e-ISSN:2320-0189
p-ISSN:2347-2308

Research & Reviews: Journal of Botanical Sciences

The Role of Siderophores on Plants under Heavy Meal Stress: A View from the Rhizosphere

Mihiri Seneviratne[1] and Meththika Vithanage[2]*

[1]Department of Botany, Faculty of Natural Sciences, Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka

[2]Chemical and Environmental Systems Modeling Research Group, National Institute of Fundamental Studies, Kandy, Sri Lanka

Review Article

Received date: 09/10/2015
Accepted date: 10/11/2015
Published date: 12/11/2015

***For Correspondence**

Meththika Vithanage, Chemical and Environmental Systems Modeling Research Group, National Institute of Fundamental Studies, Kandy, Sri Lanka,
Tel: +94 81 2 232002

E-mail: meththikavithanage@gmail.com

Keywords: Phytoremediation, Iron, Oxidative stress, IAA, Chlorophyll, Siderophore biosynthesis.

ABSTRACT

Siderophores are Fe chelators produced by both microbes and plants. Since Fe is an essential element to all forms of life, siderophores plays a vital role to overcome the Fe limitations. It has been revealed that in the rhizosphere, where many complex biochemical reactions takes place, both microbial and plant siderophores involve to fulfill Fe requirements of the plant. Interestingly, siderophores exhibit a tremendous role in protecting the plant from oxidative stress caused by heavy metals. Even though they have the ability to bind trace metals and toxic heavy metals; the affinity towards them is somewhat low. Even though siderophores form complexes with heavy metals, unlike Fe it restrains they deliver through the plasma membrane of the root cells. Thereby siderophores reduce the metal accumulation in the plant. However, conflicting results are observed in different studies. Under some plant siderophore combinations, plant heavy metal uptake exhibited an increase, which shows its favorability to enhance phytoremedation. Furthermore, siderophores are able to reduce the oxidative stress by inhibiting the free radical formation and can inhibit the IAA destruction. Collectively they are able to reduce the plant stress factors and induce plant growth promotion. In this review, we have summarized the protective role of siderophores, their heavy uptake strategies, biosynthesis and the siderophore transport through the cell membrane. This is a novel field of research with numerous gaps are to be filled, which would light the pathway to understand the marvels of nature.

INTRODUCTION

Siderophores are relatively low molecular weight complexes, which are specific ferric chelating agents. They are mostly produced by bacteria and fungi growing under low iron stress [1]. Iron is an essential element for both plants and microbes. It is important in numerous metabolic activities; electron transport system, formation of heme, act as cofactors for enzymes, synthesis of chlorophyll. In the presence of oxygen, iron converts to oxyhydroxide, which is relatively a less soluble complex. These environmental limitations shows, the requirement of specific molecules that can release Fe from the immobilized complex. Moreover, actinomycetes and certain algae growing under low ironic stress are able to produce siderophores [2,3]. Both plants and microbes have the ability to synthesis siderophores. Phytosiderophores are somewhat similar to siderophores but synthesized plants under iron deficiency conditions. Microbial siderophores were reported to increase Fe concentrations in certain plant species [4].

Phytoremediation is an efficient and environmentally friendly method of heavy metal remediation where many research studies have focused on this aspect during the past two decades. Since the rhizosphere microbes play an important role in many plant physiological activities, the attention has focused on to assess the influence of these organisms on plant heavy metal uptake. Not only with Fe, siderophores are able to form complexes with other metals as well [5]. However, there is no clear understanding whether the siderophores reduces or increases the heavy metal uptake of plants [6]. This review summarizes the different interactions between plant root and rhizospheric microbes under heavy metal stressed conditions, their diversity, synthesis and transport to the plant cells.

Structural Diversity of Siderophores

About 500 different siderophores have identified to date [7]. Even though there are structural differences between the siderophores, there is a common feature for every siderophore. That is the ability to coordinate 06 octahedral complexes with Fe ion due to the presence of oxygen or nitrogen (electron donor) atoms, which can bind metal cations [8]. Some bacterial siderophores are polycarboxylates, but most bacterial siderophores in soil are catecholates, whereas, most fungi produce hydroxamate siderophores. Moreover, Azotobacter vinelan produces mixed siderophores such as azotobactin and yersiniabactin [9].

