

10. Aided phytostabilization of mine waste

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Abstract

Mining activities are major sources of metallic contamination worldwide. The dissemination and transport of mine tailings and spoils, characterized by a lack of organic matter and nutrients, high acidity and sulfide minerals content, containing potentially toxic metals and metalloids, may cause massive environmental degradation, water and soil contamination, biodiversity loss and health risks to humans. Aided phytostabilization is being proposed as a suitable strategy to decrease environmental risks by integrating application of adequate amendments with revegetation. In this technique, metals bioavailability can be reduced by the application of a range of soil ameliorants (e.g. biochar, organic residues). A vegetation cover (with tolerant plant species), supported by the amended soil, further improves the soil characteristics boosted by the increased soil organic matter and biological activity. In this context, a range of aided phytostabilization systems are reviewed and discussed towards their

effect on soil chemical and biological parameters and plant parameters with the aim to identify challenges and opportunities.

Keywords: Mine waste; Mine tailings; Mine spoils; Abandoned mines; Metal-contaminated soil; Aided phytostabilization; Phytoremediation; Revegetation; Heavy metals; Soil amendments; Bioavailability.

CHAPTER STARTS HERE

10.1. Introduction

Mining activities disseminate several organic and inorganic contaminants in all ecosystems media (Karbowska, 2016). Many toxic elements from mining areas and their drainage effluents can be leached into soils after minerals containing such elements are eroded, spreading into the environmental media (e.g. surface and groundwater and/or entering within the food chain) (He et al., 2005).

Soils that ultimately receive mine wastes without any type of treatment, or mine abandoned sites, constitute one important type of marginal land (Gibbs and Salmon, 2015). Other physical, biological and environmental factors, already existent before land contamination can act synergistically with mine wastes properties in order to exacerbate environmental degradation, water and soil contamination, biodiversity loss and health risks to humans (Confalonieri et al., 2014). Mine soils are generally mechanically, physically, chemically and biologically deficient, and characterized by high instability and limited cohesion, high acidity, containing low nutrients and organic matter, and with high content in potentially toxic heavy metals (PTM) (Crane et al., 2017; González et al., 2017). Heavy metal toxicity and mobility in soils is dependent not only on the total concentration, but also on their chemical form, their binding state,

metal properties, environmental factors and soil properties such as pH, organic matter content, type of soil, redox conditions and root exudates acting as chelates (Rodríguez et al., 2009). All those facts should be considered in order to provide an effective remediation method for a particular waste land containing mining wastes.

Different remediation options for mining wastes and acid mine drainage (AMD) with different advantages and disadvantages have been applied, in order to provide sustainable rehabilitation for waste lands containing mining wastes (rich in inorganic compounds such as heavy metals)(Wuana and Okieimen, 2011): zero-valent iron barriers; desulphurization by H₂O₂ (alone) or with cement paste backfill; electro-dialytic remediation; passive treatments by carbonate, lime, marble and fly ash; soil washing; solar thermal desorption and vitrification; precipitation through the use of amendments; metal-binding amendments; placing pyrite-rich mining waste under water level; treating tailings with Fe (II) sulfate; metal recovery from mine tailings with polymers; AMD treatment by nanoparticles; metals recovery from waste by algal/microbial biomass; suppression of pyrite oxidation by carrier microencapsulation, glycerol or biochar; biochar-aided rehabilitation; aided phytostabilization of mine wastes; use of a vegetation cover on mine tailings; compacted soil covering and vegetation over coal waste dumps, among many others.

Phytomanagement and in detail phytostabilization aims to establish a vegetation cover and progressively promote *in situ* inactivation of trace elements by using metal-excluder's or tolerant plant-species (González et al., 2017). Aided phytostabilization encompasses both incorporation of adequate amendments and the revegetation with tolerant plant species. This is being proposed as a suitable technique to decrease environmental risks, since it can reduce PTM mobility by altering speciation and/or stabilizing PTM through adsorption/absorption mechanisms. Additionally, the vegetation

cover will improve soil physico-chemical properties and fertility, increasing microbial diversity, and, restoring the function of PTM-contaminated sites in the long term (Bolan et al., 2011; González et al., 2017). Aided phytostabilization technology provides contaminant containment within the vadose zone by heavy metal accumulation on roots or precipitation within the rhizosphere (among others), preventing their migration via wind and water erosion, leaching and soil dispersion (Bolan et al., 2011).

