Cultivos Tropicales, 2021, vol. 42, no.4, e14
ISSN impreso: 0258-5936
ISSN digital: 1819-4087

octubre-diciembre
Ministerio de Educación Superior. Cuba
Instituto Nacional de Ciencias Agrícolas

http://ediciones.inca.edu.cu

Bibliography review

Association between heavy metals and arbuscular mycorrhizae-forming fungi

Thaylin Riopedre-Galán[1*]

Anicel Delgado-Álvarez[1]

Juan Adriano Cabrera-Rodríguez[1]

Omar E. Cartaya-Rubio[1]

[1]Instituto Nacional de Ciencias Agrícolas (INCA), carretera San José-Tapaste, km 3½, Gaveta Postal 1, San José de las Lajas, Mayabeque, Cuba. CP 32 700

[*]Author for correspondence: thaylin@inca.edu.cu

ABSTRACT

In recent years, heavy metal contamination has been a topic that has aroused special interest worldwide, due to the toxicity of heavy metals. Heavy metals can reach the trophic chain by different routes, since many of them are essential nutrients and they are absorbed by plants. There are several technologies to remediate contaminated soils, including phytostabilization and phytoextraction, as part of phytoremediation strategies. Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with plants and help those combat different stress types, including metal stress. Essential micronutrients are absorbed in greater quantities by mycorrhizal plants; however, when these elements are found in high concentrations in the soil as contaminants, mycorrhizal fungi can store these cations, avoiding toxicity in plants or hyperaccumulation, a phenomenon known as phytostabilization.

Key words: pollution, phytoremediation, phytostabilization

INTRODUCTION

Heavy metals (HM) constitute a danger to mankind, because once the element reaches the soil, it follows two pathways leading to the trophic chain: by absorption by plants or by washing into groundwater, and can reach living organisms and cause acute damage, even death [1,2].

The polluting sources of heavy metals can be various, from the use of an old industrial land for agriculture to the indiscriminate use of agrochemicals in an agricultural ecosystem [3]; however, plants have developed defense mechanisms against this polluting situation, even achieving a hyperaccumulation of these metals in some cases [4].

In some plant species, tolerance to heavy metals, through the use of arbuscular mycorrhizae, constitutes an example of bioaccumulation and biosorption [5,6] and they can be used in phytoremediation programs, since it has been seen how these fungi are able to accumulate heavy metals in their spores and hyphae and decrease the content of these metals in accumulator plants [7].

For this reason, some aspects of the phytostabilization of heavy metals by arbuscular mycorrhizal fungi are discussed in this work.

Heavy metals in the agroecosystem

Heavy metals are naturally present in soils, some to a greater and others to a lesser extent, depending on the material that gave rise to them, but there has been an anthropogenic accumulation due to industrial and agricultural activities and the disposal of waste of all kinds [3,6,8].

A heavy metal is considered to be that element that has a density equal to or greater than 5 g cm^3 when in elemental form or whose atomic number is greater than 20 g cm^3, excluding alkaline and alkaline-earth metals [9]. Due to the small quantities commonly handled, these are referred to as "trace elements" or "trace metals" and include aluminum, which cannot be qualified as a "heavy metal" because of the characteristics mentioned above, but because of its toxicity [6,10], although this definition also includes essential elements for plants such as Iron (Fe), Copper (Cu), Manganese (Mn), Zinc (Zn) and Nickel (Ni) or others essential for animals such as Cobalt (Co) and Chromium (Cr) [11].

Essential micronutrients are required in only a few milligrams or micrograms per day and when they pass a certain concentration threshold they become toxic, such is the case of Selenium and Zinc, which have very close limits between the required dose and the toxic one [4].

The non-essential heavy metals or those with no known biological function, whose presence in certain quantities in living beings leads to dysfunctions in organisms, are: antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), strontium (Sr), mercury (Hg), lead (Pb) and titanium (Ti) [8]. The main sources of soil contamination with heavy metals are irrigation with water from streams and wastewater contaminated by industry, the application of contaminated solid waste and the use of former industrial land contaminated by oil and industrial waste discharges, as well as poor irrigation and drainage practices and the intensive use of fertilizers and pesticides [9].