Streptomyces, Vibrio cholera and Pseudomonas aeruginosa are examples for catecholate siderophore producers [1,10]. Enterobactine is the characteristic siderophore for bacteria of the family Enterobacteriaceae which is a catecholate type siderophore [11]. This is a cyclic trimer with 2,3-dihydroxy-N-ben-zoylserine, which produced by most of the enterobacterial genera. Azotochelin and myxochelin are other catecholate type siderophores are produced by Gram-negative bacteria. They are produced by Azotobacter vinelandii and Angiococcus disciformis, respectively [12]. Alcaligin and staphyloferrin produced by Alcaligenes denitrificans, Staphylococcus spp. are hydroxymate siderophores [13]. Hydroxamate siderophores contain three secondary hydroxamate groups, where each hydroxamate group provides two oxygen molecules, which form a bidentate ligand with iron. Fungal siderophores, are mainly hydroxymates and few are phenolate [14].

Siderophores in Fe Uptake

Plants have different strategies for Fe uptake, from the Fe complexes. Under Fe-deficient conditions, non-graminaceous plants release reductants or chelators into the rhizosphere and increase their ferric reduction capacity at the root surface, and transport Fe II ion through the FeII-transporter in the plasma membrane. Therefore, ferric reductase is an important enzyme to tolerate of Fe-deficiency, in non-graminaceous plants. Graminaceous monocots release Fe-chelating substances such as mugineic acid family phytosiderophores (MAs), in response to Fe-deficiency stress. These phytosiderophores solubilize inorganic FeIII compounds by chelation, and the Fe III-MAs complexes are enter through specific transport systems in the root cells [15-17].

Siderophores and Heavy Metal Stress

In the presence of heavy metals, it causes destruction in membrane bound ferric reductase enzyme, and thereby declines the Fe uptake in plant. This Fe deficiency exhibits as young leaf chlorosis. Hence, inoculation of plants with siderophore producing bacteria prevent iron deficiency even under heavy metal polluted conditions [18,19]. For instance, with inoculation of siderophores producing Pseudomonas sp on Vigna radiate showed a reduction of chlorotic symptoms and increase in chlorophyll level (Sharma et al. 2003). The effects of rhizosphere microorganisms on Fe uptake by oat (Avena sativa) and maize (Zea mays) were studied within a short-time period (10hr) [20]. Fe was supplied either as microbial siderophores (pseudobactin [PSB] or ferrioxamine B [FOB]) or as phytosiderophores obtained as root exudates from barley (epi-3-hydroxy-mugineic acid [HMA]) under different population densities of rhizosphere microorganisms. It has observed that the supply of FeHMA enhanced both uptake rate and translocation rate. However, with the increase of microbial density, it resulted in a decrease in Fe uptake rate. It has explained as microbial degradation of FeHMA. However, as FeFOB or FePSB used as Fe source, it increased population density of microorganisms and the Fe uptake was improved [21].

Oxidative Stress Reduction

Moreover, stress reduction is mainly via the production of ACC deaminase by the rhizospheric microbes. ACC is the precusure of ethylene, which act as a stress signal in plant body. The enzyme ACC deaminase reduce the ACC level near the root surface and facilitates an internal ACC flow from root interior to the external soil environment [22]. This causes a decline in the internal ACC level and subsequently the stress reduces. Not only the rhizospheric ACC deaminase production is involved in the stress reduction process, but also the siderophores plays an important role. As, the cowpea plants were grown under heavy metal stressed soil with sufficient Fe, it showed a chlorophyll and carotenoid reduction. Which is due to lipid peroxidation in cellular oxidative damage [23,24].

It was observed that, with addition of siderophores to the plants under heavy metal stress, resulted in high chlorophyll content than in the plants grown under heavy metal free condition, even though it contains higher amounts of bioavailable Fe. This reveals the ability of siderophores to solubilize Fe for plant use, even in the presence of heavy metals, that cause inhibition Fe uptake under normal conditions **(Figure 1)** [25].