Therefore, the aim of this review is to integrate results from literature regarding the utilization of aided phytostabilization on mine wastes as an effective and low cost alternative to physico-chemical treatments providing several environmental, economic and social benefits.

10.2. Phytostabilization: processes involved and influencing factors

Phytostabilization of mine tailings requires the use of hardy native plants with an extensive root system to create a stable vegetative cap that does not accumulate metals into above-ground tissues (Mendez and Maier, 2008). Phytostabilization involves contaminant removal, soil cover, rhizosphere modification and hydraulic control processes; it is affected by soil, plant, contaminant and environmental factors; and can be enhanced by plant growth-promoting bacteria, inorganic and organic amendments as well as by geotextile capping. It is dependent on the bioavailability of heavy metals and intends to minimize it, or by direct influence of the presence of the plant in soil, or by adding soil amendments (Bolan et al., 2011). In this process, plant roots change the physical, chemical, and biological conditions in soil in the rhizosphere, enriching the soil with organic substances either from plant or microbial origin, including organic acids, sugars, amino acids, lipids, coumarins, flavonoids, proteins, enzymes, aliphatics, aromatics and carbohydrates (Bolan et al., 2011). Moreover, organic acids of microbial

origin are virtually of the same composition as those synthesized by plants and enter the rhizosphere as cell lysis, root leakage and secretion of root exudates; and include the following: acetic, butyric, citric, fumaric, lactic, malic, malonic, oxalic, propionic, and succinic acids (Chang et al, 2002). Furthermore, chemical processes involving organic acids mobilize not readily available plant nutrients such as iron, phosphorus, and trace elements and induce weathering of soil minerals through reduction, dissolution, and complexation reactions (Chang et al., 2002).

Revegetation of mine wastes/heavy metal contaminated soils based on aided phytostabilization requires both incorporation of adequate amendments and the revegetation with suitable plant species (Yang et al., 2016). It aims to establish a vegetation cover and progressively promote *in situ* inactivation of trace elements by using metal-excluder's or tolerant plant-species (González et al., 2017), and ideally it should use plants that promotes PTM mobility reduction by changing speciation, at the same time that soil physico-chemical properties and fertility are improved, as well microbial diversity increases (phytostimulation), and soil functions are restored in the long term (Barbosa et al., 2016; Bolan et al., 2011; González et al., 2017). Spontaneous pioneer plant species represent key stress-tolerant genetic resources that can be used in the remediation of abandoned tailing dumps (Ginocchio et al., 2017). Nevertheless, fast-growing and high yield tolerant plant species will offer an added opportunity to produce biomass and fiber in such type of soils, offering several environmental benefits.

Heavy metal removal is dependent on the ability of plants to tolerate and accumulate metals. Some hyperaccumulators can be used for phytoextraction since are able to: transport heavy metals throughout the plasma membrane of their cells into the root; use metal uptake and its translocation within the xylem; and allow the rehab and sequestration of metals on certain plant components, or at the cellular level (Lombi et

al., 2001). Alternatively, phytostabilization using high yield/tolerant crops, such as perennial grasses, can be more suitable than other phytoremediation approaches using hyperaccumulator plants, since their biomass can be valorized for bioenergy, fiber and other by-products (Barbosa et al., 2015b; Dale et al., 2016). In fact, some energy crops, and in particular perennial energy crops, are well suited for phytostabilization of several metals and metalloids due to their deep and extensive root systems, tolerance to PTM and nutrient and water deficiency, and high ability to re-sprout after harvesting (Barbosa et al., 2015a, 2015b; Costa et al., 2016; Fernando et al., 2015, 2017). The establishment of these crops on mine waste contaminated soils, and their use for aided phytostabilization purposes, can help on the stabilization of metals through precipitation, complexation, sorption or accumulation in root tissues (Mendez and Maier, 2008; Mirza et al., 2011). Soil amendments like liming agents, phosphates and apatites, Fe, Al and Mn oxy/hydroxides, organic amendments, industrial waste products, organic residues such as compost, manure or sewage sludge, among others, can effectively improve soil physical properties, water infiltration and water holding capacity (González et al., 2017).

