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Metodologia (Methodology)

Phytohyperaccumulator-AMF (arbuscularmycorrhizal fungi) interaction in heavy metals detoxification of soil

Interação entre hiperacumuladores-FAM (fungos arbusculares micorrizais) na desintoxicação de solos metalíferos

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Soil fungi (micropartner) develop mycorrhizal interactions with 80 % of land plant species (macropartner) (WANG & QIU, 2006). Soil composed of non-degradable heavy metals toxicity that inhibits the growth (LOMBI *ET AL.*, 2001) and water status of plants (BARCELÓ AND POSCHENRIEDER, 1990). HMs in the soil causes vegetation free world. Phytohyperaccumulators gather more than 1 % Zn or Mn, 0.1 % Ni, Cu, Co or Pb and 0.01 % Cd in the shoots (COBETT, 2003) than roots (VÁZQUEZ *ET AL.*, 1994). These plants can cope with low levels of fertility and poor soil structure, which may induce mineral deficiencies (STANLEY AND ISABELLE, 2015). Mycorrhizae are the mutualistic symbiotic association (non-pathogenic) of a specific group of soil-borne fungi with the roots of higher plants (SIEVERDING, 1991). Arbuscular mycorrhizal fungi colonize the roots of approximately 65 % of all known land plant food and bio energy crops

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(Wang & Qiu, 2006) may interfere with heavy metal absorption (Liao *et al.*, 2003). AMF is reported to enhance nutrient supply and improve water use efficiency and photosynthesis in salt marsh plant species, but the rate of AMF colonization drastically decreases at moderate salinities (Caravaca *et al.*, 2005).

Root exudates (organic chemicals) enhance the mobility of metals and nutrients by (Pérez-Esteban *et al.,* 2013) (i) acidification due to proton (H^+) release or by forming organic/amino acid-metal/mineral complexes(ii) intracellular binding compounds (*e.g.,* phytochelatins, organic acids, and amino acids) (iii) electron transfer by enzymes in the rhizosphere (*e.g.*, redox reactions), therefore enhancing phytoremediation efficiency (Sessitsch *et al.,* 2013). The low molecular weight organic acids (LMWOAs) *e. g.*, oxalate, released by both mycorrhizal and non-mycorrhizal seedlings contributed to metal immobilization by stable metal complexes in soil (Johansson *et al.,* 2008).

Establishment of Mutualistic Symbiosis b/w Phytoaccumulator-AMF

a) Phyto Chemotaxis

Root exudates are chemo attractant signals for AMF (Chaparro *et al.*, 2013) in unique environment of rhizosphere and sources of organic and inorganic elements for fungi (Compant *et al.*, 2010) therefore creating crosstalk in plants and fungi (Compant *et al.,* 2011).

b) AMF Association

Zn violets enhance the rhizospheric phenomenon in polluted soil (Tonin *et al.*, 2001). Plant-fungal association is a species specific and competitive process (Reinhold-Hurek and Hurek, 2011). Rate of colonization of roots by mycorrhizal fungi increases with increasing heavy metal content in serpentine soil (Audet and Charest, 2006).AMF needed maximum nutrients during reproductive stage so they are suitable to flourish in HMs (reproductive period (Vogel-Mikus *et al.,* 2006) HMs from AMF (cell wall, cytoplasm, Vesicles, arbuscules, intraradical hyphae) stores in inner root parenchyma cells. Literature supported the vesicle as a storage compartment of HMs (Turnau, 1998; Weiersbye *et al.*, 1999. AMF makes macro and micro colonies inside and outsides tissues of the plants (Ma *et al.,* 2015; Wang *et al.,* 2016).

Performance of Mutualistic Symbiosis

Plant–Fungal crosstalk is a significant and beneficial process to distinguish the underground communities. Metal resistant activity of AMF enhances membrane permeability and metabolic functions of phytohyperaccumulators in serpentine soil.

Nutrient-absorbing AMF facilitate the hyperaccumulators to absorb maximum minerals and nutrients from the contaminated soil as well as proficient in increasing the fertility of heavy metals contaminated soil (NAVARRO-NOYA *ET AL.,* 2012). This association prevents the plant from production of ethylene in soil stress conditions. AMF actors act as a biomodifiers and modify the original appearance of roots in prosperous style (Ahemad and Kibret, 2014).They act as biopesticides that kill phyto pathogens by releasing antifungal agents (Fig 1).