Siderophore and IAA

IAA, is a plant growth hormone, produced by both microbes and plant, plays a vital role in plant growth and development. It is well documented that heavy metals possess a negative effect against this hormone [26]. This, causes destruction of IAA, and thereby causes growth inhibition in plant. The oxidative degradation of IAA has been reported in metal-stressed plants for instance, auxin degradation was reported in leaves of pea (Pisum sativum L.) seedlings treated with Cd and Cu [27,28]. Interestingly it has observed that, in the presence of siderophores the IAA degradation was reduced **(Figure 1).** Thereby, it enhances the ability of plant to withstand against heavy metal stress [29]. Has carried out a detailed study to assess the effect of siderophores on the synthesis of auxins in the presence of toxic metals. Since they have the ability to produce a variety of secondary metabolites, different sp of Streptomyces was used. It was revealed that Al^{3+}, Cd^{2+}, Cu^{2+}, Fe^{3+} and Ni^{2+} metal cations, or a combination of Fe^{3+} and Cd^{2+}, and Fe^{3+} and Ni^{2+} were negatively affected on auxin production. Moreover they have concluded that, siderophores promote auxin synthesis in the presence of Al^{3+}, Cd^{2+}, $Cu^{2+}$and Ni^{2+} by chelating them, and the chelation makes the metals less able to inhibit auxins synthesis.

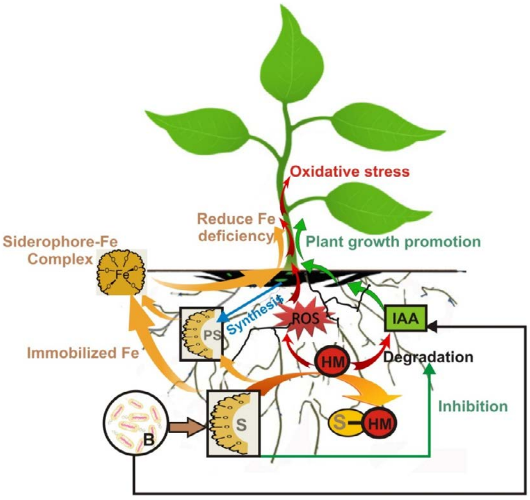

Figure 1. The role of siderophores on plants under heavy metal stress.

Metal Availability and Immobilization

Metal availability is a critical point in phytoremediation of heavy metal. Rhizosphere of the hyper-accumulator plants possess a number of ways to mobilize metals. Rhizosphere acidification and siderophore production are the major processes. Siderophores bind to various metal ions and convert them into available forms. The affinity of siderophores towards Fe is great than the affinity to divalent cations [29]. Metals act as signal for siderophore production. Therefore, In the presence of metals it enhances the siderophore production **(Table 1)** [26]. Briefs the studies published on plants and their associated bacteria that protect them against heavy metal stress.

Table 1. Plants and their Associated Bacteria that Protect them Against Heavy Metal Stress.

Organism	Metal	Plant	Author/Year
Streptomyces acidiscabies	Ni	Vigna unguiculata	(Dimkpa et al. 2008a)
Kluyvera ascorbata SUD165	Ni	Canola	(Burd et al. 2000)
Pseudomonas aeruginosa	Cd	Mustard, pumpkin	(Sinha and Mukherjee 2008)
Bacillus edaphicus	Pb	Brassica juncea	(Sheng et al. 2008)
Pseudomonas putida	Pb, Cd	Vigna radiata	(Tripathi et al. 2005)
Pseudomonas	Cr	Vigna mungo	(Rajkumar et al. 2005)
Sphingomonas macrogoltabidus, Microbacterium liquefaciens Microbacterium arabinogalactanolyticum	Ni	Alyssum murale	(Abou-Shanab et al. 2003)

The nickel-resistant Streptomyces acidiscabies was able to produce 3 different hydroxamate siderophores under Ni stressed conditions [26]. It has been revealed under electrospray ionization mass spectrometry (ESI-MS) that in addition to iron, all 3 siderophores could bind nickel. The siderophore production and metal binding rate is not uniform in each siderophore. In this experiment, they have seen a progressive increase in siderophore production up to 72 hrs.

There are still conflicting theories, whether complexation by bacterial siderophores makes trace elements more or less available for plants [30]. Inoculation of plants with siderophore producing bacteria has shown to both increase and decrease of heavy metal uptake which depends on the plant type, the associated bacterium and metal [6]. (Dimkpa et al. 2008a) reported a protection from oxidative stress in the presence of siderophores [26]. In the presence of siderophore containing cell free culture of Streptomyces acidiscabies reduced the plant Ni under sufficient Fe. The stability constants of siderophore- metal complexes have found to be different and the stability constant for Fe seemed to be far greater than that is for Ni [31]. Therefore, the binding effect is more favorable with Fe. The remaining siderophores, form complexes with Ni and play a protective role against Ni stress [26].