In soil, the mobility of heavy metals in their cationic forms decreases as pH increases, because they precipitate forming hydroxides, carbonates or by forming organic complexes that are not assimilated by organisms [10]. The quantities of Ni in soils depend on the physical-chemical characteristics of the soil. This element is highly mobile and considered essential for plant metabolism, requiring minimal amounts (0.001 mg kg^{-1}) [12,13]. It is deposited in leaves and seeds, and chlorosis is a common symptomatology associated with high levels [13].

Potentially toxic substances can also enter the plant through the foliar route, depending on the morphology and respiration rate of the plant that allows its entrance, from the accumulation and variation in concentration gradients. Metals from aerial sources of contamination, such as Pb, reach the plant as a result of wind drift. Likewise, foliar fertilizer applications generate reactions that facilitate the translocation of metals to the interior of the tissue [14,15]. Pb can cause damage to plant germination, reduce enzymatic activity, carbon assimilation, and photosynthesis, among others [16].

In the case of cadmium, given its high solubility in the soil, it is translocated from the roots to the aerial parts of plant, increasing the risk of its incorporation into the food chain, due to its similarity with calcium (Ca^{2+}) [17]. It has been reported that this element can cause leaf rolling and chlorosis, alter RNA synthesis, reduce photosynthetic activity, inhibit stomatal opening and decrease enzymatic activity in plants [18].

In a study carried out in Cuban soils of low or null anthropic activity, high natural contents of HM were found in mg kg^{-1}: Cu (163-138), Ni (68-676), Cr (78-1259), Zn (83-462), Pb (36-67) and Cd (2-10.9) which, when compared with the international norms, are much higher [19].

Soil is one of the matrices most closely linked to the pollution retention and its magnification in the trophic chain. The introduction of pollutants into the soil can result in damage to its structure, loss of vital ecological functions for the ecosystem homeostasis and consequently of its agricultural and environmental value [19,20]. Agricultural soils require special attention, since they serve as a nutritional source for plants destined for human and animal consumption and must guarantee the safety of food generated in them [21]. If toxic elements such as Cd and Pb reach crops, they can be a problem for the entire trophic chain [22]. In this regard, a study carried out in China determined that there is a high risk for consumers of rice grown in areas near the Yangtze River, as high levels of heavy metals were found in soil, stalks and grains. According to the risk quotients, people were exposed to cancer risk mainly due to Cd, Pb and As concentrations [23].

The technological process applied to crops can itself be a source of heavy metal contamination in soils. This pollutant load generated by the technology can be transferred to the crops grown in these soils, due to the adaptive and intrinsic characteristics of each one of them [24]. There are plant species that have the capacity to remove and store these elements from the soil in high concentrations; these plants are classified as heavy metal accumulators and hyperaccumulators [20].

Among plants that accumulate metals, species have been found that have the capacity to store extraordinary quantities, such as potatoes (*Solanum tuberosum* L.), tomatoes (*Solanum lycopersicum* L.), rice (*Oryza sativa* L.), among others; these concentrations are notably higher than the indexes considered toxic for the plant kingdom, which are called hyperaccumulator plants. The effect of heavy metals on plants results in a change in their biochemical activity, as well as in their functioning [25]. The ability to accumulate metals is not a common characteristic of most plants; on the contrary, it is the result of an evolutionary response, since the natural occurrence of high levels of metals in the biosphere is sporadic [26].

Arbuscular mycorrhizal symbiosis

Mycorrhizal symbiosis in ecosystems is a plant adaptation mechanism to different stressful conditions, since it facilitates increases in the absorption of nutrients and water, improves soil aggregates, causes a bioprotection effect against some pathogens, among other benefits [27,28].

This union is defined as a symbiotic association, since both organisms establish successive exchanges of nutritive substances, essential metabolites and hormonal substances, as well as lead to the creation of new structures, representing a mutual benefit for both symbionts [29].