Aided phytostabilization using energy and fiber crops is a suitable technology that can be offered to waste lands in order to create an abundant and diverse heterotrophic microbial community that together with plant growth and obviously with time, may (ideally) transform tailings materials into soil (Mendez and Maier, 2008). Moreover, the use of perennial crops provide soil structure development, offering as well: high vegetation cover and permanence in the soil under formation; wind and water erosion control; high water and nutrients utilization efficiencies; and the minimization of the contamination by leaching (Zhang et al., 2011). Following we review case studies of how some crops can be used for the different types of mine wastes and how they are

able together with soil amendments to provide the conditions to transform wastes on fertile and functional soil.

10.3. Aided phytostabilization: enhancement of phytostabilization

10.3.1. Contaminant removal, stabilization and rhizosphere modification

The establishment of crops on mine waste contaminated soils, and their use for aided phytostabilization purposes, can help on the stabilization of metals through precipitation to less soluble forms, enhancing metal reduction, offering as well the complexation of metals with organic products, the sorption of metals onto root surfaces and metal accumulation in root tissues, perceived here as metal/ contaminant removal (Mendez and Maier, 2008; Mirza et al., 2011). Since the presence of toxic metals such as Pb, Zn and Cu can adversely affect the number, diversity, and activity of soil organisms, inhibiting soil organic matter decomposition and N mineralization processes, aided phytostabilization can be very important to increase biodiversity on soil ecosystems (Dongmei and Changqun, 2008).

Miscanthus spp. is a suitable perennial industrial crop that can be used for metal removal by the rhizome system and for its stabilization on the rhizosphere under waste lands, being able also to provide rehabilitation of several soil properties, important for overall functioning of soil. Red mud was tested as an amendment on highly contaminated soils in the vicinity of a former Pb–Zn smelter in Romania, and the perennial plant species show low bioaccumulation factors and translocation factors values and the aboveground biomass show low concentrations of Zn, Cd and Pb, suggesting that *Miscanthus spp.* can be considered an excluder of heavy metals, especially of Pb on waste lands. Moreover, the use of red mud lead to a significant decrease in the labile concentration of heavy metals in soil to which corresponded a low

uptake by plant tissues, especially in stems. Interestingly, increased biomass production was observed (Pavel et al., 2014). Such findings show that *Miscanthus* spp. can be used for the production of renewable biomass on metal-contaminated soils and on the presence of mine tailings, since low levels of heavy metals were found in aerial biomass. The same was also observed with giant reed (*Arundo donax* L.) that show no toxicity effects on biometric parameters and physiological processes when grown under Cd and Ni contaminated soils (Papazoglou, 2007).

Such type of information is very important if we considered that *Miscanthus* spp. (as well giant reed and other perennial industrial crops) is well suited on marginal lands; and that under such circumstances they produce high aboveground biomass yields without requiring any additional nutrients and water (Morandi et al., 2016). *Miscanthus* spp., for example, can be adapted in a large range of soil types, from loam to clay soils, characterized by low plant-available water, limited or slow water infiltration and high erosion (Randall et al., 2016). Nevertheless, perennial grasses yields are generally lower on poor soils than in standard fields. Barbosa et al. (2015b) registered lower yields and a decrease in the biomass quality on *Miscanthus* spp. and *Arundo donax* under soils with a high degree of marginality due to contamination with heavy metals. Equally, biomass yields can be even lower under mine tailings (Li and Huang, 2015). However, *Miscanthus* spp. and *Arundo donax* accumulated metals preferentially on belowground plant components and in a lesser extent on aerial components (Barbosa et al., 2015b), and such type of results support the implementation of both perennial crops for the immobilization/phytostabilization of heavy metals on soil. Nevertheless, for some authors, building-up soil biocapacity, rather than the selection and long-term establishment of plants should be a central goal in metal tailings phytostabilization (Li

and Huang, 2015). However, such type of operation may not be the most cost-effective for many cases.