Similarly, the ability of siderophore desferrioxamine B (DFOB) to increase heavy metal phytoavailability has been tested [18]. Its natural occurrence in the rhizosphere is the reason for selection of the particular siderophore for the experiment. The use of hydroxamate siderophores similar to DFOB that form positively charged complexes are not favorable for phytoremediation [18]. Increasing mobility of metals in the presence of siderophores has been reported with platinum-group elements (PGEs) which are released to the environment from catalytic converters [32]. The experiment was to assess the abilities of microbially produced siderophores to complex with the PGEs. Batch experiments using the synthetic siderophore desferrioxamine-B (DFO- B) and powdered metal forms of Pt, Pd, or Rh showed that DFO-B enhances the solubility of Pt and Pd due to the formation of Pt- and Pd- DFO- B aqueous complexes.

Hyperaccumulators are a specific group of plants, which are adapted for heavy metal phytoextraction that are able to produce phytosiderophores for metal extraction. *L. hexandra* is a graminaceous plant which responds to iron deficiency by producing phytosiderophores [33]. Interestingly, the phytosiderophores mobilize iron and also other metals in the rhizosphere (Awad and Römheld). The Cr (III) uptake by *L. hexandra* has explained by considering the similarity of valence state and ionic radius between Cr (III) and Fe (III). Whereas, Cr (III) is able to bind with phytosiderophores (PS) enter to *L. hexandra* root cells. through membrane transporters for Fe(III)–PS complex [33]. Which is similar to uptake of Cr(III) and Fe(III) by fungal siderophore rhizoferrin to the fungal hyphae [34].

The mobilization of Zn by formation of Zn-phytosiderophores and uptake through Fe- phytosiderophore transporters were tested with 65Zn labeled siderophores in Fe efficient maize cultivar and maize mutant carrying defect in Fe-phytosiderophore uptake [35]. Finally they have proposed two pathways for Zn uptake by root cells, which are as Zn -phytosiderophores and as free Zn cations dissociated from Zn phytosiderophores during membrane transport [35].

The influence of Cu phytotoxicity in Fe nutrition has tested with *Triticum turgidum* plant. Copper and Fe concentrations and amounts of Cu and Fe accumulated in shoots varied inversely which reflected an antagonism between Cu and Fe leading to Fe deficiency. Moreover it was concluded that the Cu uptake is mediated by Cu induced phytosiderophore production [36]. As inoculating, of the rhizosphere of the accumulator plant with suitable microorganisms or by growing phytosiderophore-producing grass species in combination it, can enhance the phytoextraction process.

Biosynthesis of Siderophores

Siderophore biosynthesis by bacteria is a complex biosynthetic pathway. Both, the amount of iron present in the environment and iron acquired by the bacteria are major factors affecting siderophore production [37]. Since the Fe level in the cell is a critical factor, microorganisms possess a tight regulation in enzymes and transport systems for siderophore biosynthesis, secretion, siderophore-delivered iron uptake, and iron release.

Nonribosomal peptide synthatases (NRPS) pathway and independent of NRPS are the major pathways that are reported for siderophore biosynthesis [37,38]. It has been reported that many siderophores are peptides which biosynthesised by the well-studied nonribosomal peptide synthetase (NRPS) multienzyme family. Mainly, the Fe gene regulation mediate at the transcriptional level by the ferric uptake repressor Fur or the diphtheria toxin regulator DtxR. whereas; Fur is the global iron regulator in many gram-negative bacteria and gram-positive bacteria that contains low-GC-content. Similarly, DtxR act in gram-positive bacteria with a high GC content [38].

Desferrioxamines are trihydroxamate type siderophores that synthesized from the amino acids lysine and ornithine. Desferrioxamine B is the main siderophore of Streptomyces pilosus. The first step in Desferrioxamine biosynthesis is, decarboxylation of lysine, which catalyzed by lysine decarboxylase DesA [39].

Biosynthesis of Phyto-Siderophores

Iron homeostasis in plants maintains through transcriptional control of gene expression. This regulation does not seem to mediate by a transcription factor. Transcription of the ferritin genes in both maize and in Arabidopsis, is dependent on a combination of positive and negative promoter cis-acting elements which results in the accumulation of ferritin mRNA in response to iron overload [40]. Expression of the iron-deficiency response genes, FRO2,IRT1, and IRT2, controls at the level of transcript accumulation by iron status. All three mRNAs accumulated in roots in response to iron deficiency are rapidly switched off with resupply of iron [41].