The role of mycorrhizae in the absorption of nutrients is very complex, and may be the result of several possible mechanisms (30), such as:

Increase in the surface area of root absorption and soil exploration (physical effect).

Increase in root absorption capacity (physiological effect).

Morphological and physiological modifications in mycorrhizal roots, in relation to non-mycorrhizal roots.

Absorption of available nutrients not accessible to non-mycorrhizal roots directly through hyphae or indirectly by favoring root development.

Utilization of forms not available to non-mycorrhizal roots through solubilization and mineralization in the case of ectomycorrhizae and modifications in the dynamics of the nutrient balance between the solid and liquid phase of the soil, in the case of AMF.

Temporary storage of nutrients in the fungal biomass or roots avoiding their chemical and biological immobilization or leaching.

Establishment of mineralizing, nutrient solubilizing and diazotrophic microorganisms in the mycorrhizosphere.

Amortization or mitigation of the adverse effects of heavy metals, salinity, water stress and attack of root pathogens on nutrient uptake.

In recent years in Cuba, a wide group of positive results have been achieved on the management of arbuscular mycorrhizal symbiosis in agroecosystems, based on the existence of inoculants that are applied in low quantities and the knowledge of the bases for an effective management of these and integrated not only with mineral fertilizers, but also with green and organic fertilizers (31-34).

AMF effect against heavy metals

Plants and fungi have developed strategies to obtain nutrients from soils of varied composition, using different mechanisms in the assimilation of metals, at the same time that they prevent toxicity, coordinate transport, chelation and sequestration of metallic elements at the cellular level, to maintain the ionic balance (35).

High amounts of metals can be accumulated in a variety of physiological processes, independently of the associated metabolic pathway, using biomass (live-dead), as well as cellular products (polysaccharides), in the removal of heavy metals (36). For this reason, the genome of eukaryotes encodes several families of metal transporters, which direct the translocation process inside plants and fungi, differing in location at the cellular level, specific substrate on which expression patterns act [35].

Different microorganisms are capable of actively and passively concentrating metals at levels that are substantially higher than those of the surrounding environment, which is why for several decades there has been a growing interest in microorganism-metal interaction and its possible commercial applications. The immobilization of HM by active (energy-dependent) and passive (energy-independent) processes are known as bioaccumulation and biosorption, respectively, and include mechanisms such as chelation, ion exchange, and encapsulation [4].

Plants have developed mechanisms that modify their environment by excreting organic compounds through the root, as a rich substrate for the surrounding microbial community [37,38], involving basic aspects such as chelation and acidification of the rhizosphere, among others, which decrease the mobility of heavy metals [39]. The most important structures of arbuscular mycorrhizal fungi involved in symbiosis and tolerance to heavy metals are the arbuscules, vesicles and hyphae [40].

Several investigations have shown the stabilizing capacity of these fungi on the absorption of metals by the plant. This buffering effect translates into an increase in the supply of micronutrients to the plant when it grows in soils deficient in these micronutrients, while reducing the incorporation of metals into plant tissues when plants grow in soils with high levels of these metals [40].

Other authors demonstrated that mycorrhizal fungi were able to increase the concentration of Zn by the plant under conditions of deficiency of this element in the soil, while, when levels of the metal in the soil exceeded a certain threshold, the concentration of Zn decreased considerably [41,42].

The phytostabilizing effect of mycorrhizae on the aerial part of the plant has been observed on multiple occasions, and protection against Al, U, Cs, Sr, Cd, Mn, Zn and Cu has been described [40]. This protective effect is mainly due to the immobilization of the metal in the mycelium of the fungus, especially in cell walls [42], but also in internal mycelial structures such as vesicles or, at an intracellular level, polyphosphate granules [40]. Metal accumulation in the fungus internal mycelium is what would explain its accumulation in roots of mycorrhizal plants considered as a whole (root + fungus) [41]. In fact, the aerial biomass tissues of mycorrhizal plants have lower levels of heavy metals than those of non-mycorrhizal roots when the plant grows in soils with elevated levels of metals [43]. When comparing the effect of fungi isolated from contaminated soils in relation to fungi isolated from non-contaminated soils, it is observed that the former are more effective,

