the application of chemical, physical and/or biological techniques (Baker and Walker 1990). Experimentation utilizing phytoaccumulator plants to clean contaminated soil has been undertaken at the Institute of Minerals and Materials Technology (IMMT, Bhubaneswar), located in east India. Phytoremediation tests have employed several plant species, to wit: tree species, Acacia (*Acacia mangium* Willd.), Shisham (*Dalbergia sissoo* Roxb.), Ashoka (*Saraca asoca* (Roxb.) de Wilde), Sal (*Shorea robusta* Gaertn.f.); vegetable species such as tomato (*Lycopersicon esculentum* Mill.) and grass species such as lemon grass (*Cymbopogon flexuosus* (Nees ex Steud.) (Wats.)) (Figs. 1, 2, and 3; IMMT, Bhubaneswar unpublished data). All plants tested for growth on iron-ore tailings have survived. Other associated testing indicated that use of synthetic chelating agents, e.g., ethylenediaminetetraacetic acid (EDTA), organic acids or diethylene triamine penta acetate (DTPA), in the phytoremediation process, increased heavy metal uptake by plants. The degree to which different plant parts of *Brassica juncea* absorbed heavy metals during the course of this experiment is presented in Table 3. Although it is clear from this study that phytoremediation can be

Fig. 1 Luxuriant growth of Lemon grass showing different treatments (*right* to *left* – garden soil (control), I:S (1:3), I:S (1:1), I:S (3:1), IOT at time of harvest (90 days after treatment; DAT)) *I* iron-ore tailings, *S* garden soil and *IOT* iron-ore tailings

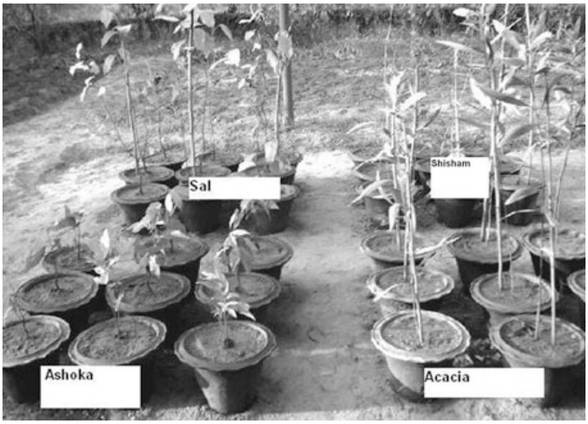

Fig. 2 Growth of tree species (90 DAT) under different soil and iron-ore tailings treatment regimes. (This research performed at IMMT – Institute of Minerals and Materials Technology, Bhubaneswar, India)

Fig. 3 Growth and fruiting in tomato plants grown in 1:1 iron-ore tailings and soil (IMMT, Bhubaneswar)

Table 3 The content (mg/kg) of metals phytoaccumulated into *B. juncea* from soil

Brassica juncea	Pb	Hg	Zn	Cr	Mn	Fe	Process
Leaf	113.97	3.65	28.35	2.41	50.93	192.88	AAS
Flower	26.19	7.35	44.35	2.21	18.61	127.29	AAS
Root	7.16	3.54	25.55	0.99	6.29	134.31	AAS
Stalk	7.37	4.02	25.22	5.77	6.43	60.09	AAS
Total	147.53	18.56	123.47	11.38	82.26	514.57	

AAS atomic absorption spectrometry
Source: http://www.saneko98.com/PHYTOREMEDIATIONNEWTECHNOLOGY2006.pdf

successful, it has yet to become a commercially available technology in India. The current status of phytoremediation in the world is still in the developmental stage and more research is needed to understand and fully implement this remediation technology. But, bench-scale studies are ongoing in the United States to understand

and assist in implementation of this alternative technology. For example, in 1996, a trial in Maine on phytoremediation for removal of lead (Pb) was implemented at selected sites by Edenspace Systems, and in 1997 at another site in Trenton, New Jersey (Henry 2000).

Phytoremediation may be carried out by methods that are either ex situ or in situ. If the method employed is ex situ, the contaminated soil or waste is removed from its native site for treatment and is later returned to the restored site. Conventional ex situ methods, when applied to remediate polluted soils, rely on excavation, detoxification and/or contaminant destruction (by physical or chemical means). Such methods are designed to stabilize, solidify, immobilize, incinerate or otherwise destroy contaminants.

