



HAL
open science

The Role of the Rhizosphere and Microbes Associated with Hyperaccumulator Plants in Metal Accumulation

Petra S. Kidd

► **To cite this version:**

Petra S. Kidd. The Role of the Rhizosphere and Microbes Associated with Hyperaccumulator Plants in Metal Accumulation. *Agromining: Farming for Metals*, 2018, *Mineral Resource Reviews*, 978-3-319-61898-2. 10.1007/978-3-319-61899-9_9. hal-02008731

HAL Id: hal-02008731

<https://hal.science/hal-02008731>

Submitted on 5 Feb 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/320737111>

The Role of the Rhizosphere and Microbes Associated with Hyperaccumulator Plants in Metal Accumulation

Chapter · January 2018

DOI: 10.1007/978-3-319-61899-9_9

CITATIONS

9

READS

443

2 authors:



Emile Benizri

University of Lorraine

83 PUBLICATIONS 1,734 CITATIONS

[SEE PROFILE](#)



Petra Kidd

Spanish National Research Council

99 PUBLICATIONS 2,462 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Cultivation of Ni-hyperaccumulating Mediterranean plant species in ultramafic soils for phytomining [View project](#)



Microbial diversity of ultramafic soils [View project](#)

The Role of the Rhizosphere and Microbes Associated with Hyperaccumulator Plants in Metal Accumulation

Emile Benizri and Petra S. Kidd

Abstract

Phytomining can be limited by low biomass productivity by plants or limited availability of soil metals. Ongoing research attempts to overcome these potential constraints and to make phytomining a successful commercial technique in the recovery of metals from polluted or naturally metal-rich soil by (hyper)accumulating plants. Recently, the benefits of combining phytoremediation with bioremediation, which consists in the use of beneficial microorganisms such as endophytes or rhizosphere bacteria and fungi, for metal removal from soils have been demonstrated. Metal-resistant microorganisms play an important role in enhancing plant survival and growth in these soils by alleviating metal toxicity and supplying nutrients. Furthermore, these beneficial microorganisms are able to enhance the metal bioavailability in the rhizosphere of plants. An increase in plant growth and metal uptake increases the effectiveness of phytoremediation processes coupled with bioremediation. Herein, we highlight the specificity of the rhizosphere and the critical roles in soil nutrient cycling and provision of ecosystem services that can be brought by rhizosphere microorganisms. We discuss how abiotic factors, such as the presence of metals in polluted sites or in naturally rich (ultramafic) soils modulate activities of soil microbial communities. Then we introduce the concept of microbe-assisted phytomining, and underline the role of plant-associated microorganisms in metal bioavailability and uptake by host plants that has attracted a growing interest over the last decade. Finally, we present various techniques, including phenotypic, genotypic, and metagenomic approaches, which allow for characterising soil microbial community structure and diversity in polluted or naturally metal-rich soils.

E. Benizri (✉)
UMR 1120 Sols et Environnement – INRA, Université de
Lorraine, Vandoeuvre-lès-Nancy 54518, France
e-mail: emile.benizri@univ-lorraine.fr

P.S. Kidd
Instituto de Investigaciones Agrobiológicas de Galicia
(IIAG), Consejo Superior de Investigaciones Científicas
(CSIC), Santiago de Compostela 15706, Spain

| | | | | | |
|---|---|---|---------------|--|---|
| <i>B. napus</i> | <i>Pseudomonas fluorescens</i> G10, <i>Microbacterium</i> sp. G16 | IAA; Siderophore; ACCD; PO ₄ | Pb | ↑ plant biomass (root elongation) ↑ Pb uptake (shoot) | Sheng et al. (2008a) |
| <i>B. napus</i> | <i>Pseudomonas putida</i> UW4 | ACCD | Ni | ↑ shoot biomass ↑ Ni tolerance | Farwell et al. 2007 |
| <i>B. napus</i> | <i>Pseudomonas putida</i> UW4, <i>Pseudomonas putida</i> HS2 | ACCD High Ni-tolerance (<i>P. p</i> HS2) | Ni | ↑ plant growth ↑ Ni yield | Farwell et al. (2006) |
| <i>B. napus</i> | Not determined | Cd-resistant | Cd | ↑ [Cd] shoot | Sheng and Xia (2006) |
| <i>B. napus</i> , <i>L. esculentum</i> , <i>Z. mays</i> , <i>Sorghum sudanense</i> | <i>Bacillus</i> sp. J119 | Metal-resistance; Antibiotic resistance; Biosurfactant; IAA; Siderophore | Cd | ↑ shoot/root biomass of <i>L. esculentum</i> ; ↑ [Cd] shoot (<i>B. napus</i> , <i>L. esculentum</i>); ↑ [Cd] root (<i>B. napus</i> , <i>L. esculentum</i> , <i>Z. mays</i>) | Sheng et al. (2008b) |
| <i>Heliathus annuus</i> | <i>Bacillus weihenstephanensis</i> SM3 | IAA; PO ₄ ; Cu, Ni, Zn mobilization | Cu, Ni, Zn | ↑ plant biomass ↑ Cu, Zn uptake | Rajkumar et al. (2008) |
| <i>H. annuus</i> | <i>Pseudomonas fluorescens</i> | IAA, Siderophore | As | ↑ shoot biomass; ↑ [As] shoot; ↑ phloem fluxes | Shilev et al. (2006) |
| <i>Lycopersicon esculentum</i> | <i>Pseudomonas</i> sp. RJ10, <i>Bacillus</i> sp. RJ16 | IAA; Siderophore; ACCD; Cd, Pb mobilization | Cd, Pb | ↑ plant biomass and root length ↑ Cd, Pb uptake | He et al. (2009) |
| <i>Medicago sativa</i> | <i>Pseudomonas fluorescens</i> (strains Avm, U), <i>Rhizobium leguminosarum</i> bv <i>phaseoli</i> (strains CPMex44, CPMex46), <i>Azospirillum lipopherum</i> (strains UAP40, UAP154) | Siderophore Growth promotion | Cu | ↑ Cu, Fe root-shoot translocation (<i>CPMex46</i> , <i>Avm</i>) | Carrillo- Castañeda et al. (2002) |
| <i>Nicotiana tabacum</i> | <i>Sanguibacter</i> sp., <i>Enterobacter</i> sp., <i>Pseudomonas</i> sp. | nd | Cd | ↑ plant biomass (<i>Sanguibacter</i> sp. S-d2 and consortia) ↑ Cd translocation ↑ Cd, Fe uptake | Mastretta et al. (2009) |