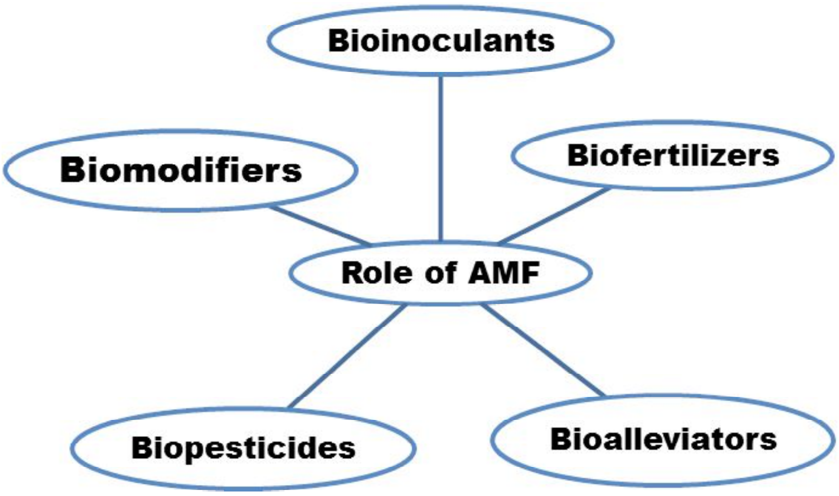

Fig. 1. Action of AMF for phytohyperaccumulators.

Phosphorous is major macronutrients unavailable for plant growth in soil (HARRIS AND LOTTERMOSER, 2006). The insoluble P compounds in soil can be solubilized by enzymes, organic acids and/or chelating agents excreted by both plants and fungi (JEONG *ET AL.*, 2013). AMF *Glomus* spp. is benefited for plant growth and nutrient (N, P, and K) uptake by leguminous trees grown on Pb/Zn mine tailings. Arbuscular mycorrhizal fungi (AMF) are capable of boosting plant growth (ORLOWSKA *ET AL.,* 2013) and nutrients uptake (GUO *ET AL.,* 2013), reduce metal induced toxicity (MEIER *ET AL.*, 2011), change metal availability through alteration of soil pH (RAJKUMAR *ET AL.,* 2012) and affect metal translocation (HUA *ET AL.,* 2009). Exudates from plant roots create intricate communication systems (nutrient and energy) with fungi of metalliferous sites called allelopathic actions, which attracts AMF. AMF induces the defense mechanisms against phytopathogens directly through the solubilization of mineral nutrients (nitrogen, phosphate, potassium, iron, etc.), production of plant growth promoting substances (*e.g.*, phytohormones- indole-3-acetic acid (IAA), gibberellic acid, abscisic acid, and secretion of specific enzymes (*e.g.*, 1-aminocyclopropane-1-carboxylate deaminase) under stress conditions of soil (ULLAH *ET AL.,* 2015).Insoluble specific glycoprotein glomalin produced by hyphae of AMF helps in sequestering heavy metals outside the mycelium (GONZALES-CHAVEZ *ET AL.*, 2004). Accumulated HMs by AMF enters to plants and excreted from there by different organs.

AM fungi releases Myc factors lipochitooligosaccharide (MAILLET *ET AL.*, 2011) that lead to root and AM symbiosis. Genes encoding proteins (*e.g.*, metallothionein and glutathione) efficiently help in tolerance of AMF in contaminated soil. Expression of genes is done in intra and extraradical mycelium.Seven genes (SYM genes) have been identified that are required for fungal-root symbioses (Table 1).

ROLE OF PHYTOACCUMULATORS

Phytoaccumulators associated with AMF store and release the heavy metals in the following organs.

1: Trichome excretions

Cadmium is excreted by trichomes in a glycophyte species (tobacco) (CHOI *ET AL.*, 2004). SARRET *ET AL.* (2006) reported that Zn exposure increased trichome density in young leaves but not in mature leaves of tobacco. Similarly, Cu induced the expression of genes coding for sequestering metallothionein (MT) in *Arabidopsis* trichomes (GUO *ET AL.*, 2003). Glandular trichomes of the hyperaccumulating species *A. halleri* accumulate heavy metals but do not excrete them at the leaf surface.

2: Salt glands

Heavy metals especially Zn excretion takes place through glandular trichomes or salt glands (WEIS AND WEIS (2004).

3: Leaf succulence

In some phtohyperaccumulators,leaf lusciousness help in dilution of concentrated heavy metal contents and toxic impacts in photosynthetic leaves (WANG *ET AL.*, 2012). Absorbed salts increases leaf succulence (KATSCHNIG *ET AL.*, 2013) called reservoir due to sufficient space where water contaminated with toxic ions and heavy metals stores (THOMAS AND BOHNERT, 1993).

4: Histological distribution

Heavy metal accumulated compartments exhibit less metabolic activity. Vacuoles and Cell walls can tolerate HMs concentration (CARRIER *ET AL.*, 2003).