Cultivos Tropicales, 2021, vol. 42, no.4, e14
ISSN impreso: 0258-5936
ISSN digital: 1819-4087
octubre-diciembre
Ministerio de Educación Superior. Cuba
Instituto Nacional de Ciencias Agrícolas
http://ediciones.inca.edu.cu

although their successive cultivation in non-contaminated soils may reduce this capacity [44]. The fact that not all mycorrhizal fungi have the same tolerance to heavy metals could facilitate the use of the most sensitive isolates as biomarkers of contamination [45].

Other researchers obtained as a result that inoculation with AMF and salicylic acid increased the tolerance of bell pepper plants (*Capsicum annum* L.) to high concentrations of Cu in the soil, inducing tolerance mechanisms to stress caused by heavy metals [46].

In Mexico, the capacity of the genus *Amaranthus* to accumulate Pb and Cd when inoculated with mycorrhizal fungi of the genus *Glomus* has been evaluated, showing a higher percentage of colonization of the fungus and greater extraction of the crop when concentrations of these metals increase, even when none of these are essential nutrients for plants [47].

Siderophores, apart from their ability to bind Fe, can also form complexes with other metals such as Al, Cd, Cu, Pb and Zn, which causes an increase in the solubility of these metals in the soil [48].

Glomalin, a glycoprotein produced by mycorrhizal hyphae, has shown its potential to establish links with highly toxic molecules such as heavy metals, which constitutes an effective barrier that accumulates them in the mycelial mass without allowing them to enter plant cells [49].

Heavy metals can be immobilized by secretion of glycoproteins or adsorbed on fungal cell walls, thus reducing their toxic effect on plants [50]. Both the capacity to increase the acquisition of mineral micronutrients by plants growing in deficient soils, and to decrease it in those growing in soils contaminated with heavy metals, depend on the action of a set of processes to maintain homeostasis in arbuscular mycorrhizal fungi [40].

In Brazil, a study was conducted on the biochemical and nutritional changes induced by Pb in sunflower plants (*Helianthus annus* L.). Pb toxicity generates changes in the nutritional balance of Ca and Mg, which can be used as a nutritional marker of Pb toxicity in sunflower. Proline concentrations, which are proportional to the increase of Pb concentrations in the plant, can also be used as a biochemical marker in this crop. This amino acid reduces the toxic effect of metals and can contribute as an available source of carbon and nitrogen [51].

Several studies have shown that phytostabilization of heavy metals generated by arbuscular mycorrhizal fungi in the plant can be a good management solution to the contamination problem [52]; however, it is characterized by its great distance in practical terms.

For the application of this technique, each case must be considered as unique and unrepeatable, because the environmental characteristics of each crop exposed to these conditions, as well as the elements involved (heavy metal, plant, environment, mycorrhizae) infers particular features and in constant dynamics, which directly influences this technique success [(4)]. Therefore, phytostabilization of heavy metals by means of AMF can constitute a phytoremediation strategy for contaminated soils.

CONCLUSIONS

- Heavy metals in the agroecosystem constitute a risk for the food chain since some of them, despite being micronutrients necessary for plants and animals, large concentrations of these can cause toxicity or other damage.
- Arbuscular mycorrhizal fungi are an alternative to counteract the toxic effect caused by heavy metals for plants, by phytostabilizing concentrations of these elements.

BIBLIOGRAPHY

1. Achiba WB, Gabteni N, Lakhdar A, Du Laing G, Verloo M, Jedidi N, et al. Effects of 5-year application of municipal solid waste compost on the distribution and mobility of heavy metals in a Tunisian calcareous soil. Agriculture, Ecosystems & Environment. 2009;130(3):156–163.

2. Barrueta-Gálvez A, Echemendía-Pérez M. Evaluación del uso de plaguicidas en la campaña de producción de semillas de papa (*Solanum tuberosum* L.) y el nivel de Pb y Cd en semilla y suelo. Revista de Protección Vegetal. 2015;30:148–148.