Miscanthus sinensis Andersson was tested together with *Pteridium aquilinum* L. in aided phytostabilization of Pb/Zn mine tailings, and the application of Fe-rich amendments significantly reduced the amount of soluble and extractable heavy metals in mine tailings (Lee et al., 2014). The authors tested four kinds of amendments: bone mill, furnace slag, bottom ash, and red mud obtained from a commercial fertilizer vendor, a steel plant, a coal power plant, and an alumina smelter, respectively (Lee et al., 2014). Amendments acted as chemical stabilizers of heavy metals and reduced their availability and mobility, and the tested plant species show high ability to act as physical stabilizers, even in the presence of high concentrations of heavy metals in the tailings. In fact, furnace slag and *Miscanthus sinensis* reduced CaCl₂-extractable heavy metals by 56-91%, red mud and *Pteridium aquilinum* treatment was the most effective at decreasing bio accessible Pb, reducing it to 34% of the total Pb, and when compared to control, water soluble Cd, Cu, Pb, and Zn were reduced by 99, 99, 98, and 99%, respectively, in the red mud and *Pteridium aquilinum* tailings. Moreover, *Miscanthus sinensis* accumulated heavy metals mainly at the root level, showing lower translocation factors compared with *Pteridium aquilinum*. *Miscanthus sinensis* is appropriate for aided phytostabilization programs, and Fe-rich amendments such as furnace slag and red mud are effective at reducing the availability and mobility of metals in Pb/Zn mine tailings (Lee et al., 2014).

Soil amendments such as acetic acid, ethylenediaminetetraacetic acid (EDTA), and citric acid enhanced biomass production of *Arundo donax* under As (254 mg kg⁻¹), Cd (76.1 mg kg⁻¹), and Pb (1552 mg kg⁻¹) soil contamination, that accumulates the metals mainly at the level of the root system (Guo and Miao, 2010; Miao et al., 2012). This

study confirms that perennial grasses are able to adapt to extreme conditions on soil, and that metal uptake occur mainly at the rhizome and root level. Giant reed promoted also the improvement of soil quality parameters such as pH, EC, organic carbon, microbial counts, and soil enzyme activity, at the same time that Cd, Pb, Co and Fe where accumulated mainly at underground level, when grown under polluted soil with bauxite-derived red mud (Alshaal et al., 2013). In this study, high translocation factor was observed for Ni, a result that represents the phytoextraction of Ni and its removal from soil and containment on the biomass.

Tailings are normally deficient in organic matter, but organic matter can be introduced in many forms including: agricultural plant residues (or compost), biochar, animal manure, municipal biosolids (or peat), industrial organic residues, and woodchips/ wood sawdust (Li and Huang, 2015). Generally, the acute effects of organic amendments vary with the chemistry of both the organic matter and the tailings. Pyrolysed biomass (biochar) can be applied to ameliorate mine tailings properties and used on aided phytostabilization (Fellet et al., 2011). Four substrates were obtained by mixing mine tailings from a dumping site in Cave del Predil (NE, Italy) with biochar from orchard prune residues at four dosages (0%, 1%, 5% and 10% biochar in the mine tailings). The changes promoted by the described mixtures help the establishment of a green cover in a phytostabilization process since the pH, the nutrient retention in terms of cation exchange capacity and the water-holding capacity increased as the biochar content increased in the substrates and the bioavailability of Cd, Pb, Tl and Zn of the mine tailings decreased. Nevertheless, the authors warn that many hazardous chemicals such as PAHs, PCDD and others which result from the feedstock used and from the pyrolysis process parameters can still pose pollution risks (Fellet et al., 2011). Biochar from different feedstock and charring conditions show different chemical and physical