(continued)

Table 4 (continued)

| Plant species | Bacterial strain | Characteristics | Metal | Effect | Reference |
|---|--|--|----------------|---|------------------------------|
| <i>Orychophragmus violaceus</i> | <i>Bacillus subtilis</i> , <i>B. cereus</i> , <i>Flavobacterium</i> sp., <i>Pseudomonas aeruginosa</i> | Zn-tolerance | Zn | ↑ plant biomass and root length ↑ Zn solubilization and uptake | He et al. (2010b) |
| <i>Pteris vittata</i> | <i>Rhodococcus</i> sp. TS1, <i>Delftia</i> sp. TS33, <i>Comamonas</i> sp. TS37, <i>Delftia</i> sp. TS41 <i>Streptomyces lividans</i> sp. PSQ22 | As-reducing | As | ↑ plant biomass ↑ As uptake ↑ As solubilization ↓ As leaching | Yang et al. (2012) |
| <i>Populus deltoides</i> | <i>Agrobacterium radiobacter</i> | As-tolerance IAA; Siderophore | As | ↑ plant biomass ↑ chlorophyll, enzymatic activity ↑ [As] root, stem, leaf ↑ As uptake and translocation | Wang et al. (2011) |
| <i>Ricinus communis</i> | <i>Pseudomonas</i> sp. Psm6, <i>P. jessenii</i> PjM15 | IAA; Siderophore; ACCD; Cu, Ni, Zn mobilization | Cu, Ni, Zn | ↑ plant biomass ↑ Zn translocation and uptake | Rajkumar and Freitas (2008a) |
| <i>Salix caprea</i> | <i>Agromyces</i> sp. AR33, <i>Streptomyces</i> sp. AR17 | – | Cd, Zn | ↑ soil extractable-Cd/ Zn; ↑ plant growth ↑ Cd/Zn uptake | Kuffner et al. (2008) |
| <i>Salix viminalis</i> and <i>S. alba</i> x <i>alba</i> | <i>Rahnella</i> sp., <i>Sphingobacterium</i> sp., <i>Caulobacter</i> sp., <i>Curtobacterium</i> sp., <i>Pseudomonas</i> sp. | Acid; IAA, ACCD | Cd, Zn | ↑ Twig biomass, ↑ Cd/Zn extraction potential (with <i>Rahnella</i> sp.) | Janssen et al. (2015) |
| <i>Sedum alfredii</i> | <i>Burkholderia</i> sp. D54 | IAA; Siderophore; ACCD; PO ₄ | Cd, Pb, Zn | ↑ plant biomass; ↑ [Cd] shoot and root; ↑ Cd, Pb, Zn uptake | Guo et al. (2011) |
| <i>S. alfredii</i> | 5 bacterial strains (unidentified) | nd | Cd, Cu, Pb, Zn | ↑ plant biomass ↑ chlorophyll and nutrient content ↓ Cd, Cu, Pb, Zn toxicity ↑ Cd, Cu, Pb, Zn uptake from contaminated water | Xiong et al. (2008) |

| | | | | | |
|--|---|---|-------------------|---|---------------------------|
| <i>S. atfredii</i> | <i>Burkholderia cepacia</i> | - | Cd, Zn | ↑ plant biomass; ↑ [Cd/Zn] shoot; ↑ metal tolerance; ↑ [Cd/Zn] _{leaf} : [Cd/Zn] _{root} ratio | Li et al. (2007) |
| <i>Sedum plumbizincicola</i> | <i>Phyllobacterium myrsinacearum</i> RC6b | Metal-resistance; Metal mobilization; IAA; Siderophore; ACCD; PO ₄ | Cd, Pb, Zn | ↑ plant biomass ↑ [Cd, Zn] root and shoot | Ma et al. (2013) |
| <i>Sorghum bicolor</i> , <i>Z. mays</i> | <i>Bacillus subtilis</i> , <i>B. pumilus</i> , <i>Pseudomonas pseudoalcaligenes</i> , <i>Brevibacterium halotolerans</i> | - | Cu, Cr, Pb, Zn | ↑ plant biomass (with inoculum mixture); ↑ shoot biomass (<i>Br. h. P. p.</i>); ↑ solubility Cr, Cu (<i>B. s., B. p.</i>); ↑ [Cu, Cr, Pb, Zn] shoot on Cu-rich soil; ↑ [Cr] shoot on Cr-rich soil | Abou-Shanab et al. (2007) |
| <i>S. bicolor</i> | <i>Pseudomonas monteilii</i> | nd | Cd | ↑ plant biomass ↑ Cd uptake | Duponnois et al. (2006) |
| <i>Thlaspi caerulescens</i> | Mixed inoculum (<i>Microbacterium saperdae</i> , <i>Pseudomonas monteilii</i> , <i>Enterobacter cancerogenes</i>) | - | Zn | ↑ [Zn] _{water-soluble} ; ↑ [Zn] shoot | Whiting et al. (2001) |
| <i>Thlaspi caerulescens</i> | Mixed inoculum: <i>Bacillus pumilus</i> and <i>Micrococcus</i> sp. | Ni-resistant | Ni | ↓ [Ni] _{water-soluble} ; ↑ plant biomass; ↑ Ni yield | Aboudrar et al. (2013) |
| <i>Trifolium repens</i> Linn. | Bacterial strain mix (<i>Bacillus cereus</i>) | Metal-tolerance; IAA | Cd | ↑ plant biomass and phytoextraction | Azcón et al. (2009) |
| <i>Trifolium hybridum</i> , <i>Alopecurus pratensis</i> , <i>Poa pratensis</i> , <i>Hordeum violaceum</i> , <i>Ranunculus kotschyi</i> , <i>Cerastium</i> sp. | <i>Bacillus megaterium</i> var. <i>phosphaticum</i> | Nutrient-solubilization; Pathogens control | B, Ni, Mn, Pb, Zn | ↑ Ni, Pb, Fe, Zn, Na, B desorption from the soil ↑ Pb, Ni, B, Mn, Zn uptake | Gullap et al. (2014) |
| <i>Zea mays</i> | <i>Pseudomonas aeruginosa</i> , <i>Pseudomonas fluorescens</i> , <i>Ralstonia metalidirans</i> | Siderophore | Cr, Pb | ↑ Cr, Pb exchangeable fraction in the soil (<i>P. aeruginosa</i>) ↑ [Cr, Pb] shoot | Braud et al. (2009) |