3. Bainard LD, Klironomos JN, Gordon AM. The mycorrhizal status and colonization of 26 tree species growing in urban and rural environments. Mycorrhiza. 2011;21(2):91–96.

4. Aguirre W, Fischer G, Miranda D. Tolerancia a metales pesados a través del uso de micorrizas arbusculares en plantas cultivadas. Revista Colombiana de Ciencias Hortícolas. 2011;5(1):141–154.

5. Giuffré L, Ratto S, Marbán L, Schonwald J, Romaniuk R. Riesgo por metales pesados en horticultura urbana. Ciencia del suelo. 2005;23(1):101–106.

6. García I, Dorronsoro C. Tema 15. Contaminación por metales. Introducción. [Internet]. [cited 20/07/2021]. Available from: http://edafologia.ugr.es/conta/tema15/introd.htm

7. Kozłowski M, Naumnik W, Nikliński J, Milewski R, Łapuć G, Laudański J. Lymphatic vessel invasion detected by the endothelial lymphatic marker D2-40 (podoplanin) is predictive of regional lymph node status and an independent prognostic factor in patients with resected esophageal cancer. Folia Histochemica et Cytobiologica. 2011;49(1):90–97.

8. Huancaré Pusari RK. Identificación histopatológica de lesiones inducidas por bioacumulación de metales pesados en branquias, hígado y músculo de trucha arcoíris (*Oncorhynchus mykiss*) de cultivo en etapa comercial de la laguna de Mamacocha, área de influencia minera, Cajamarca-Perú. [Tesis de grado]. [Lima-Perú]: Universidad Nacional Mayor de San Marcos; 2014. 127 p.

9. Nanos N, Martín JAR. Multiscale analysis of heavy metal contents in soils: spatial variability in the Duero river basin (Spain). Geoderma. 2012;189:554–562.

10. Miranda Lasprilla D, Carranza C, Fischer G. Calidad del agua de riego en la sabana de Bogotá. 1ra ed. Bogotá, Colombia: Gente Nueva; 2008. 234 p.

11. Peris Mendoza M. Estudio de metales pesados en suelos bajo cultivos hortícolas de la provincia de Castellón. [Doctorado]. [España]: Universitat de València; 2005. 327 p.

12. Ker K, Charest C. Nickel remediation by AM-colonized sunflower. Mycorrhiza. 2010;20(6):399–406.

13. Acevedo E, Carrasco A, León O, Martínez E, Silva P, Castillo G. Criterios de calidad de suelos y aguas de riego [Internet]. 2005. [cited 20/07/2021]. Available from: http://biblioteca-digital.sag.gob.cl/documentos/medio_ambiente/criterios_calidad_suelos_aguas_agricolas/inicio.htm

14. Janoušková M, Pavlíková D, Vosátka M. Potential contribution of arbuscular mycorrhiza to cadmium immobilisation in soil. Chemosphere. 2006;65(11):1959–1965.

15. Entry JA, Rygiewicz PT, Watrud LS, Donnelly PK. Influence of adverse soil conditions on the formation and function of arbuscular mycorrhizas. Advances in Environmental Research. 2002;7(1):123–138.

16. Zulfiqar U, Farooq M, Hussain S, Maqsood M, Hussain M, Ishfaq M, et al. Lead toxicity in plants: Impacts and remediation. Journal of environmental management. 2019;250:109557.

17. Albert LA. Introduccion a la toxicologia ambiental. Metepec, México: ECO; 1997. 417 p.

18. Huang D, Gong X, Liu Y, Zeng G, Lai C, Bashir H, et al. Effects of calcium at toxic concentrations of cadmium in plants. Planta. 2017;245(5):863–873.

19. Amaral Sobrinho N, Febles González JM, Lopéz Y., Guedes J., L. Magalhães M., Zoffoli HJ. Natural content of heavy metals on cattle regions soils of Mayabeque and Artemisa province in Cuba. Cuban Journal of Agricultural Science. 2013;47(2):8.