properties, so in some cases its adding can help plant growth and in other cases be harmful for plants. Nevertheless, phytostabilization itself can also act synergistically with amendments, since it can provide sorption, precipitation, complexation/metal valence reduction (Ghosh and Singh, 2005), and the degradation of organic compounds (Mirza et al., 2011). The *in situ* aided phytostabilization of waste lands offer an alternative strategy to contain and reduce risks to the environment and human health (Kumpiene et al., 2012), and the research on this field should continue. Biosolids stockpiles from sewage treatment plants are a valuable source of organic matter which could be utilized to improve the nutritional status and physical properties of mine tailings, such as those of Au, and support the growth of phytostabilization plant species in the tailings (Alcantara et al., 2015). Indian mustard and carrot were successfully established in tailings amended with biosolids (75% biosolids – 25% mine tailings), an approach that improved the physicochemical properties of the substrate, which helped to support plant growth and development. The amendment with biosolids increased organic matter content, improved water infiltration rate and increased the concentration of essential macro and micro-nutrients (Alcantara et al., 2015). So, aided phytostabilization, when uses the right proportion between the amendment and mine waste might be important to rehabilitate soil properties that will be important on supporting other ecosystem functions.

Under tin tailings, garbage compost mixed with tailings sands (1:12 w/w) and *Leucaena leucocephala* (Lam.) de Wit were tested, and high stabilization on site and high plant growth were observed; and for Pb-Zn mines, among other plant species, *Miscanthus sinensis* was pointed as ideal for revegetation; on copper mines *Typha angustifolia* L., *Pennisetum purpureum* Schum. and *Miscanthus sinensis* have proven successful initial colonization of pure tailings stands fertilized and irrigated (Li, 2006).

Phytostabilization plant crops can promote the growth of bacteria and other microbial communities. Cropping systems with *Silphium perfoliatum* L. increased the abundance of anecic and endogeic earthworms, under marginal lands, and during nine years the presence of such plant on soils had positive ecological implications for soil biodiversity and ecosystem services: increase on functional diversity and soil processes such as water infiltration, erosion resistance and nutrient cycling (Schorpp and Schrader, 2016). Nevertheless, other authors refer that earthworms can increase N₂O and CO₂ emissions from soils (Lubbers et al., 2015). By adding soil amendments, bacterial communities can be stimulated and together with root exudates, mine tailings properties and plant action developed to form a new soil. In fact, perennial grasses such as *Miscanthus sinensis* x *giganteus* and giant reed can significantly stimulate soil enzymes especially in the shallow soil layer (0–0.15 m) and bacterial community structure, increasing also the accumulation of carbon and nitrogen, being important in supplying C and N to the soil through their residual above-ground parts and root systems (Cattaneo et al., 2014). The use of plants and associated microorganisms could be a sustainable, cost-effective option to reduce pollutant exposure (Nsanganwimana et al., 2014). On mine degraded land, nitrogen is a major limiting factor and addition of N fertilizer becomes a common practice to maintain healthy growth and persistence of vegetation. An alternative approach is to introduce local legumes and other N₂-fixing species (Li, 2006).

Understanding the interaction between indigenous microorganisms and geochemical parameters is a key factor for devising improved strategies for managing mine wastes, and preventing the formation of AMD. Also, the knowledge concerning the distribution and diversity of acidic bacteria on tailings is also important for AMD formation and prevention. Diaby et al. (2007) studied the distribution and diversity of microbial communities in a porphyry copper tailings impoundment and their impact on the

geochemical dynamics of the mine waste. The tailings have low sulfide (1.7% pyrite equivalent) and carbonate (1.4% calcite equivalent) contents and were stratified into three distinct zones: a surface (0-70-80 cm) 'oxidation zone' characterized by low-pH (2.5-4), a 'neutralization zone' (70-80 to 300-400 cm) and an unaltered 'primary zone' below 400 cm. Microbial biomass was greatest in the top 125 cm of the tailings, and the largest numbers of bacteria (10^9 g⁻¹ dry weight of tailings) were found at the oxidation front (the junction between the oxidation and neutralization zones), and the dominant iron-/sulfuroxidizing bacteria identified at the oxidation front included bacteria of the genus *Leptospirillum*, and Gram-positive iron-oxidizing acidophiles related to *Sulfobacillus* (Diaby et al., 2007). Nevertheless, even under extremely acid mine soils, contaminated after receiving AMD (or produced by bacteria on soil), aided phytostabilization with tolerant plant species can offer an effective method of control of pollution, as well as enhance soil properties in mine wastes soils. Two amendments, lime and chicken manure, and five tolerant plant species (*Cynodon dactylon* L., *Pennisetum purpureum*, *Neyraudia reynaudiana* (Kunth.) Keng., *Panicum repens* L. and the non-native *Eucalyptus robusta* Smith) were tested in a 2 ha remediation trial site at Dabaoshan Pyrite Mine (China) and the plants show metal and acid tolerance, resulting in a rapid and effective revegetation of this metalliferous and sulphide-bearing mine wasteland, providing also a well-developed vegetation cover within the two year period of the study, enhancing nutrient accumulation in the mine soil (Yang et al., 2016). Moreover, soil physicochemical factors can also be determinant of the compositional variation of pioneer vegetal species on abandoned tailing dumps (Ginocchio et al., 2017).