Phytosiderophores are composed of a family of mugineic acids (MAs), including mugineic acid (MA), 2-deoxymugineic acid (DMA), 3-epihydroxymugineic acid (epi-HMA), and 3-epihydroxy 2-deoxymugineic acid (epi-HDMA). Where, each graminaceous plant is secreting its own specific set of MAs. Condensation of three molecules of S-adenosyl methionine (SAM) to produce one molecule of nicotianamine (NA) is the first step of MA production [42]. The critical enzyme in the specific pathway in grasses is the nicotianamineaminotransferase (NAAT) that catalyzes the transfer of an amino residue to NA, resulting in the production of 2 -deoxymugineic acid (DMA), which is the precursor of all other MAs. In contrast to the biosynthetic pathway of MAs, the molecular mechanisms of MAs secretion remain unclear [43].

Transport of Siderophore-Meal Complex Through Membrane

Transport of siderophores through the membrane is a complex reaction. As the siderophore -Fe^{3+} complex forms it can transport as siderophore-Fe^{3+} complex or as free Fe ions. Once it enters to the periplasm the Fe^{3+}-siderophore complex transports across the inner membrane either through the ABC transporters or through permeases. The Fe^{3+}-siderophore complex vary between microbes and different siderophore types. For instance, in E. coli ferrichrome and ferrienterobactin pathways, iron releases into the cytoplasm, whereas in P. aeruginosa ferric-pyoverdine pathway iron releases into the periplasm.

Pyoverdine (PVDI) is a siderophore composed of a fluorescent chromophore linked to an octapeptide. As secreted from the bacteria, PVDI chelates Fe ions and results Fe-PVDI complexes that taken up by the bacteria through a cell surface receptor protein. The iron releases into the periplasm and the resulting PVDI is recycled. It secrets out of the bacterial cell but the mechanism is still not revealed. Whereas, mutation of genes encoding this efflux pump (named PvdRT-OpmQ) prevented recycling of PVDI from the periplasm into the extracellular medium. Interestingly it was found that recycling did not occur after transporting PVDI–Ga3+, even when the PvdRT-OpmQ efflux pump was functional [5]. The uptake of Fe3+-siderophore complex mediates through the outer membrane receptor proteins, which are specific to the siderophores such as, FepA (for enterobactin), FhuA (for ferrichrome), and FecA (for ferric citrate). It suggests that a conformational change of domains of these receptors allow the passage of the complex [44,45]. The ABC type transporter proteins are also involved in the delivery of iron-siderophore complex into the cytosol. These are extra-cytoplasmic substrate binding proteins are located in the preiplasm in Gram-negative bacteria, whereas, present as lipoproteins attached to the external surface of the cell membrane in Gram-positive bacteria [46]. With the aid of substrate binding unit of the ABC transporter, the Fe siderophore complex is able to transfer through the membrane.

Interveinal chlorosis characteristic of iron deficiency was observed in the yellow-stripe 3(ys3) maize mutant shows due to a defect in MAs secretion, and it is suggested to co-cultivate with a wild-type plant or apply exogeneous Mas [47]. Very little information is presently available on intracellular iron movement in plant cells [47].

Future Perspectives

Siderophores are an important aspect in plant metal uptake. Even though many studies have been carried out there are several gaps to be filled. Siderophore that forms a positive charge complex has been discussed by many studies, but they do form negatively charged complexes as well. More research should focused towards the negatively charged siderophore complexes. Over the past two decades, structures for the proteins involved in bacterial iron uptake have not solved completely, but their functions have begun to understand at the molecular level. The determination of the structure of protein channels is very important in understanding the mechanisms of both Fe transport and other metal uptake. This could again be an important research area for the field of science. At the same time, the mechanism for pyoverdine recycling in still not understood. Since it take a major role in Fe uptake, more research will give new insights to the scientific world. Many mechanisms have been suggested for the biochemical pathway of MA, which are very important siderophores in plants. However, the molecular mechanisms of MAs secretion are still unclear. Studies regarding that aspect will fill the gaps in present understanding of plant metal uptake. Many studies have conducted to determine the role of siderophores in metal uptake. However, there is no sufficient information found in the fate of siderophore-complxes inside the cell. Both the horizontal and vertical transport of siderophore-complxes in the plant has not discovered yet. More research regarding the horizontal and vertical transport may give more information to development molecular mechanisms in plant metal accumulation. Moreover, the detailed studies on overall siderophore structure and the cell membrane transporters and receptors may direct new discoveries on fertilizer carriers, which deliver the nutrients more efficiently to the plant root cells by minimizing the losses. It would be an interesting discovery since the siderophores are recyclable.