In contrast, in situ remediation methods are performed at the point of the contamination and do not employ excavation of contaminated material. The purpose of such in situ methods is to destroy or transform contaminants for purposes of reducing bioavailability and to reduce or remove contaminants from bulk soil (Reed et al. 1992). In situ techniques are favoured over ex situ techniques, because they cost less and have lower ecosystem impact. A conventional ex situ technique is to excavate soil contaminated with heavy metals and remove them for burial at a landfill site (McNeil and Waring 1992; Smith 1993). Such conventional techniques are generally inappropriate, because they merely shift the contamination elsewhere (Smith 1993); moreover, ex situ approaches impose hazards associated with transport of contaminated soil (Williams 1988). Alternatively, dilution of contaminants to a safe level by importing clean soil and mixing it with contaminated soil may be used as an on-site management approach (Musgrove 1991). Plants used in in situ remediation are increasingly important as means to treat selected solid wastes, and some of the key processes and considerations that attend their use are described below.

4.1 Phytoextraction

Plants are capable of absorbing and accumulating metals in their tissues from contaminated soils, sediments and water at high concentrations (Peterson 1975). Such a process is called phytoextraction or phytoaccumulation (U.S.EPA 2000). Plants may constitute the best approach for removing soil contamination, when one wishes to isolate contaminants without destroying soil structure and fertility. Phytoextraction, whether utilized to remove toxic metal or radionuclide contaminants from soils, is best suited for remediation of diffusely polluted areas; such areas have relatively low concentrations of pollutants, and the contaminants occur superficially in soil (Rulkens et al. 1998). Although different approaches have been employed, the two basic phytoextraction strategies that have been used are (i) chelate-assisted phytoextraction or induced phytoextraction, in which artificial chelates are added to treated soil to increase the mobility and uptake of metal contaminants and (ii) continuous phytoextraction, in which the removal of metal depends on the natural physiological ability of the plant. Hyperaccumulator plant species exist that are capable of enhanced removal efficiency and these are the species most employed in continuous phytoextraction. For this technology to be feasible, plants must extract large concentrations of heavy metals into their roots, translocate the heavy metals to surface biomass and produce a large quantity of plant biomass. When phytoextraction is employed, a potentially valuable feature is that the heavy metals taken up by phytoextraction into plant biomass can be captured and recycled (Brooks et al. 1998).

4.2 Phytovolatilization

Phytovolatilization, another phytoremediation process, employs plants that are capable of absorbing contaminants from soil and then transforming them into volatile forms that can be transpired into the atmosphere. Phytovolatilization is a normal process that occurs as trees or other plants grow, absorb and translocate water contaminated with organic and inorganic substances (Bañuelos et al. 1997; Burken and Schnoor 1999). Some contaminants are translocated to leaves and volatilize into the atmosphere, usually at comparatively low concentrations (Mueller et al. 1999; Suszcynsky and Shann 1995; Watanabe 1997). This process has been primarily used for removal of mercury from soil; absorbed mercury is transformed into volatile forms and is transpired into the atmosphere. Moreover, plants transform the mercuric ion into elemental mercury, a less toxic form. Unfortunately, mercury released into the atmosphere by phytovolatilization may be redeposited in the ecosystem through precipitation (Henry 2000).

Some metal contaminants such as As, Hg and Se may naturally exist as gaseous species in the environment. In recent years, researchers have sought naturally occurring or genetically modified plants capable of absorbing elemental forms of these metals from the soil. Once absorbed, plants can biologically convert these metals to gaseous species within the plant and release them into the atmosphere. To date, selenium phytovolatilization has received the most attention in this regard (Bañuelos et al. 1993; Lewis et al. 1966; McGrath 1998; Terry et al. 1992), because this element is a serious problem in many parts of the world where Se-rich soils are prominent (Brooks 1998). According to Brooks (1998), the release of volatile Se compounds from higher plants was first reported by Lewis et al. (1966). In addition, Gary Bañuelos of USDS's Agricultural Research Service has found that some plants grow in high Se media and produce volatile selenium in the form of dimethyl selenide and dimethyl diselenide (Bañuelos 2000). One example, identified as *Astragalus racemosus* was found to emit dimethyl diselenide (Evans et al. 1968). Moreover, selenium was released from alfalfa as dimethyl selenide, though it is not a hyperaccumulator plant for Se. Lewis et al. (1966) showed that both selenium nonaccumulator and accumulator species volatilize selenium. Terry et al. (1992) reported that members of the Brassicaceae are capable of releasing up to 40 g of Se/ha/d as various gaseous compounds. Some aquatic plants, such as cattail (*Typha latifolia* L.), show clear potential for Se phytoremediation (Pilon-Smits et al. 1999).