20. Hu Z, Wang C, Li K, Zhu X. Distribution characteristics and pollution assessment of soil heavy metals over a typical nonferrous metal mine area in Chifeng, Inner Mongolia, China. Environmental earth sciences. 2018;77(18):1–10.

21. Yongming H, Peixuan D, Junji C, Posmentier ES. Multivariate analysis of heavy metal contamination in urban dusts of Xi'an, Central China. Science of the total environment. 2006;355(1):176–186.

22. Musilova J, Arvay J, Vollmannova A, Toth T, Tomas J. Environmental contamination by heavy metals in region with previous mining activity. Bulletin of environmental contamination and toxicology. 2016;97(4):569–575.

23. Mao C, Song Y, Chen L, Ji J, Li J, Yuan X, et al. Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. Catena. 2019;175:339–348.

24. Delince W, Valdés Carmenate R, López Morgado O, Guridi Izquierdo F, Balbín Arias MI. Riesgo agroambiental por metales pesados en suelos con Cultivares de *Oryza sativa* L y *Solanum tuberosum* L. Revista Ciencias Técnicas Agropecuarias. 2015;24(1):44–50.

25. Ramos-Garza J, Bustamante-Brito R, Ángeles de Paz G, Medina-Canales MG, Vásquez-Murrieta MS, Wang ET, et al. Isolation and characterization of yeasts associated with plants growing in heavy-metal-and arsenic-contaminated soils. Canadian journal of microbiology. 2016;62(4):307–319.

26. Prieto Méndez J, González Ramírez CA, Román Gutiérrez AD, Prieto García F. Contaminación y fitotoxicidad en plantas por metales pesados provenientes de suelos y agua. Tropical and subtropical Agroecosystems. 2009;10(1):29–44.

27. Willis A, Rodrigues BF, C Harris PJ. The ecology of arbuscular mycorrhizal fungi. Critical Reviews in Plant Sciences. 2013;32(1):1–20.

28. Lanfranco L, Bonfante P, Genre A. The mutualistic interaction between plants and arbuscular mycorrhizal fungi. Microbiology Spectrum. 2016;4(6):727–747.

29. Rivera R, Fernández F, Hernández A, Triana J, Fernández K. El manejo efectivo de la simbiosis micorrízica, una vía hacia la agricultura sostenible. Estudio de caso El Caribe. La Habana, Cuba: Ediciones INCA; 2003.

30. Siqueira JO, Franco AA. Biotecnologia do solo: fundamentos e perspectivas. Brasilia, Brasil: Ministerio da Educacao e Cultura, ABEAS/ESAL/FAEPE; 1988. 235 p.

31. Rivera R, Fernández F, Fernández K, Ruiz L, Sánchez C, Riera M. Advances in the management of effective arbuscular mycorrhizal symbiosis in tropical ecosystesm. Mycorrhizae in crop production. 2007;151–196.

32. González PJ, Ramírez JF, Rivera R, Hernández A, Plana R, Crespo G, et al. Management of arbuscular mycorrhizal inoculation for the establishment, maintenance and recovery of grasslands. Revista Cubana de Ciencia Agrícola. 2015;49(4):535–540.

33. Simó González JE, Ruiz Martínez LA, Rivera Espinosa R. Manejo de la simbiosis micorrízica arbuscular y el suministro de nutrientes en plantaciones de banano cv. FHIA-18 (*Musa AAAB*) en suelo Pardo mullido carbonatado. Cultivos Tropicales. 2015;36(4):43–54.

34. João JP, Rivera-Espinosa R, Martín-Alonso G, Riera-Nelson M, Simó-González J. Sistema integral de nutrición con HMA, abonos verdes y fertilizantes minerales en *Manihot esculenta* Crantz. Cultivos Tropicales. 2017;38(3):117–128.

35. Colangelo EP, Guerinot ML. Put the metal to the petal: metal uptake and transport throughout plants. Current opinion in plant biology. 2006;9(3):322–330.