Mycorrhizal fungi inoculation can significantly increase plant biomass of *Festuca arundinacea* Schreb., *Hylotelephium spectabile* (Boreau) H. Ohba and *Tradescantia*

pallida (Rose) D.R. Hunt, along with Pb, Zn, Cu and Cd accumulation by the roots (Gu et al., 2017). However, and although aided phytostabilization is being considered a promising technology, long-term field studies are still sporadic and therefore it is difficult to evaluate the overall success of such a remediation approach (Mendez and Maier, 2008). Yet, the studies of Mummey et al. (2002a, 2002b) show that after 20 years of soil reclamation, total microbial biomass, bacterial and fungal biomarkers, microbial biomass C and soil organic matter (SOM) averaged only 20, 16, 28, 44 and 36% of the values found in undisturbed soils. Although it seems a limitation of the phytostabilization technology, it is not likely that complete restoration can be achieved in such sites, because of the irreversible disturbance of the natural ecosystems created by the physico-chemical damage under the mining activities (Mendez and Maier, 2008).

10.3.2. Soil cover, erosion and leaching control

Industrial crops cultivation used in the phytostabilization of waste lands may contribute for enhancing soil fertility and structure, and help in controlling erosion and provide leaching control and groundwater contamination (Fernando et al., 2010; Dale et al., 2016). Besides, those plant species can also provide an increase of biological and landscape diversity, contributing for the development of rural areas, for the creation of employment, providing a diversity of energy supply, energy independence from fossil fuel as well as contributing for the reduction of greenhouse gas (GHG) emissions (Fernando et al., 2010). Giant reed, for example, because of the robustness of its rhizomes allows its use in the support of sloping terrains and in erosion control, which is a beneficial trait of this crop, and with significance for its production on mine waste contaminated lands (Fernando et al., 2017). Such physiological characteristics provide physical balance on certain environments, lowering the loss of soil and

evapotranspiration as well as the stability for plant root development (Yang et al., 2014).

Aided phytostabilization can also provide leaching control of contaminants, an important aspect when we are dealing with AMD. In fact many plant species are able to filter ions from wastewaters and an aided phytostabilization approach should be used to provide contaminants risk control. Perennial plant species can be used with the purpose of remove nutrients from wastewaters (Costa et al., 2016). And such abilities can be also used for the containment of toxic elements dissolved on AMD. The preventive effect of vegetation on nutrient and metal leakage from sewage sludge used in the treatment of mine waste was investigated, and during a 10-week greenhouse study, the release of ammonium, nitrate, phosphate, Cd, Cu, and Zn from sewage sludge was analyzed in the absence (control) and presence of basket willow, fireweed, reed canary grass, and Scots pine (Neuschütz and Greger, 2010). Plants significantly decreased the amount of leachate, and lowered the concentrations of phosphate (to 0.1 mg.dm^{-3}), Cu (0.8 mg.dm^{-3}), and Zn (2.2 mg.dm^{-3}); and plants increased the pH in the leachate towards the end of the experiment. The most efficient plant was reed canary grass that significantly decreased the total leakage of all pollutants. Nevertheless, such plant species were not able to retain ammonium and nitrate and increased Cd release, along with an initial pH drop (to 4.5). Reed canary grass and fireweed used both ammonium and nitrate as nitrogen source and were more efficient in preventing nitrate leakage, compared with willow and pine that mainly used ammonium (Neuschütz and Greger, 2010). So, the introduction of reed canary grass on mine waste lands added with sewage sludge can be a promising method for phytostabilization, but alkaline additives are needed to prevent an initial decrease in pH (that helped the mobilization of Cd).