Unlike other remediation techniques, once contaminants have been removed via volatilization, there is a loss of control over their migration to other areas. Some authors suggest that addition of phytovolatilized contaminants to the atmosphere would not contribute significantly to the atmospheric pollution pool, because the contaminants are probably subject to more effective or rapid natural degradation processes such as photodegradation (Azaizeh et al. 1997). The consequences of releasing metals to the atmosphere must be considered before adopting this method as a remediation tool.

4.3 Rhizofiltration

Rhizofiltration is the process of removing contaminants from flowing water and aqueous waste streams through extensive and massive root uptake by plants. Several aquatic plant species and hyperaccumulator plants have been found to remove heavy metals (Table 4) from waste-water streams. Formally, the definition of rhizofiltration is the use of both terrestrial and aquatic plants to absorb, concentrate and precipitate contaminants from polluted aqueous sources by processing low concentrations of contaminants in their roots. Rhizofiltration can

Table 4 Examples of hyperaccumulator plants

Latin name of the plant	English name	Element/heavy metals	Notes
Brassica juncea L.	Indian mustard	Cd(A), Cr(A), Cu(H), Ni(H), Pb(H), Pb(P), U(A), Zn(H)	Cultivated
Vallisneria americana	Tape grass	Cd(H), Pb(H)	Native to Europe and North Africa; widely cultivated in the aquarium trade
Dicoma niccolifera	–	–	35 documented uses of this plant
Eichhornia crassipes	Water hyacinth	Cd(H), Cu(A), Hg(H), Pb(H), Zn(A)	Pantropical/subtropical. Roots naturally absorb pollutants; some organic compounds believed to be carcinogenic at concentrations 10,000 times that in the surrounding water
Pistia stratiotes	Water lettuce	Cd(T), Hg(H), Cr(H), Cu(T)	–
Salvinia molesta	Kariba weeds or water ferns	Cr(H), Ni(H), Pb(H), Zn(A)	–
Spirodela polyrhiza	Giant duckweed	Cd(H), Ni(H), Pb(H), Zn(A)	Native to North America

H hyperaccumulator, *A* accumulator, *P* precipitator, *T* tolerant
Source: http://en.wikipedia.org/wiki/Phytoremediation,_Hyperaccumulators

be employed to partially treat industrial discharge, agricultural runoff or acidic-mine drainage wastes. Research has shown that rhizofiltration may be effective for removing lead, cadmium, copper, nickel, zinc and chromium, all of which are primarily retained by plant roots (Chaudhry et al. 1998; U.S. EPA 2000). Rhizofiltration has the advantage of being useful for both in situ or ex situ applications and plant species other than hyperaccumulator plant species are effective and can be used (Table 4).

4.4 Phytostabilization

Plants that are metal tolerant may also be employed to reduce the mobility of metals from contaminated sites. The process is called phytostabilization (Salt et al. 1995; Fig. 4). Utilization of phytostabilization processes is sometimes favoured over remediation, because they cost less and require low maintenance (Berti and Cunningham 2000; Cunningham and Berti 1993). Phytostabilization may also be used to remediate mining sites and processing tailings and for revegetating mining areas.