Durand et al. 2016; Álvarez-López et al. 2016a). Schlegel et al. (1991) found that bacterial strains isolated from serpentine soils tolerated up to 10–20 mM Ni (in the culture medium), whereas strains from other soil types tolerated only 1 mM Ni. Turgay et al. (2012) reported that bacterial strains, isolated from Turkish serpentine soils, could tolerate up to 34 mM Ni in the growth medium. Furthermore, as described above, the rhizosphere bacterial communities associated with Ni-hyperaccumulating plants have been shown to differ from those of non-accumulating plants growing at the same site or of non-vegetated soil, but are also known to host a higher number of Ni-tolerant bacteria (Schlegel et al. 1991; Mengoni et al. 2001; Abou-Shanab et al. 2003b; Becerra-Castro et al. 2009; Álvarez-López et al. 2016a). Schlegel et al. (1991) reported a higher occurrence of Ni-resistant bacteria in soil samples collected with increasing proximity to the Ni-hyperaccumulating tree *Sebertia* (= *Pycnandra*) *acuminata*. Mengoni et al. (2001) also found a higher proportion of Ni-resistant cfu in proximity to the Ni-hyperaccumulator *A. bertolonii* than in non-vegetated soil. These authors observed simultaneous resistance to a set of metals and highest resistance from isolates of the rhizosphere. Becerra-Castro et al. (2009) found higher proportions of Ni-tolerant bacteria in the rhizosphere of *A. serpyllifolium* ssp. *lusitanicum*. This selective enrichment of Ni-tolerant bacteria in the rhizosphere was correlated with an increase in soil Ni availability (Becerra-Castro et al. 2009). Álvarez-López et al. (2016a) confirmed higher densities of Ni-tolerant bacteria associated with the Ni-hyperaccumulators *A. serpyllifolium* ssp. *lusitanicum* and *A. serpyllifolium* ssp. *malacitanum*, but observed significant differences in this selective enrichment amongst different plant populations across the Iberian Peninsula.

The screening of bacterial isolates associated with metal (hyper)accumulating plants has led to the identification of candidate inoculants for application in phytomining. Bacterial strains are commonly characterized for the presence of PGP traits such as the capacity to produce

phytohormones (IAA), to solubilize inorganic P or K, to fix atmospheric N₂, to release siderophores, or for their ACC activity. Most bioaugmentation studies have evaluated the effects of re-inoculating host plants with their associated isolates (Abou-Shanab et al. 2003a; Abou-Shanab et al. 2006; Li et al. 2007; Cabello-Conejo et al. 2014). However, the specificity of these plant-bacterial combinations is not always clear, and some inoculants have been shown to have beneficial effects on a wide range of plant hosts (Grandlic et al. 2008; Ma et al. 2011; Becerra-Castro et al. 2012). The main objective of these studies has been to improve metal yields during phytoextraction. In this technique, a simple improvement in biomass can result in an increase in overall trace element removal (Sessitsch et al. 2013). In a meta-analysis carried out by Sessitsch et al. (2013), including results from more than 70 publications and 738 individual cases, the authors found that bacterial inoculation was generally more successful in promoting plant growth and biomass production (60% of total cases analyzed) than in influencing shoot trace elements accumulation (only 30% of cases showed a significant increase in shoot trace elements concentration, and 16% a decrease in trace elements concentration).

Ma et al. (2009a, b) found that inoculation with PGP rhizobacteria (*Psychrobacter* sp. SRA1, *Bacillus cereus* SRA10 and *Achromobacter xylosoxidans* strain Ax10) improved the growth of *Brassica juncea* and *B. oxyrrhina*, enhanced soil Ni availability, and increased Ni accumulation in both species. Similarly, Rajkumar and Freitas (2008b) observed that inoculation with the PGP rhizobacterial strains *Pseudomonas* sp. PsM6 and *P. jessenii* PjM15 isolated from a serpentine soil in *R. communis* caused an increase in above-ground biomass, mainly due to IAA production and phosphate solubilization, and consequently enhanced phytoextraction efficiency. Zaidi et al. (2006) demonstrated that inoculation with *Bacillus subtilis* strain SJ-101 not only stimulated the growth of, and Ni accumulation in, *Brassica juncea*, but also protected the plant from Ni toxicity. Various authors also reported increases in

Ni uptake by *B. juncea* and other non-hyperaccumulating plant species (*B. napus*, *Ricinus communis*, *Poa pratensis*, etc.) after bacterial inoculation (Rajkumar and Freitas 2008a, b; Kumar et al. 2009; Gullap et al. 2014). With regard to Ni-hyperaccumulating species, Abou-Shanab et al. (2003b) showed that the strain *Microbacterium arabinogalactanolyticum* isolated from the rhizosphere of *A. murale* significantly increased availability of Ni in the soil and enhanced Ni accumulation by *A. murale*. In agreement with these results, a posterior study with *A. murale* grown in artificially Ni-polluted soils demonstrated that inoculation with selected rhizobacteria strains increased Ni extraction from the soil and Ni uptake by *A. murale* (Abou-Shanab et al. 2006). These authors considered the presence of such rhizobacteria to be an important factor that influenced metal hyperaccumulation. Becerra-Castro et al. (2013) used two strains of *Arthrobacter* (SBA82 and LA44) harbouring several plant growth-promoting characteristics are able to mobilize Ni from serpentine rock, as an inoculum for *A. serpyllifolium* ssp. *malacitanum* grown in ultramafic soil, and observed an increase in plant biomass and shoot Ni concentrations. Durand et al. (2016) isolated plant growth-promoting rhizobacteria from the rhizosphere soil of two hyperaccumulator plant associations: *B. tymphaea*-*N. tymphaea* (NB) and *B. tymphaea*-*A. murale* (AB), both being characteristic of a serpentine outcrop in Greece. The screening of the isolates revealed two PGPR strains (AB30 and NB24) that were affiliated to *Variovorax paradoxus* and that were used to inoculate the same plant associations growing in mesocosms. Biomass (root and shoot), shoot Ni uptake, and Ni removal by the *B. tymphaea*-*N. tymphaea* plant association inoculated with strain NB24 was significantly higher than that of the respective non-inoculated association.