Table 1. Genes of the common symbiosis pathway.

Signaling component-receptor Gene	**Function**	**References**
kinase *SymRK*	Leucine-rich receptor–like kinase that plays an essential role for root endosymbioses with Rhizobia bacteria, AM fungi and *Frankia* bacteria, and is involved in the signal transduction to the cytoplasm after the perception of Nod or Myc factors.	(Gherbi *et al.*, 2008)
NUP85/ *NUP133*	Putative components of the nuclear pore complex that are involved in the transport of macromolecules through the nuclear envelope.	(Parniske 2008)
CASTOR/ *POLLUX*	Cation channels in the nuclear envelope that are essential for the perinuclear calcium spiking after the perception of Nod or Myc factors.	(Charpentier 2008).
CCaMK	Calcium and calmodulin-dependent protein kinase with three calcium binding motifs that acts as sensor of the nuclear calcium signatures and is involved in the phosphorylation of *CYCLOPS.*	(Kistner *et al.*, 2005)
CYCLOPS	Protein with unknown function that acts as phosphorylation target of *CCaMK* downstream of the nuclear calcium spiking and is presumably the branchpoint of the common SYM pathway.	(Kistner *et al.*, 2005)
PAM1	intracellular hyphae in mycorrhizal roots	(Kistner *et al.*, 2005)
MtCbf1 and *MtCbf2*	Re-programming of root tissues during the establishment of an AM symbiosis.	(Hogekamp et al., 2011).
(BEG 34)/ (GintZnT1)	Increased transcript levels of a putative Zn transporter gene and protecting against Zn stress	(Gonzalez-Guerrero *et al.*, 2005)
GintABC1	Cd and Cu detoxification in the ERMof *G. intraradices.*	(Gonza´lez-Guerrero *et al.*, 2006)
Sy167	Alleviating the HM-induced oxidative stress	(Ulrich *et al.*, 2007)

5: Mucilage

Polysaccharides are mixed in mucilage and found in various plant organs *e.g.* rhizomes, roots and seed endosperm of several plant species. Na^+ as a divalent cations stores in halophytes (GHANEM *ET AL.,* 2010) and in heavy metal form in shoots and root tissues (JAVED *ET AL.*, 2013). Arsenic (FOX *ET AL.*, 2012), chromium (LAKSHMANRAJ *ET AL.*, 2009) and aluminium (MIYASAKA AND HAWES, 2001) gather and stores in pectic polysaccharides.

MECHANISMS OF ALLEVIATION

Acidification, precipitation, chelation, complexation, and redox reactions, phytoremediation, detoxification, mobilization, immobilization, transformation, transport and distribution in hyperaccumulating plants helps to clean up metal contaminated soils through extraction (phytoextraction), stabilization (phytostabilization), and transformation (phytovolatilization) process (LEBEAU *ET AL.*, 2008; GLICK, 2010).

PHYTOACCUMULATOR-AMF SIGNALING

Plant-released signals

Flavonoids from roots are signaling components in plant–mycorrhizal formation (STEINKELLNER *ET AL.,* 2007). Flavonoids help in AMF spore germination, hyphal growth, differentiation, and root colonization in AMF-plant interactions (BADRI *ET AL.*, 2009; MANDAL *ET AL.*, 2010).

AMF-roots possessed intermediate levels of flavonoids pattern in early establishment, whereas, high levels of flavonoids (such as phytoalexin and medicarpin) in later stages of colonized roots(LAROSE *ET AL.*, 2002; BADRI *ET AL.,* 2009). Flavonoid exerts a negative or neutral effect on different fungi due to its specificity involved in mycorrhizal symbiosis formation (SCERVINO *ET AL.,* 2005).

Microbial Signals:

Myc factor of AMF (MAILLET *ET AL.,* 2011) modulates root system architecture (*e.g.*, lateral root branching, formation of new organs), facilitating symbiotic infections (MAILLET *ET AL.*, 2011), alter the chemical composition of root exudates, plant physiology and plant defense via releasing of various signaling molecules, such as volatile organic compounds (VOCs) are enabling host plants to colonize nutrient (*e.g.*, sulfur and iron) in poor soils (BAILLY AND WEISSKOPF, 2012).