REFERENCES

1. Neilands JB. Iron absorption and transport in microorganisms. Annu Rev Nutr. (1981);1:27-46.
2. Trick C, et al. Examination of hydroxamate-siderophore production by neritic eukaryotic marine phytoplankton. Marine biology. (1983);75:9-17.
3. Amin SA, et al. Photolysis of iron–siderophore chelates promotes bacterial–algal mutualism. Proceedings of the National Academy of Sciences. (2009),106:17071-17076.
4. Yehuda Z, et al. The role of ligand exchange in the uptake of iron from microbial siderophores by gramineous plants. Plant physiology. (1996);112:1273-1280.
5. Yeterian E, et al. An efflux pump is required for siderophore recycling by Pseudomonas aeruginosa. Environmental microbiology reports. (2010);2:412-418.
6. Rajkumar M, et al. Potential of siderophore-producing bacteria for improving heavy metal phytoextraction. Trends Biotechnol. (2010);28:142-149.
7. Boukhalfa H and Crumbliss AL. Chemical aspects of siderophore mediated iron transport. Biometals. (2002);15:325-339.
8. Cox CD, et al. Pyochelin: novel structure of an iron-chelating growth promoter for Pseudomonas aeruginosa. Proc Natl Acad Sci USA. (1981);78:4256-4260.
9. Budzikiewicz H. Siderophores from bacteria and from fungi. Iron uptake and homeostasis in microorganisms Caister Academic, Norfolk. (2010);1-16.
10. Saha R, et al. Microbial siderophores: a mini review. J Basic Microbiol. (2013);53:303-317.

11. Fiedler HP, et al. Enterobactin: the characteristic catecholate siderophore of Enterobacteriaceae is produced by Streptomyces species. FEMS Microbiol Lett. (2001);196:147-151.

12. Kunze B, et al. Myxochelin A, a new iron-chelating compound from Angiococcus disciformis (Myxobacterales). Production, isolation, physico-chemical and biological properties. The Journal of antibiotics. (1989);42:14-17.

13. Nishio T and Ishida Y. Production of dihydroxamate siderophore alcaligin by Alcaligenes xylosoxidans subsp. xylosoxidans. Agricultural and biological chemistry. (1990);54:1837-1839.

14. Haselwandter K. Mycorrhizal fungi: siderophore production. Critical reviews in biotechnology. (1995);15:287-291.

15. Mori S Mechanisms of iron acquisition by graminaceous (strategy II) plants. (1994).

16. Hopkins BG, et al. Plant utilization of iron solubilized by oat phytosiderophore. Journal of plant nutrition 15. (1992);1599-1612.

17. Kinnersley A. The role of phytochelates in plant growth and productivity. Plant growth regulation. (1993);12:207-218.

18. Schmidt W. Mechanisms and regulation of reduction-based iron uptake in plants. New Phytologist. (1999);141:1-26.

19. Crowley DE and Kraemer SM. Function of siderophores in the plant rhizosphere. The rhizosphere: biochemistry and organic substances at the soil–plant interface, 2nd edn CRC, Boca Raton. (2007);173-200.

20. Bar-Ness E, et al. Short-term effects of rhizosphere microorganisms on Fe uptake from microbial siderophores by maize and oat. Plant physiology. (1992);100:451-456.

21. Sharma A, et al. Plant growth-promoting bacterium Pseudomonas sp. strain GRP 3 influences iron acquisition in mung bean (Vigna radiata L. Wilzeck). Soil Biology and Biochemistry. (2003);35:887-894.

22. Ma Y, et al. Inoculation of plant growth promoting bacterium Achromobacter xylosoxidans strain Ax10 for the improvement of copper phytoextraction by Brassica juncea. Journal of Environmental Management. (2009);90:831-837.

23. Cakmak I and Horst WJ. Effect of aluminium on lipid peroxidation, superoxide dismutase, catalase, and peroxidase activities in root tips of soybean (Glycine max). Physiologia Plantarum. (1991);83:463-468.