Benefits to plants of mycorrhizal inoculation in highly stressed and nutrient-poor environments are well documented. Inoculation with arbuscular mycorrhizae in trace elements-polluted mine tailings has proven particularly

effective in enhancing plant survival and performance during restoration (Orłowska et al. 2011; Kohler et al. 2015; Maltz and Treseder 2015). However, fewer studies have found inoculating with mycorrhizal fungi species or strains to enhance metal uptake and accumulation. In fact, until the early 2000s, hyperaccumulating plants were generally considered non-mycorrhizal (Gonçalves et al. 1997; Leyval et al. 1997; Pawłowska et al. 2000). Since then, several studies have found that hyperaccumulators can form symbioses with arbuscular mycorrhizal fungi (AMF). *Pteris vitatta*, an As-hyperaccumulating fern, tended to show higher mycorrhizal colonization on As-polluted soil. Leung et al. (2007) suggested that enhanced P uptake could be linked to increased As absorption and transport. Mycorrhizal colonisation has been observed in *Thlaspi praecox*, a Cd- and Zn-hyperaccumulator of the Brassicaceae family (generally considered to be non-mycorrhizal) growing on metal-polluted soil in Slovenia (Vogel-Mikus et al. 2005). *Berkheya coddii* was the first Ni-hyperaccumulating plant in which the presence of arbuscular mycorrhizal (AM) symbiosis was reported (Turnau and Mesjasz-Przybyłowicz 2003). Arbuscular mycorrhizal fungi (AMF) isolated from serpentine soil significantly enhanced growth and survival of the Ni-hyperaccumulator *B. coddii* when growing in the same soil (Orłowska et al. 2011). AMF inoculation reduced shoot and root Ni concentrations, however, and owing to the higher biomass the total Ni yield was up to 20 times greater in mycorrhizal plants compared to the non-mycorrhizal ones. The authors proposed that AMF enhancement of Ni uptake may help to improve Ni phytomining techniques.

5 Improving Soil Metal Removal Using Metal-Mobilizing Microbial Strains

Metal-hyperaccumulating plant species have an extraordinary capacity for trace metal accumulation. Many authors have considered the possibility that such species actively mobilize trace

elements from non-labile soil metal pools, as a means of increasing the labile concentrations and consequently plant uptake and accumulation. In accordance, several studies have shown a higher labile fraction of hyperaccumulated metals, such as Ni, at the rhizosphere of these plants compared to those of non-accumulating plant species or the surrounding non-vegetated soil (Puschenreiter et al. 2005). However, most authors have concluded that this effect is not a result of specific metal-mobilizing mechanisms employed by hyperaccumulators. It seems more likely, therefore, that the pronounced depletion of trace elements in the rhizosphere, caused by the high rate of uptake of the element from the soil solution, induces their replenishment from the less-mobile fraction to the mobile pools, and maintains a sustained high metal concentration in the soil solution. Root activity of *N. goessingensis* has been proposed to participate in an enhanced dissolution of Ni-bearing minerals, contributing to higher Ni uptake (Puschenreiter et al. 2005). Similarly, mineralogical studies have shown the presence of smectite in the rhizosphere of *A. serpyllifolium* ssp. *lusitanicum*, which was related to a more intense weathering of Ni-rich ferromagnesium minerals (chlorite, serpentine) and an increase in labile Ni (Kidd et al. 2009). Chardot-Jacques et al. (2013) found that growth of the Ni-hyperaccumulator *L. emarginata* increased the dissolution of chrysotile (a silicate mineral of the serpentine group with low Ni solubility). These authors suggested that the high Ni uptake by the plant causes a decrease in water-soluble Ni, which in turn induces chrysotile dissolution. However, whether this phenomenon is plant- or microbially-induced, or the result of complex plant-microbial interactions, is unknown. It is well established that microbial transformation of soil minerals leads to the solubilization of metals together with essential nutrients, and to the modification of their form and distribution in the solid phase (Quantin et al. 2002). Soil metal availability greatly influences the success of phytomining and its long-term sustainability, and bioaugmentation with metal-mobilizing,

plant-associated bacteria could enhance the viability of this technique (Kidd et al. 2009).

Microbes are intimately associated with the biogeochemical cycling of metals. Microbial activity can result in metal mobilization or immobilization depending on the mechanism involved and the microenvironment where the organism(s) are located (Violante et al. 2008; Ehrlich and Newman 2009; Gadd 2010) (Fig. 2). Some metal-tolerant bacterial strains associated with (hyper)accumulating plants have been shown to mobilize metals in soils, and consequently increase the phytoavailable metal fraction in the soil, as well as plant uptake and accumulation. Muehe et al. (2015) found *Arabidopsis halleri* accumulated 100% more Cd and 15% more Zn when grown on natural Cd-polluted soil than on the same soil that had undergone gamma-irradiation. Gamma irradiation affected neither plant growth nor soil metal availability, but strongly altered the composition and density of the soil microbial community. Bacteria can modify trace elements mobility and bioavailability through several mechanisms: the release of chelating agents (such as organic acids, phenolic compounds, and siderophores), and acidification or redox changes in the rhizosphere (Lloyd 2003; Glick 2010). Sessitsch et al. (2013) reviewed potential mechanisms for microbial effects on bioavailability in the rhizosphere environment. Sorbed, precipitated, and occluded trace elements can be solubilized by acidification, chelation, and ligand-induced dissolution. To date, two groups of bacterially produced natural chelators are known: organic acids and siderophores. Low-molecular mass carboxylic acids can play an important role in chemical attack of minerals, providing protons as well as a metal-chelating anion (Jacobs et al. 2002; Huang et al. 2004; Lian et al. 2008).

Oxalic acid can leach metals such as Al and Fe that form soluble oxalate complexes (Strasser et al. 1994). Bacteria that produce trace element-chelating organic acids, such as citric, oxalic, or acetic acid, have been shown to mobilize various trace elements in soil (Becerra-Castro et al. 2013). As mentioned above, siderophores form