METAL DETOXIFICATION

AMF are capable of metal translocation and distribution in inner root parenchyma cells (KALDORF *ET AL.*, 1999). The mechanisms involved (1) cell surface biosorption/precipitation of metals; (2) active efflux pumping of metals out of the cell via transporter system; (3) sequestration of metals in intracellular compartments (mainly cell vacuole); (4) exclusion of metal chelates into the extracellular space; and (5) enzymatic redox reaction through conversion of metal ion into a non-toxic or less toxic state (Fig 2)

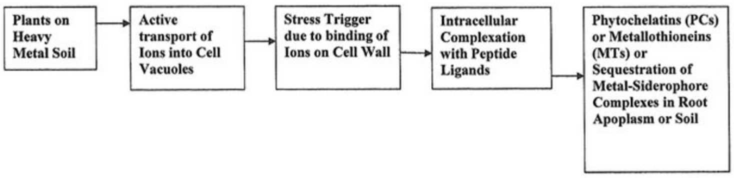

Fig.2 Mechanism of heavy metals detoxification.

Roots release exudates called LMWOAs (succinic acid, citric, oxalic, malic) (Meier *et al.,* 2012) that encourage AMF growth. Chelators in rhizosphere dissolves sparingly soluble mineral, nutrients (Zn, Fe, P), and detoxify metals and metalloids (Pb, As, Cd, Cu) (Li *et al.,* 2013) and facilitate apoplast/symplastic movement of metal ions (Magdziak *et al.,* 2011).

a) Bioaccumulation

Intracellular accumulation of HMs called Bioaccumulation, a complex process. Bioaccumulation process concentrates the toxic metals in non-living (biosorption) (Ma *et al.,* 2013) or living (bioaccumulation) cells (Rajkumar *et al.,* 2012).

Physical and chemical Bonding of metals with waste materials of fungi called passive biosorption. It is not dependent on metabolism of fungi. But the metabolism-dependent active bioaccumulation involved carrier mediated ion pumps, complex permeation and endocytosis (Chojnacka, 2010).

S-layer proteins entrap metal ions either in bio or non bio cells called biosorption (Gadd, 2004), while facilitator or carrier proteins are involved in bioaccumulation of P and S essential nutrients (Suarez and Reyes, 2002; Elangovan *et al.,* 2005).

b) Bioleaching

Penicillium, *Aspergillus*, *Trichoderma* and *Fusarium*are (Mulligan and Galvez-Cloutier, 2003) uses their metabolic machineries in alleviating metal phytotoxicity bydissolution, complexation, adsorption and Redox reactions (Pathak *et al.*, 2009). This reaction helps in bioleaching of heavy metals (Cd, Zn, Cu, Cr, Fe, Pb) from sediments, soils and sludge.

Metal Mobilization

Strong binding of metals to soil particles accounts for the insolubilization of metals in soil and contributes to their unavailability for plant uptake phytoextraction (Ma *et al.*, 2013).Metal mobilizing fungi modify the rhizosphere and mobility in soil through biogeochemical cycling processes of heavy metals by acidification, protonation and chelation (Rajkumar *et al.*, 2012; Sessitsch *et al.*, 2013).

c) Biogeochemical cycling of heavy metals

The influence of fungal activity on metal mobilization/immobilization, translocation and transformation improve metal bioremediation processes (Sessitsch *et al.*, 2013; Ahemad and Kibret, 2014). Acidification, chelation and protonation lead to mobilization of metals, whereas precipitation, alkalinization, and complexation cause metal immobilization whereas chemical transformation can cause metal mobilization or immobilization of heavy metals.

d) Acidification

Mobility of metals decreases with increasing soil pH (Richards *et al.*, 2000) has influenced on the activities of both plants and fungi. The hydrogen ions excreted by plant roots can displace heavy metal cations adsorbed on soil particles, leading to acidification of the rhizosphere. Root exudates can lower the pH of rhizosphere (Sheoran *et al.*, 2011), which enhancing soil metal mobility and plant metal bioavailability in soil solution (Alford *et al.*, 2010).

e) Chelation

Natural organic chelators are known as metal-binding compounds, organic acid anions, siderophores, biosurfactants, and metallophores (Sessitsch *et al.*, 2013) are released from both plants and fungi which scavenge metal ions (Gadd, 2004) and reactive oxygen species (Leitenmaier and Küpper, 2013).

Reactive oxygen species (ROS- O_2^-, H_2O_2, and –OH) are generated under stress conditions and bear strong oxidizing activities that can attack all types of biomolecules and represent intermediates emerging during the successive reduction of O_{2-}, to H_2O_2 (Mittler 2002; Panda 2008).Plants experience certain heavy metal ions during the conversion plant accumulation of H_2O_2into highly reactive –OH molecule in a metal-catalyzed reaction via the Fenton reaction. The oxidized metal ions undergo are-reduction in subsequent reaction withsuperoxide radicals (O_2^-).