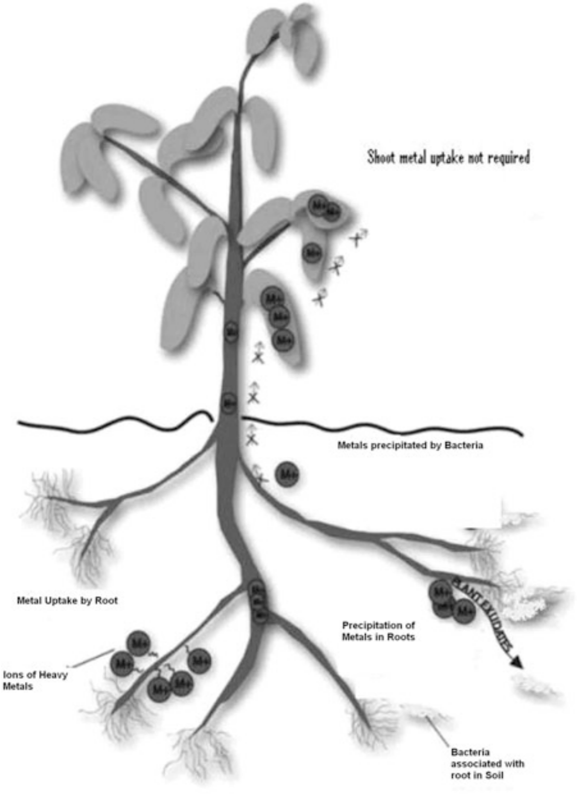

Fig. 4 Schematic picture showing phytostabilization mechanisms (Source: Mendez and Maier 2008)

Several perennial grasses, shrubs and trees (*Quail bush, Anthyllis vulneraria, Festuca arvernensis, Koeleria vallesiana, Armeria arenaria, Lantana camara, Cassia tora, Datura innoxia, B. juncea, Brassica campestris, Phragmites karka, Leersia hexandra*) are being used to revegetate mine-tailing sites. These plants are suitable and effective in achieving phytostabilization. Grasses grow rapidly and provide ground cover that may temporarily limit dispersion of tailings. However, trees and shrubs are important because they provide an extensive canopy and establish a deeper root network that may prevent erosion over the long term. Shrubs or trees provide a environment rich with nutrients for grasses and also reduce moisture stress and improve soil characteristics in arid and semiarid climates (Belsky et al. 1989; Tiedemann and Klemmedson 1973, 2004). Additionally, the establishment of different functional plant species increases plant productivity and yield. Although a few plants may eventually dominate the ecosystem as a result of selection pressure, the presence and effect of less abundant species is still significant in promoting a self-sustainable ecosystem (Tilman et al. 2001). A listing of the different plant species that are being used for phytostabilization is presented in Table 5.

Table 5 Plant families from which potential phytostabilization candidates may be sourced

Plant/family	Metal contaminants	Location	Note
Anacardiaceae			
Pistacia terebinthus Bieberstein	Cu	Cyprus	Field study using 1:1 chicken fertilizer:soil and mine waste
Schinus molle L.	Cd, Cu, Mn, Pb, Zn	Mexico	Plant survey
Asteraceae			
Baccharis neglecta Britt.	As	Mexico	Plant survey
Bidens humilis H.B.K.	Ag, As, Cd, Cu, Pb, Zn	Ecuador	Plant survey
Isocoma veneta (Kunth) Greene	Cd, Cu, Mn, Pb, Zn	Mexico	Plant survey
Viguiera linearis (Cav.) Sch.			
Chenopodiaceae			
Teloxys graveolens (Willd.) W.A. Weber	Cd, Cu, Mn, Pb, Zn	Mexico	Plant survey
Atriplex lentiformis (Torr.) S. Wats.	As, Cu, Mn, Pb, Zn	USA	Greenhouse study using compost
Atriplex canescens (Pursh) Nutt.	As, Hg, Mn, Pb	USA	Field study
Euphorbiaceae			
Euphorbia sp.	Cd, Cu, Mn, Pb, Zn	Mexico	Plant survey
Fabaceae			
Dalea bicolor Humb. & Bonpl. ex Willd.	Cd, Cu, Mn, Pb, Zn	Mexico	Plant survey
Plumbaginaceae			
Lygeum spartum L.	Cu, Pb, Zn	Spain	Plant survey
Poaceae			
Piptatherum miliaceum (L.) Coss.	Cu, Pb, Zn	Spain	Plant survey

Source: Mendez and Maier 2008

4.5 Plants Species Suitable for Phytoremediation

Several plant species can be used to phytoremediate mining and processing tailings and for revegetation of mining sites. Such species are biologically active plants and most are suitable for removal of heavy metal ions. An example of an effective plant species is *B. juncea*. This plant is capable of phytoaccumulating heavy metals from soil to a total content of 897 ppm; such metals are mainly translocated to green leaves. *B. juncea* effectively transports lead from roots to leaves, which is essential for phytoextraction of lead. Another related species, oil rape (*Brassica napus* var. Banacanka), has demonstrated hyperaccumulative capability (Mendez and Maier 2008). This plant may be useful for cleaning the air, ground water, waste water and soil matrices. Research performed with *B. napus, Helianthus annuus, Calamagrostis epigejos, Tussilago farfara, Sisymbrium orientale* has clearly shown that these plants may be useful as phytoremediator species in contaminated terrain.