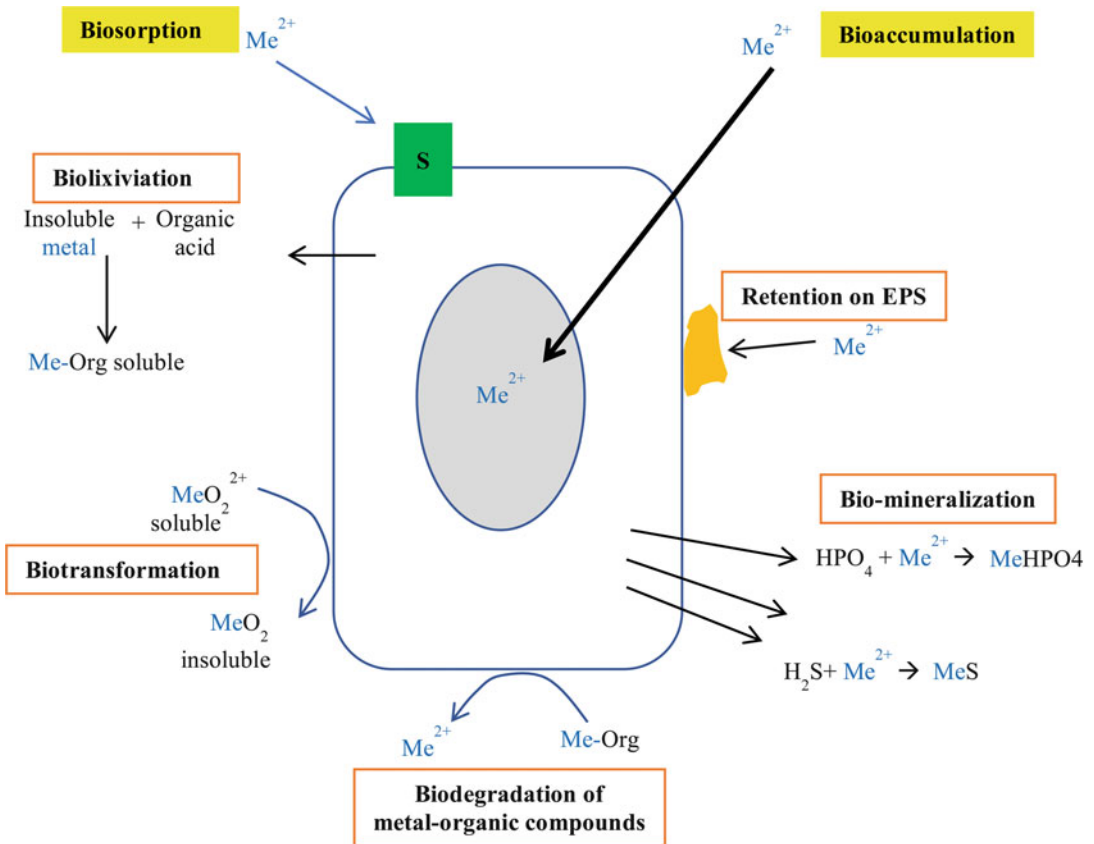


Fig. 2 Interactions between metals and bacteria (adapted from Ledin 2000). S corresponds to the reactive groups present on the bacterial cell wall. Me^{2+} represents a cation metallic. Org corresponds to an organic compound

high-affinity complexes with Fe(III), but can also form complexes of lower stability with other trace elements (Al, Cd, Cu, Ga, In, Ni, Pb and Zn), thus affecting their bioavailability (Schalk et al. 2011; Rajkumar et al. 2012; Sessitsch et al. 2013). Plants can then take up metals from siderophores via various mechanisms, such as chelate degradation, the direct uptake of siderophore-metal complexes, or by a ligand exchange reaction (Schmidt 1999). Braud et al. (2009) reported that inoculating soils with siderophore-producing *P. aeruginosa* significantly increased the concentrations of bioavailable Cr and Pb compared with non-inoculated controls. Enhanced heavy metal uptake was correlated with the increased production of siderophores. Siderophore-producing bacteria that are present in metal-polluted or metal-enriched soil, and their interaction with

hyperaccumulators, could be used in MAP. Several siderophore-producing bacterial strains associated with plants, such as the non-hyperaccumulator *Brassica juncea*, and the hyperaccumulators *T. goesingense*, *A. bertolonii*, and *A. murale*, have been isolated and characterized from metal-rich soils. They belong to different genera, such as *Staphylococcus* sp., *Microbacterium* sp., *Pseudomonas* sp., *Curtobacterium* sp., *Bacillus* sp., *Arthrobacter* sp., *Paenibacillus* sp., *Leifsonia* sp., *Methylobacterium mesophilicum*, *Methylobacterium extorquens*, *Methylobacterium* sp., *Burkholderia terricola*, *Okibacterium fritillariae*, *Rhodococcus fascians*, *Rhodococcus* sp. (Idris et al. 2004; Barzanti et al. 2007). Becerra-Castro et al. (2013) evaluated the weathering capacities of, and Ni mobilization by, two rhizobacterial strains associated with the

Ni-hyperaccumulator *A. serpyllifolium* ssp. *lusitanicum* and ssp. *malacitanum*. A minimal culture medium containing ground ultramafic rock was inoculated with either of two *Arthrobacter* strains: LA44 (indoleacetic acid [IAA] producer) or SBA82 (siderophore producer, PO₄ solubilizer, and IAA producer). Strain LA44 is a more efficient Ni mobilizer, apparently solubilizing Ni associated with Mn oxides, and this appeared to be related to the exudation of oxalate. On the other hand, strain SBA82 also led to the release of Ni and Mn, albeit to a much lower extent. In the latter case, the concurrent mobilization of Fe and Si reflects preferential weathering of Fe-oxides and serpentine minerals, possibly related to siderophore production capacity of the strain. However, some conflicting results showed that the presence of siderophore producers decreased the uptake of metals by plants. Siderophores produced by *Pseudomonas* sp., *Serratia marcescens*, and *Streptomyces* sp. had either no effect or negatively affected Zn and Cd uptake by *Salix caprea* (Kuffner et al. 2010). These contrasting effects suggest that the mechanisms underlying metal uptake are largely plant dependent, but that the efficiency of siderophore producers to either mobilize or immobilize heavy metals from soils is also dependent on several factors such as the binding form of the heavy metals present, the charge of the siderophores, and the pH of the soil and its mineral composition and organic content.

The influence of organic matter content in soil on metal availability and uptake by plants has been extensively studied. It was reported that metal adsorption onto soil constituents declined with decreasing organic matter content in soils (Zeng et al. 2011). Moreover, dissolved organic matter (DOC) in soils may increase the mobility and uptake of heavy metals by plant roots (Du Laing et al. 2008). In fact, organic matter decomposition appears to be one of the most important microbial activities in the rhizosphere, and it is well known that microbes, mainly bacteria and fungi, utilize a wide spectrum of organic compounds such as sugars, organic acids, and amino acids to more complex molecules such as cellulose, pectin, lignin,

lignocellulose, chitin, and starch. Consequently, organic matter decomposition by soil microorganisms releases metals such as Fe, Mn, Zn, Cu, Mo, Ni, Co and Se, which are typically found in the tissues of organisms.