24. Bueno P and Piqueras A. Effect of transition metals on stress, lipid peroxidation and antioxidant enzyme activities in tobacco cell cultures. Plant growth regulation. (2002);36:161-167.

25. Dimkpa CO, et al. Metal-induced oxidative stress impacting plant growth in contaminated soil is alleviated by microbial siderophores. Soil Biology and Biochemistry. (2009);41:154-162.

26. Dimkpa C, et al. Hydroxamate siderophores produced by Streptomyces acidiscabies E13 bind nickel and promote growth in cowpea (Vigna unguiculata L.) under nickel stress. Canadian journal of microbiology. (2008a);54:163-172.

27. Chaoui A and El Ferjani E. Effects of cadmium and copper on antioxidant capacities, lignification and auxin degradation in leaves of pea (Pisum sativum L.) seedlings. C R Biol. (2005);328:23-31.

28. Potters G, et al. Stress-induced morphogenic responses: growing out of trouble? Trends Plant Sci. (2007);12:98-105.

29. Neubauer U, et al. Siderophores, NTA, and citrate: potential soil amendments to enhance heavy metal mobility in phytoremediation. International journal of phytoremediation. (2000);2:353-368.

30. Glick BR. Phytoremediation: synergistic use of plants and bacteria to clean up the environment. Biotechnol Adv. (2003);21:383-393.

31. Crumbliss A (1991) Aqueous solution equilibrium and kinetic studies of iron siderophore and model siderophore complexes. Handbook of microbial iron chelates:177-232.

32. Dahlheimer SR, et al. Potential mobilization of platinum-group elements by siderophores in surface environments. Environ Sci Technol. (2007); 41:870-875.

33. Liu J, et al. Characteristics of chromium (III) uptake in hyperaccumulator Leersia hexandra Swartz. Environmental and Experimental Botany. (2011);74:122-126.

34. Pillichshammer M, et al. Biosorption of chromium to fungi. Biometals. (1995);8:117-121.

35. Von Wirén N, et al. Roots of iron-efficient maize also absorb phytosiderophore-chelated zinc. Plant physiology. (1996);111:1119-1125.

36. Michaud AM, et al. Copper phytotoxicity affects root elongation and iron nutrition in durum wheat (*Triticum turgidum* durum L.) (2008) Plant and soil. (2008);310:151-165.

37. Challis GL. A widely distributed bacterial pathway for siderophore biosynthesis independent of nonribosomal peptide synthetases. Chembiochem. (2005);6:601-611.

38. Miethke M and Marahiel MA . Siderophore-based iron acquisition and pathogen control. Microbiol Mol Biol Rev. (2007);71:413-451.

39. Schalk IJ, et al. New roles for bacterial siderophores in metal transport and tolerance. Environ Microbiol. (2011);13:2844-2854.

40. Petit JM, et al. Characterization of an Iron-dependent Regulatory Sequence Involved in the Transcriptional Control of AtFer1and ZmFer1 Plant Ferritin Genes by Iron. Journal of Biological Chemistry. (2001);276:5584-5590.

41. Eide D, ET AL. A novel iron-regulated metal transporter from plants identified by functional expression in yeast. Proc Natl Acad Sci USA. (1996);93: 5624-5628.

42. Negishi T, et al. cDNA microarray analysis of gene expression during Fe-deficiency stress in barley suggests that polar transport of vesicles is implicated in phytosiderophore secretion in Fe-deficient barley roots. The Plant Journal. (2002);30:83-94.

43. Thomine S and Lanquar V. Iron transport and signaling in plants. In: Transporters and Pumps in Plant Signaling. Springer. (2011);pp:99-131.

44. Chakraborty R, et al. Molecular mechanism of ferricsiderophore passage through the outer membrane receptor proteins of Escherichia coli. Biometals. (2007);20:263-274.

45. Eisenhauer HA, et al. Siderophore transport through Escherichia coli outer membrane receptor FhuA with disulfide-tethered cork and barrel domains. Journal of Biological Chemistry. (2005);280:30574-30580.

46. Dale SE, et al. Role of siderophore biosynthesis in virulence of Staphylococcus aureus: identification and characterization of genes involved in production of a siderophore. Infection and immunity. (2004);72:29-37.

47. Basso B, et al. The yellow-stripe-1 and-3 mutants of maize: nutritional and biochemical studies. Maydica. (1994);39:97-105.