Fenton reaction

$$H_2O_2 + Fe_2+ /Cu+ \Rightarrow \cdot OH + OH- + Fe_3+ /Cu_2+\cdot O_2- + Fe_3 /Cu_2+ \Rightarrow Fe_2 /Cu + O_2$$

Haber Weiss reaction

$H_2O_2 + O_2 \Rightarrow \cdot OH + OH- + O_2$

The ·OH molecule is one of the most reactive species known to initiate radical chain reactions leads to irreversible chemical modifications of various cellular components. protonated form of ·O2-in lipid peroxidation Heavy metals (HM) like Cu, Zn, Cd, Cr, Pb, Hg, As, Fe etc under toxic concentration inactivates enzymic antioxidant defense system in plants resulting into increased ROS signaling generally leading to death of a plants including membrane permeability, chlorosis, growth retardation, browning of roots, effects on both photosystems, cell cycle arrest and others can be observed (MITTLER, 2002; TIWARI *ET AL.*, 2008).Plants and AM fungi have evolved several mechanisms to maintain ion homeostasis under elevated HM concentrations (CLEMENS 2001; HALL 2002).The basic principles of detoxification mechanisms include the extracellular HMchelationby root exudates and/or binding of HM to the rhizodermal cell walls uptake of HM avoiding. Active plant efflux systemscontrol cytosolic concentrations of HMs.

Intracellularly the plant cell produceschelating agents such as phytochelatins and metallothioneins, which have high-affinity HM binding properties. The resulting complex can finally be exported from the cytoplasm across the tonoplast and become sequestered inside the vacuole (HALL, 2002). Proteinsare involved in linkages with metals, thereby forming complex biochemical compounds called metal-proteins, metallothionein and peptideslike phytochelatins. Besides these, organic acids and amino acids take active part in detoxification of heavy metals in plants(PAL and RAI, 2009).

Metal-binding peptides (MTs-cysteine-rich) can eradicate the phytotoxic effect of free metal ions and allow metal uptake, sequestration, compartmentation, xylem loading, and transport within the plants (CAI AND MA, 2002). Phytochelatins (PCs) are synthesized from the tripeptide glutathione under PCs synthase (SOLANKI AND DHANKHAR, 2011). These PCs is immediately induced by heavy metal exposurein plant tissues (PAL AND RAI, 2010).

MTs also occur in AMF and those genes encoding several enzymes for PCs synthesis in mycorrhizal roots exposed to metal stress and enhancing photosynthetic activity (RIVERA-BECERRIL *ET AL.,* 2005).

Siderophore is producing in fungi due to Fe acquisition by different plant species (GAONKAR and BHOSLE, 2013). Chelation through binding toxic metals to siderophores triggers the enhancement of plant Fe uptake capacity and the decrease of free metal ion concentration (DIMKPA *ET AL.*, 2008). Fe is a micronutrient and its low concentration in soil is necessary to support robust plant and fungal life due to its low solubility under metal stress. Plants acquires sufficient Fe through three mechanisms, 1: (Fe solubilization by all dicots and monocots via rhizosphere acidification) 2: Secretion of phytosiderophores (PSs) and uptake Fe^{3+}-PS, 3: uptake Fe^{3+}-microbial siderophores by plants). Many studies have shown that PSs are able to solubilize and transport metals by chelation, and thus being secreted into the rhizosphere through a potassium-mugenic acid symporter (SAKAGUCHI *ET AL.*, 1999).

METAL IMMOBILIZATION

Some AM fungi also reduce plant metal uptake or translocation to aerial plant parts by decreasing metal bioavailability in soil via precipitation, alkalinization, and complexation processes.

a) Alkalinization

Some AMF exhibit the ability to absorb metals through substratum alkalinization activity by release of OH^-, therefore affecting the metal stability in soil (Büdel et al., 2004) and a reduction in metal phytoavailability in the rhizosphere by secreting glomalin (GIASSON *ET AL.*, 2008). AMF can act as metal sinks to reduce the mobile and available metal cations in soil suitable environment for plants growth in metal contaminated soils (Göhre and PASZKOWSKI, 2006) (Fig 3).

b) Complexation

The excretion of EPSs by plant associated (HOU *ET AL.,* 2013) metal biosorption onto to EPS include metal ion exchange, complexation with negatively charged functional groups, adsorption and precipitation (ZHANG *ET AL.,* 2006). AMF can reduce metal mobility in soil by excreting glomalin (insoluble metal-sorbing glycoprotein) that reduces metal mobility or sequesters metals and metal biostabilization in soil (VODNIK *ET AL.,* 2008) (Fig 3).