6 Final Remarks and Future Directions

It seems clear that the rhizosphere microbiome plays an important role in plant trace elements bioaccumulation, given experimental evidence suggesting that by reshaping this microbiome we can further enhance the efficiency of phytoextraction and phytomining. However, the efficacy of plant-associated bioinoculants is dependent on a complex array of interacting factors: plant-microbe specificity, soil type and properties, trace elements concentration and type (mono- or poly-metallic), proliferation and survival of the inoculant, *etc.* Moreover, from the literature it can be seen that inoculation methods differ greatly among studies (inoculation of seed/plant/soil, frequency/timing of inoculation events, bacterial cellular densities, *etc.*), and these aspects are likely to influence whether or not a beneficial microbially induced effect is observed.

Bioaugmentation can be challenged by the strong competition encountered in the soil when a selected microbe is introduced. Also, the selected host plant species may not necessarily be compatible with the inoculated bacterial or fungal strain, since these are not naturally selected for by the host (Thijs et al. 2016). The importance of rhizosphere competence or effective root colonization in beneficial plant-microbe interactions is underlined by several studies as contributing to the success of bioaugmentation (Lugtenberg and Dekkers 1999). Moreover, inoculation methods should be optimised in order to enhance the success of the introduced microorganisms (Álvarez-López et al. 2016b). Pereira et al. (2015) and Álvarez-López et al. (2016b) recently showed that the size of the inoculum applied in the soil rhizosphere, and the mode of application (seed or soil

inoculation), are important factors that should be taken into account when planning MAP strategies. Endophytes do not have to compete with the large abundance and diversity of soil microorganisms, which may enhance their chances of establishing a stable and active population. To date, the field of MAP has focused on the use of individual bioinoculants. However, promising results have been found when using mixtures or consortia of different PGP-strains with complementary actions. Visioli et al. (2015) reported that co-inoculating the Ni-hyperaccumulator *Noccaea caerulea*, when growing in serpentine soil with two root endophytes belonging to the *Arthrobacter* and *Microbacterium* genera, had a more positive effect on plant growth, soil Ni removal, and Ni translocation, than when inoculated individually. Both strains were strong IAA producers and presented ACC deaminase activity. Moreira et al. (2016) showed the benefits of combined inoculation of AMF and PGPR for the growth of maize as an 'energy-crop' in metal-polluted soils and their potential application in phytomanagement strategies.

Ultramafic rocks occupy <1% of Earth's land surface and these outcrops have the potential to provide multiple ecosystem services and contribute to producing renewable raw materials and energy (i.e. agromining). In the same way, polluted soils are an ever-increasing environmental concern due to increased industrialization. Phytoremediation coupled with bioaugmentation could be a solution towards the recovering soil quality, underlining the role of the rhizosphere and microbes associated with hyperaccumulator plants in metal accumulation.

References

- Aboudrar W, Schwartz C, Benizri E, Morel JL, Boularbah A (2007) Microbial diversity as affected by the rhizosphere of the hyperaccumulator *Thlaspi caerulescens* under natural conditions. *Int J Phytoremediation* 9:41–52
- Aboudrar W, Schwartz C, Morel JL, Boularbah A (2013) Effect of nickel-resistant rhizosphere bacteria on the uptake of nickel by the hyperaccumulator *Noccaea caerulea* under controlled conditions. *J Soils Sediments* 13:501–507
- Abou-Shanab RI, Delorme TA, Angle JS, Chaney RL, Ghanem K, Moawad H, Ghazlan HA (2003a) Phenotypic characterization of microbes in the rhizosphere of *Alyssum murale*. *Int J Phytoremediation* 5:367–379
- Abou-Shanab RA, Angle JS, Delorme TA, Chaney RL, van Berkum P, Moawad H, Ghanem K, Ghazlan HA (2003b) Rhizobacterial effects on nickel extraction from soil and uptake by *Alyssum murale*. *New Phytol* 158:219–224
- Abou-Shanab R, Angle J, Chaney R (2006) Bacterial inoculants affecting nickel uptake by *Alyssum murale* from low, moderate and high Ni soils. *Soil Biol Biochem* 38:2882–2889
- Abou-Shanab RI, van Berkum P, Angle JS (2007) Heavy metal resistance and genotypic analysis of metal resistance genes in gram-positive and gram-negative bacteria present in Ni-rich serpentine soil and in the rhizosphere of *Alyssum murale*. *Chemosphere* 68:360–367
- Aislabie J, Deslippe JR (2013) Soil microbes and their contribution to soil services. In: Dymond JR (ed) *Ecosystem services in New Zealand—conditions and trends*. Manaaki Whenua Press, Lincoln, New Zealand, pp 112–161
- Álvarez-López V, Prieto-Fernández Á, Becerra-Castro C, Monterroso C, Kidd PS (2016a) Rhizobacterial communities associated with the flora of three serpentine outcrops of the Iberian Peninsula. *Plant Soil* 403:233–252
- Álvarez-López V, Prieto-Fernández Á, Janssen J, Herzig R, Vangronsveld J, Kidd PS (2016b) Inoculation methods using *Rhodococcus erythropolis* strain P30 affects bacterial assisted phytoextraction capacity of *Nicotiana tabacum*. *Int J Phytoremediation* 18:406–415
- Azcón R, Medina A, Roldán A, Biró B, Vivas A (2009) Significance of treated agrowaste residue and autochthonous inoculates (arbuscular mycorrhizal fungi and *Bacillus cereus*) on bacterial community structure and phytoextraction to remediate soils contaminated with heavy metals. *Chemosphere* 75:327–334
- Badri DV, Chaparro JM, Zhang R, Shen Q, Vivanco JM (2013) Application of natural blends of phytochemicals derived from the root exudates of *Arabidopsis* to the soil reveal that phenolic-related compounds predominantly modulate the soil microbiome. *J Biol Chem* 288:4502–4512
- Bandick AK, Dick RP (1999) Field management effects on enzyme activities. *Soil Biol Biochem* 31:1471–1479
- Bani A, Echevarria G, Sulçe S, Morel JL (2015) Improving the agronomy of *Alyssum murale* for extensive phytomining: a five-year field study. *Int J Phytoremediation* 17:117–127
- Banowetz GM, Whittaker GW, Dierksen KP, Azevedo MD, Kennedy AC, Griffith SM, Steiner JJ (2006) Fatty acid methyl ester analysis to identify sources of soil in surface water. *J Environ Qual* 35:133–140