5 Hyperaccumulation by Plant Species

Some plants accumulate larger amounts of heavy metals in their tissues than do others. A key success factor, when trying to establish an effective phytoremediating plant community, is to find native plant species that grow well in the area to be remediated, but to choose ones that are also effective absorbers of targeted toxic elements from soil. Use of native plants avoids introduction of non-native and potentially invasive new species that could threaten regional plant diversity. Few field trials have yet to take advantage of native plant diversity; not doing so has often resulted in poor plant colonization at waste sites. Some examples of hyperaccumulator plant species are presented in Table 4.

Conesa et al. (2007) recently conducted a greenhouse study to examine metal uptake from tailings by the needlegrass plant *Lygeum spartum,* grown from both seed and rhizomes. Plants grown in the greenhouse from seeds absorbed significantly more metal than did plants grown from rhizomes. However, plants collected from the tailings site itself showed one order of magnitude lower metal accumulation than those tested in the greenhouse. Therefore, one can conclude that prospectively certain entities at the tailings site inhibited uptake into these plants. In fact, an essential point for successful use of a plant in phytostabilization is that it be able to self-propagate successfully, with no additional inputs. The available literature reveals that the long-term fate of metals at revegetated tailings sites has not been explored thoroughly. Such information is needed to evaluate the efficacy of phytostabilization as means to permanently reduce metal toxicity of waste tailing materials.

Different heavy metals behave differently in trees. Pb, Cr and Cu are not very mobile in trees and are retained primarily in roots. In contrast, Cd, Ni and Zn are more easily translocated to the aerial portions of woody plants. Such differences in mobility and storage have important implications for how effective phytoremediation may be as means to control leaching of heavy metals from soils or waste areas.

Two tree species (*Salix viminalis* and *Salix dasyclados*) have considerable potential as vegetative cover for phytoremediation of land contaminated by heavy metals. Evidence from natural establishment of trees on contaminated sites supports the view that some tree types can survive under adverse conditions. Some tree species may not tolerate levels of contamination as high as others, but that does not detract from the utility that these tree species may have for remediation. Such trees may survive because of facultative tolerance, such as avoidance by roots of highly contaminated substrate or by immobilization of heavy metals in the root system. There is no evidence to support a specific, genetically transmitted tolerance system in such plants. However, some evidence exists to show that tolerance may be increased by acclimation of individual trees to low concentrations of heavy metals (Pulford and Watson 2003).

Phytoremediation technology is only in its infancy in India. However, it is a cost-effective and unfolding process that comprises a viable alternative to conventional remedial methods. However, further research results are needed to identify factors that affect what constitutes suitable plant species for remediation and what mine-tailings chemistry is most compatible for utilization of phytoremediation technologies.

6 Summary

Large quantities of iron-ore tailings are being generated annually in the world from mining and processing of iron ores. It has been estimated that around 10–15% of the iron ore mined in India has remained unutilized and discarded as slimes during mining and subsequent processing. Soil contamination resulting from mining activities affects surrounding flora and fauna and presents a large clean-up challenge to the mining industry. Innovative new methodologies have been proposed and among the most promising are those that rely on new phytoremediation technology.

In this paper we address and review the status of phytoremediation as a technology to reduce and control contaminated mine wastes. Several different approaches and different plant species are used to remove environmentally toxic metals from mine waste sites. Such approaches have the objective of restoring mining waste sites to human and animal use, or at least, to curtail or eliminate the off-site movement of toxic entities that potentially could reach humans. How well phytoremediation performs as an alternative soil restoration technology depends on several factors, including the composition of soil, toxicity level of the contaminant, degree to which plant species fit natural local growth patterns and type and concentration of metal/contaminant in such plants.

Phytoremediation has opened prospects for less costly, yet practicable approaches to clean-up contaminated waste sites, particularly those associated with mineral extraction mining. We discuss several plant species that are capable of phytoextracting and/or phytostabilizing harmful elements from contaminated soil and water; such processes are prospectively effective for addressing waste problems that derive from mining and processing activities, as well as those that derive from mitigating the threat posed by waste that surrounds mining sites. Unfortunately, phytoremediation is still in the embryonic stage, and more research is needed to find the plant species that will be most effective for addressing different mining waste scenarios. Such plants must be able to survive and even thrive in heavily contaminated soil and be able to mitigate the pollutants that exist in the soil in which these plants will grow.

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