Glomalin-related soil proteins (GRSP) are sequestering Pb (0.21–1.78%) and Cd (0.38–0.98%) in an *in situ* field experiment consisted humic and fulvic acids in soil (WU ET AL., 2014).

c) Klebsiella planticola precipitated cadmium (SHARMA *ET AL.,* 2000).

METAL TRANSPORT AND DISTRIBUTION

Different metals are differently mobile rate within a plant, *e.g.,* Cd and Zn are more mobile than Cu and Pb. The metal chelation with ligands (e.g., organic acids, amino acids, and thiols) facilitates the metal movement from roots to shoots (ZACCHINI *ET AL.*, 2009). Due to the high cation exchange capability of the xylem cell, the metal movement is severely retarded when the metals are not chelated by ligands (SHENG *ET AL.,* 2008)

The future research should be focused on: (1) the mechanism of plant-microbe-metal interactions under stressful environmental conditions; (2) the effectiveness of co-inoculation of PGPB and AMF response to multiple biotic and/or abiotic stress; (3) the identification of functional genes of beneficial microbes for growth enhancement and metal metabolism; (4) the optimization of techniques for application in large scale polluted fields; and (5) the exploration of commercial production of bioinoculants for use in metal decontamination.

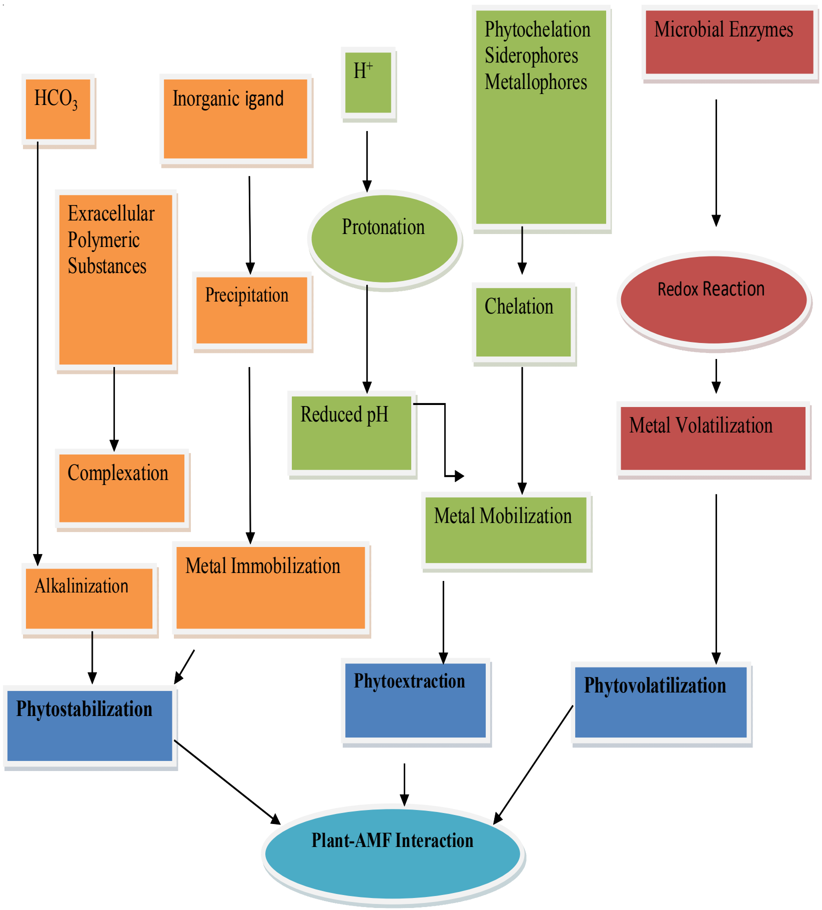

Fig. 3. Mechanism of heavy metals detoxification.