- Barzanti R, Ozino F, Bazzicalupo M, Gabbriellini R, Galardi F, Gonnelli C, Mengoni A (2007) Isolation and characterization of endophytic bacteria from the nickel hyperaccumulator plant *Alyssum bertolonii*. *Microb Ecol* 53:306–316
- Baudoin E, Benizri E, Guckert A (2001) Metabolic structure of bacterial communities from distinct maize rhizosphere compartments. *Eur J Soil Biol* 37:85–93
- Baudoin E, Benizri E, Guckert A (2002) Impact of growth stages on bacterial community structure along maize roots by metabolic and genetic fingerprinting. *Appl Soil Ecol* 19:135–145
- Baudoin E, Benizri E, Guckert A (2003) Impact of artificial root exudates on the bacterial community structure in bulk soil and maize rhizosphere. *Soil Biol Biochem* 35:1183–1192
- Beattie GA (2007) Plant-associated bacteria: survey, molecular phylogeny, genomics and recent advances. In: Gnanamanickam SS (ed) *Plant-associated bacteria*. Springer, Dordrecht, pp 1–56
- Becerra-Castro C, Monterroso C, García-Lestón M, Prieto-Fernández A, Acea MJ, Kidd PS (2009) Rhizosphere microbial densities and trace metal tolerance of the nickel hyperaccumulator *Alyssum serpyllifolium* subsp. *lusitanicum*. *Int J Phytoremediation* 11:525–541
- Becerra-Castro C, Monterroso C, Prieto-Fernández A, Rodríguez-Lamas L, Loureiro-Viñas M, Acea MJ, Kidd PS (2012) Pseudometallophytes colonising Pb/Zn mine tailings: a description of the plant-microorganism-rhizosphere soil system and isolation of metal-tolerant bacteria. *J Hazard Mater* 217–218:350–359
- Becerra-Castro C, Kidd P, Kuffner M, Prieto-Fernández A, Hann S, Monterroso C, Sessitsch A, Wenzel W, Puschenreiter M (2013) Bacterially induced weathering of ultramafic rock and its implications for phytoextraction. *Appl Environ Microbiol* 79:5094–5103
- Belimov AA, Hontzeas N, Safronova VI, Demchinskaya SV, Piluzza G, Bullitta S, Glick BR (2005) Cadmium-tolerant plant growth-promoting bacteria associated with the roots of Indian mustard (*Brassica juncea* L. Czern.) *Soil Biol Biochem* 37:241–250
- Bending GD, Turner MK, Jones JE (2002) Interaction between crop residue and organic matter quality and the functional diversity of soil microbial communities. *Soil Biol Biochem* 34:1073–1082
- Benizri E, Nguyen C, Piutti S, Slezack-Deschaumes S, Philippot L (2007) Additions of maize root mucilage to soil changed the structure of the bacterial community. *Soil Biol Biochem* 39:1230–1233
- Berg J, Brandt KK, Al-Soud WA, Holm PE, Hansen LH, Sørensen SJ, Nybroe O (2012) Selection for Cu-tolerant bacterial communities with altered composition, but unaltered richness, via long-term Cu exposure. *Appl Environ Microbiol* 78:7438–7446
- Blom D, Fabbri C, Connor EC, Schiestl FP, Klauser DR, Boller T, Eberl L, Weiskopf L (2011) Production of plant growth modulating volatiles is widespread among rhizosphere bacteria and strongly depends on culture conditions. *Environ Microbiol* 13:3047–3058
- Boominathan R, Doran P (2003) Cadmium tolerance and antioxidative defences in hairy roots of the cadmium hyperaccumulator, *Thlaspi caerulescens*. *Biotechnol Bioeng* 83:158–167
- Bordez L, Jourand P, Ducouso M, Carriconde F, Cavaloc Y, Santini S, Claverie JM, Wantiez L, Leveau A, Amir H (2016) Distribution patterns of microbial communities in ultramafic landscape: a metagenetic approach highlights the strong relationships between diversity and environmental traits. *Mol Ecol* 25:2258–2272
- Braud A, Jézéquel K, Bazot S, Lebeau T (2009) Enhanced phytoextraction of an agricultural Cr- and Pb-contaminated soil by bioaugmentation with siderophore-producing bacteria. *Chemosphere* 74:280–286
- Burd GI, Dixon DG, Glick BR (2000) Plant growth-promoting bacteria that decrease heavy metal toxicity in plants. *Can J Microbiol* 46:237–245
- Cabello-Conejo MI, Becerra-Castro C, Prieto-Fernández A, Monterroso C, Saavedra-Ferro A, Mench M, Kidd PS (2014) Rhizobacterial inoculants can improve nickel phytoextraction by the hyperaccumulator *Alyssum pintodasilvae*. *Plant Soil* (1–2):35–50
- Carrillo-Castañeda G, Juárez Muñoz J, Peralta-Videa J, Gomez E, Tiemann K, Duarte-Gardea M, Gardea-Torresdey J (2002) Alfalfa growth promotion by bacteria grown under iron limiting conditions. *Adv Environ Res* 6:391–399
- Chaparro J, Sheflin A, Manter D, Vivanco J (2012) Manipulating the soil microbiome to increase soil health and plant fertility. *Biol Fertil Soils* 48:489–499
- Chardot-Jacques V, Calvaruso C, Simon B, Turpault MP, Echevarria G, Morel JL (2013) Chrysotile dissolution in the rhizosphere of the nickel hyperaccumulator *Leptoplax emarginata* (2013). *Environ Sci Technol* 47:2612–2620
- Compant S, Duffy B, Nowak J, Clément C, Barka EA (2005) Use of plant growth promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action, and future prospects. *Appl Environ Microbiol* 71:4951–4959
- Crowley D, Kraemer SM (2007) Function of siderophores in the plant rhizosphere. In: Pinton R, Varanini Z, Nannipieri P (eds) *The rhizosphere: biochemistry and organic substances at the soil-plant interface*. Soil-Plant Interface. CRC Press, Boca Raton, FL
- Daghino S, Murat C, Sizzano E, Giralanda M, Perotto S (2012) Fungal diversity is not determined by mineral and chemical differences in serpentine substrates. *PLoS One* 7(9):e44233
- De Souza M, Huang C, Chee N, Terry N (1999) Rhizosphere bacteria enhance the accumulation of selenium and mercury in wetland plants. *Planta* 209:259–263
- De-la-Peña C, Víctor M, Loyola-Vargas ML (2014) Biotic interactions in the rhizosphere: a diverse