36. Andrade SAL, Silveira APD, Mazzafera P. Arbuscular mycorrhiza alters metal uptake and the physiological response of *Coffea arabica* seedlings to increasing Zn and Cu concentrations in soil. Science of the Total Environment. 2010;408(22):5381–5391.

37. Sharma P, Dubey RS. Lead toxicity in plants. Brazilian journal of plant physiology. 2005;17:35–52.

38. Küpper H. Lead toxicity in plants met ions. Life Sci. 2017;491–500.

39. Cabral L, Soares CRFS, Giachini AJ, Siqueira JO. Arbuscular mycorrhizal fungi in phytoremediation of contaminated areas by trace elements: mechanisms and major benefits of their applications. World Journal of Microbiology and Biotechnology. 2015;31(11):1655–1664.

40. Guerrero MG. Estudio de los mecanismos implicados en la homeostasis de metales pesados en el hongo formador de micorrizas arbusculares *Glomus intraradices*: tesis doctoral. Editorial Universidad de Granada; 2005.

41. Chen BD, Li XL, Tao HQ, Christie P, Wong MH. The role of arbuscular mycorrhiza in zinc uptake by red clover growing in a calcareous soil spiked with various quantities of zinc. Chemosphere. 2003;50(6):839–846.

42. Konieczny A, Kowalska I. The role of arbuscular mycorrhiza in zinc uptake by lettuce grown at two phosphorus levels in the substrate. Agricultural and Food Science. 2016;25(2):124–137–124–137.

43. Rivera-Becerril F, Calantzis C, Turnau K, Caussanel J-P, Belimov AA, Gianinazzi S, et al. Cadmium accumulation and buffering of cadmium-induced stress by arbuscular mycorrhiza in three *Pisum sativum* L. genotypes. Journal of experimental botany. 2002;53(371):1177–1185.

44. Malcová R, Rydlová J, Vosátka M. Metal-free cultivation of *Glomus* sp. BEG 140 isolated from Mn-contaminated soil reduces tolerance to Mn. Mycorrhiza. 2003;13(3):151–7.

45. Jacquot E, van Tuinen D, Gianinazzi S, Gianinazzi-Pearson V. Monitoring species of arbuscular mycorrhizal fungi in planta and in soil by nested PCR: application to the study of the impact of sewage sludge. Plant and Soil. 2000;226(2):179–188.

46. Bernardo V, Collado F. Efecto del ácido salicílico sobre plantas de pimiento (*Capsicum annuum*) micorrizadas, en presencia de metales pesados en el suelo [phdthesis]. Universidad Nacional de La Plata; 2016.

47. Ortiz-Cano HG, Trejo-Calzada R, Valdez-Cepeda RD, Arreola-Ávila JG, Flores-Hernández A, López-Ariza B. Fitoextracción de plomo y cadmio en suelos contaminados usando quelite (*Amaranthus hybridus* L.) y micorrizas. Revista Chapingo. Serie Horticultura. 2009;15(2):161–168.

48. Rajkumar M, Sandhya S, Prasad MNV, Freitas H. Perspectives of plant-associated microbes in heavy metal phytoremediation. Biotechnology advances. 2012;30(6):1562–1574.

49. Hildebrandt B, Wust P, Ahlers O, Dieing A, Sreenivasa G, Kerner T, et al. The cellular and molecular basis of hyperthermia. Critical reviews in oncology/hematology. 2002;43(1):33–56.

50. Kirchman DL, Hanson TE. Bioenergetics of photoheterotrophic bacteria in the oceans. Environmental microbiology reports. 2013;5(2):188–199.

51. de Abreu CB, do Sacramento BL, Alves AT, Moura SC, Pinelli MS, de Azevedo Neto AD. Nutritional and biochemical changes induced by lead in sunflower (*Helianthus annuus* L.). Semina: Ciências Agrárias. 2016;37(3):1229–1242.

52. Zhan F, Li B, Jiang M, Yue X, He Y, Xia Y, et al. Arbuscular mycorrhizal fungi enhance antioxidant defense in the leaves and the retention of heavy metals in the roots of maize. Environmental Science and Pollution Research. 2018;25(24):24338–24347.