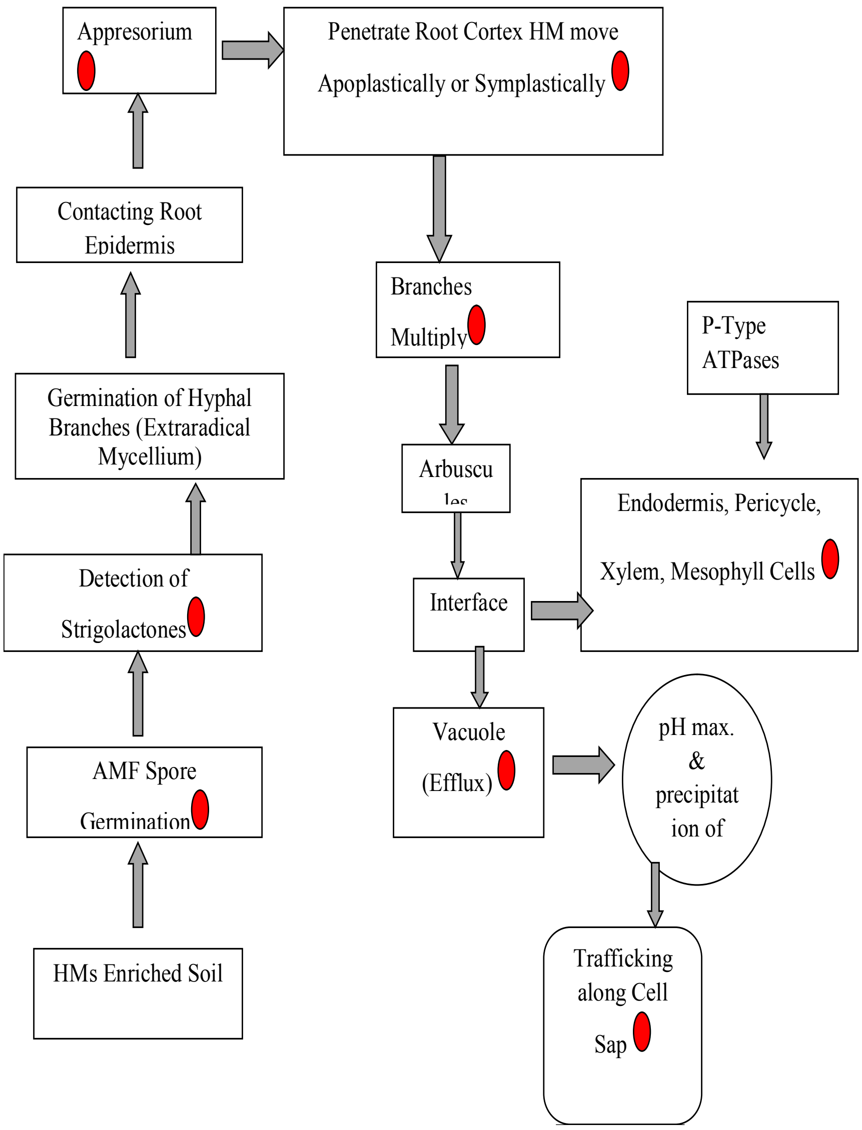

Fig. 4. Pathway for movement of heavy metals from soil to phytohyperaccumulators.

Table 2. Examples of AMF in HM's detoxification (literature citation).

Host Plant	Colonizing AMF	Soil Condition	Mechanism	Experimental Area	Reference
Sunflower	*Rhizophagus irregularis* metal mobilization or immobilization	Soils contaminated with three different Cd concentrations	Phytoextraction of Cd	Greenhouse	(Ma *et al.*, 2011).
Sunflower	*Funneliformis mosseae*	HM Contaminated Soil	Phytostabilization of Cd and Zn	In Field	(Ma *et al.*, 2011).
Litchi chinensis	*Glomus intraradices* and *Gigaspora margarita*	HM Contaminated Soil	Increased endogenous phytohormones level (IAA and isopentenyl adenosines), Plant Growth	In Field	(Yao *et al.*, 2005)
	Aspergillus and *Rhizopus*	HM Contaminated Soil	Biosorption of Cr and Cd	In Field	(Zafar *et al.*, 2007)
Yeast	AMF *Tuber melanosporum*	HM Contaminated Soil	Polypeptides MTs (TmelMT) and PC synthase (TmelPCS) enhanced tolerance to essential (Cu and Zn) and non-essential (Cd, As, and Hg), thiophilic metal ions	In Field	(Bolchi *et al.*, 2011)
S. alfredii, *Lolium perenne*	AMF *Glomus caledonium* and *G. mosseae*	Cd-contaminated acidic soil	Decreased soil DTPA-extractable Cd by 21–38% via alkalinization process	In Field	(Hu *et al.*, 2013)
Salix viminalis *S. caprea*	*Hebeloma crustuliniforme* ectomycorrhiza associated bacteria *Micrococcus luteus* and *Sphingomonas* sp		Cd 53 and 62%, respectively and Zn	In Field	(Zimmer *et al.*, 2009)
Salix caprea	fungus *Cadophora finlandica* inoculation with the rhizobacteria *Streptomyces* sp. and *Agromyces* sp.	Cd and Zn	Higher translocation of metals from roots to shoots	In Field	(Susanna *et al.*, 2011)
Sorghum bicolor	*Glomus intraradices* and *G. spurcum (AMF)*	Cu- and Zn-contaminated soil	(Phytoremediation) reduced Cu and Zn under elevated Cu-Zn conditions, increased Cu and Zn uptake and translocation under normal Cu-Zn conditions	In Field	(Toler *et al.*, 2005)
Thlaspi ssp, *Medicago truncatula*	*Gene-* Sy167 (Intra and extraradical mycelia of *Glomus intraradices*	Cd, Cu or Zn contaminated soil	Metallothionein (90 kD) and glutathione *S*-transferase- alleviation of damage caused by reactive oxygen species	In Field/ Breinigerbergsoil	(Ulrich *et al.*, 2007)
Tomato	*Glomus intraradices*	"Breinigerberg" soil-Zn	Reduction in Zn uptake	In Field	(Fouad *et al.*, 2005)
Thlaspi praecox		Highly Cd, Zn and Pb contaminated substrate	Elevated nutrient demands on heavy metal uptake and tolerance	Greenhouse experiment	(Katarina *et al.*, 2006)
Thymus polytrichus	(AM) fungi	Zn contamination	Enhancing plant uptake of P and Zn	River South Tyne, United Kingdom	(Whitfield *et al.*, 2004)