Other plant crops are suited for erosion control, namely from wind and water. *Miscanthus* spp. is suitable for the semiarid and heavily eroded marginal lands placed on the Loess Plateau in China being able to reduce surface runoff, preventing water and soil loss, providing feedstock for bioenergy development and contributing to the sustainable path of the economy and society (Liu et al., 2014).

Aided phytostabilization is also a suitable technology to deal with radioactivity present on mine wastes. The addition of sheep manure and bone meal, single or mixed to uranium mining on soils in Urgeiriça (Portugal), independently of the type and concentration of the amendments, lead to a decrease in the total uranium available fraction concentration and the activity of radium, helping on the revegetation and restoration of such mine waste soils, as well on the availability of nutrients to plants (Abreu et al., 2014). This study shows that aided phytostabilization is a suitable technology to be applied on radioactive mine wastes, to control their effects on the environment and to offer the possibility of a future soil development. Also, association of plants with fungus may also improve the phytostabilization of radioactive mine waste soils. Medic and ryegrass plants were used as host plants to examine whether inoculation with the fungus, *Glomus intraradices*, would help phytostabilization of U tailings (350 mg kg^{-1} ; 4200 Bq kg^{-1}) (Chen et al., 2008). The need of amending with uncontaminated soil for supporting plant survival was also examined by mixing soil with U tailings at different mixing ratios. Soil amendment increased plant growth and P uptake, and ryegrass produced a more extensive root system and a greater biomass than medic plants at all mixing ratios. Medic roots were extensively colonized by *G. intraradices* whereas ryegrass was more sparsely colonized. Plant growth was not improved by mycorrhizas, which, however, improved P nutrition of medic plants. When comparing U uptake, U concentrations on medic plants were higher compared to

ryegrass. In the presence of U tailings, most U was retained in plant roots, and this distribution pattern was further enhanced by mycorrhizal colonization. The results of this study suggest a role for Arbuscular mycorrhizas (AM) fungi in phytostabilization of U tailings (Chen et al., 2008). So, the presence of phytostabilization plant species combined with AM, on radioactive mine tailings and the receiving contaminated soils, can be a suitable approach to: prevent for several environmental and health concerns (since such type of tailings contain not only U, but other radionuclides); contain U dispersion at the root levels, thus meaning that uranium will not be dispersed on soil surface by runoff, or into the air by wind and to groundwater by leaching; offer also an aesthetical positive impact on local environment. These studies support the application of aided phytostabilization as a suitable technology for the treatment and containment of mine tailing wastes, along with the opportunity to provide the rehabilitation of the site. Moreover, the use of tolerant plants with high yields may provide an additional income through the use of those biomasses to energy or materials.

10.4. Conclusions

Inefficiencies caused by mining, mineral processing and metallurgical extraction produces different types of mine wastes such as sulfidic mine wastes, mine waters, tailings, cyanidation wastes of gold-silver ores, radioactive wastes of uranium ores, wastes of phosphate and potash ores that remaining on site involve several environmental impacts. Aided phytostabilization is a well-suited technology that can help on the stabilization of metals through precipitation to less soluble forms, enhancing metal reduction, offering the complexation of metals with organic products, the sorption of metals onto root surfaces and metal accumulation in root tissues, providing immobilization, metal uptake on plant components, and leaching and erosion control of

several types of pollutants contained on different types of mine tailings, inclusive radionuclides, and their toxic risks for the environmental chain. Moreover, soil amendments like liming agents, phosphates and apatites, Fe, Al and Mn oxy/hydroxides, organic amendments, and industrial waste products, organic residues such as compost, manure or sewage sludge, among others; when used together with tolerant crops, effectively improve soil physical properties, provide water infiltration and increase water holding capacity. Fast-growing, high yielding and tolerant to PTM plants species are well-suited for phytomanagement operations. Their deep and extensive underground systems, and tolerance to nutrient deficiency on soils along with PTM, improve soil physicochemical properties and fertility, reduce PTM mobility by changing speciation, increase microbial diversity and restore the functionality of the PTM contaminated sites in the long term, and biomass can be further exploited to bioenergy or materials.

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