Table 2 (cont.)

Table 2 (conclusion)

Deschampsia flexuosa (C3 grass)	AMF soil biota	Zn contamination	Reduced Zn concentrations in shoots of *D. flexuosa*	In Field	(Sydney and Brenda, 2012)
Sorghastrum nutans(C4 grass)	AMF + Soil microbes	low-contaminated (LC) soil	Increased the efficacy of AMF from LC soils but decreased the efficacy of AMF from HC soils in promoting plant growth.	In Field	(Sydney and Brenda, 2012)
Phytolacca mericana, *Rehmannia glutinosa* *Perilla frutescens* *Litsea cubeba* *Dysphania ambrosioides*	AMF communities	Heavily polluted rhizospheric soils	*(Glomus show nil effect on D. ambrosioides), Kuklospora* and *Ambis pora* show *D. ambrosioides* and the rhizosphere of *P. americana.*	Dabaoshan Mine region, China	(Liang *et al.*, 2010)
Spore germination, presymbiotic hyphal extension, symbiotic extraradical mycelium expansion and sporulation	*Glomus etunicatum* and *Gl omus intraradices*	Cd, Pb, and Zn	*G. etunicatum* more sensitive than *G. intraradices*	in vitro	(Teresa and Iris, 2004)
Aster tripolium	*Glomus geosporum*	Cd and Cu concentrations	AMF enhance metal accumulation in the root system of *A. tripolium*	In Lab	(Luis *et al.*, 2006)
Aster tripolium	*Contaminated Soil*	AMF	AMF clearly increased Cd and Cu accumulation	In Field	(Carvalho *et al.*, 2006)

SUMMARY

Plants and fungi coexist in serpentine soil (enrich with heavy metals) and their cohesive interactions play a vital role in metalliferous soil. Metallophytes colonized by AMF helps to alleviate the toxicity of metalliferous environments. In this work phytohyperaccumulator-AMF interaction heavy metals (HMs) stress called biology-based technology is examined. Phytohyperaccumulator includes phytovolatilization, phytostabilization, phytoextraction, chelate-enhancement strategy. AMF enhance the efficiency of hyperaccumulator by different mechanism. Acidification, precipitation, chelation, complexation, redox reactions, phytoremediation, detoxification, mobilization, immobilization, transformation, transport and distribution in hyperaccumulating plants helps to clean up metal contaminated soil through extraction (phytoextraction), stabilization (phytostabilization), and transformation (phytovolatilization) processes.

Keywords: Arbuscular; mycorrhizal fungi; glomalin; detoxification

SUMÁRIO

Plantas e fungos coexistem em solos serpentinos (ricos em metais pesados) e suas interações têm um papel fundamental nesses solos metalíferos. Metalófitos colonizados por fungos arbusculares micorrizais auxiliam a aliviar a toxicidade dos ambientes metalíferos. Neste trabalho, as interações de hiperacumuladores, FAM (fungos arbusculares micorrizais), que se desenrolam em condições de estresse por metais pesados, e que constituem uma parte da biologia tecnológica, são discutidas. Essas interações incluem estrategias de: fitovolatilização, fito-estabilização, fitoextração, *aprimoramento* quelático. FAM confere eficiência aos hiperacumuladores por meio de diferentes mecanismos. *E. g.,* acidificação, precipitação, quelação, complexificação, reações-redox, fitoremediação, detoxicação, mobilização, imobilização, transformação, transporte, distribuição, *i.e.,* processos que em plantas acumulantes ajudam a limpar a contaminação metálica mediante mecanismos de extração e estabilização.

PALAVRAS-CHAVE: Arbuscular; fungos mycorrizais; glomalina; detoxificação

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