- cooperative enterprise for plant productivity. *Plant Physiol* 166:701–719
- Dell'Amico E, Cavalca L, Andreoni V (2008) Improvement of *Brassica napus* growth under cadmium stress by cadmium-resistant rhizobacteria. *Soil Biol Biochem* 40:74–84
- DeSantis T, Brodie EL, Moberg J, Zubieta I, Piceno Y, Andersen G (2007) High-density universal 16S rRNA microarray analysis reveals broader diversity than typical clone library when sampling the environment. *Microb Ecol* 53:371–383
- Dick RP (1997) Soil enzyme activities as integrative indicators of soil health. In: Pankhurst CE, Doube BM, Gupta VVSR (eds) *Biological indicators of soil health*. CAB International, Wallingford, pp 121–156
- Doelman P (1985) Resistance of soil microbial communities to heavy metals. In: Jensen V, Kjølner A, Sørensen LH (eds) *Microbial communities in soils*. Elsevier, London, pp 369–384
- Dominati E, Patterson M, MacKay A (2010) A framework for classifying and quantifying natural capital and ecosystem services of soils. *Ecol Econ* 69:1858–1868
- Du Laing G, De Vos R, Vandecasteele B, Lesage E, Tack FMG, Verloo MG (2008) Effect of salinity on heavy metal mobility and availability in intertidal sediments of the Scheldt estuary. *Estuar Coast Shelf Sci* 77:589–602
- Duca D, Lorv J, Patten CL, Rose D, Glick BR (2014) Indole-3-acetic acid in plant-microbe interactions. *A Van Leeuw J Microb* 1–41
- Duineveld BM, Kowalchuk GA, Keijzer A, van Elsas JD, van Veen JA (2001) Analysis of bacterial communities in the rhizosphere of *Chrysanthemum* via Denaturing Gradient Gel Electrophoresis of PCR-amplified 16S rRNA as well as DNA fragments coding for 16S rRNA. *Appl Environ Microbiol* 67:172–178
- Duponnois R, Kisa M, Assigbetse K, Prin Y, Thioulouse J, Issartel M, Moulin P, Lepage M (2006) Fluorescent pseudomonads occurring in *Macrotermes subhyalinus* mound structures decrease Cd toxicity and improve its accumulation in sorghum plants. *Sci Total Environ* 370:391–400
- Durand A, Piutti S, Rue M, Morel JL, Echevarria G, Benizri E (2016) Improving nickel phytoextraction by co-cropping hyperaccumulator plants inoculated by Plant Growth Promoting Rhizobacteria. *Plant Soil* 399:179–192
- Egamberdieva D, Renella G, Wirth S, Islam R (2011) Enzyme activities in the rhizosphere of plants. In: Shukla G, Varma A (eds) *Soil enzymology, soil biology*, vol 22. Springer, Berlin, Heidelberg. doi:10.1007/978-3-642-14225-3_8
- Ehrlich HL, Newman DK (2009) *Geomicrobiology*, 5th edn. CRC Press, Taylor & Francis, Boca Raton, FL
- Ellis RJ, Morgan P, Weightman AJ, Fry JC (2003) Cultivation-dependent and -independent approaches for determining bacterial diversity in heavy-metal-contaminated soil. *Appl Environ Microbiol* 69:3223–3230
- Epelde L, Becerril JM, Hernández-Allica J, Barrutia O, Garbisu C (2008) Functional diversity as indicator of the recovery of soil health derived from *Thlaspi caerulescens* growth and metal phytoextraction. *Appl Soil Ecol* 39:299–310
- Epelde L, Mijangos I, Becerril JM, Garbisu C (2009) Soil microbial community as bioindicator of the recovery of soil functioning derived from metal phytoextraction with sorghum. *Soil Biol Biochem* 41:1788–1794
- Farwell AJ, Vesely S, Nero V, Rodriguez H, Shah S, Dixon DG, Glick BR (2006) The use of transgenic canola (*Brassica napus*) and plant growth-promoting bacteria to enhance plant biomass at a nickel-contaminated field site. *Plant Soil* 288:309–318
- Farwell AJ, Vesely S, Nero V, Rodriguez H, McCormack K, Shah S, Dixon DG, Glick BR (2007) Tolerance of transgenic canola plants (*Brassica napus*) amended with plant growth-promoting bacteria to flooding stress at a metal-contaminated field site. *Environ Pollut* 147:540–545
- Fritze H, Pennanen T, Vanhala P (1997) Impact of fertilizers on the humus layer microbial community of Scots pine stands growing along a gradient of heavy metal pollution. In: Insam H, Rangger A (eds) *Microbial communities. Functional versus structural aspects*. Springer, Berlin, pp 68–83
- Gadd GM (2010) Metals, minerals and microbes: geomicrobiology and bioremediation. *Microbiology* 156:609–643
- García-Gonzalo P, Pradas del Real AE, Lobo MC, Pérez-Sanz A (2016) Different genotypes of *Silene vulgaris* (Moench) Garcke grown on chromium-contaminated soils influence root organic acid composition and rhizosphere bacterial communities. *Environ Sci Pollut Res* 1–12
- Garland JL, Mills AL (1991) Classification and characterisation of heterotrophic microbial communities on the basis of patterns of community-level-sole-carbon-source-utilization. *Appl Environ Microbiol* 57:2351–2359
- Glick BR (2010) Using soil bacteria to facilitate phytoremediation. *Biotechnol Adv* 28:367–374
- Gołębiewski M, Deja-Sikora E, Cichosz M, Tretyn A, Wróbel B (2014) 16S rDNA pyrosequencing analysis of bacterial community in heavy metals polluted soils. *Microb Ecol* 67:635–647
- Gonçalves SC, Goncalves MT, Freitas H, Martins-Loucao MA (1997) Mycorrhizae in a Portuguese serpentine community. In: Jaffré T, Reeves RD, Becquer T (eds) *The ecology of ultramafic and metalliferous areas. Proceedings of the Second International Conference on Serpentine Ecology*. Centre ORSTOM de Nouméa, New Caledonia, pp 87–89
- Grandlic CJ, Mendez MO, Chorover J, Machado B, Maier RM (2008) Plant growth promoting bacteria for phytostabilization of mine tailings. *Environ Sci Technol* 42:2079–2084
- Grayston SJ, Wang S, Campbell CD, Edwards AC (1998) Selective influence of plant species on microbial

- diversity in the rhizosphere. *Soil Biol Biochem* 30:369–378
- Gullap MK, Dasci M, Erkovan Hİ, Koc A, Turan M (2014) Plant Growth-Promoting Rhizobacteria (PGPR) and phosphorus fertilizer-assisted phytoextraction of toxic heavy metals from contaminated soils. *Commun Soil Sci Plant Anal* 45:2593–2606
- Guo J, Tang S, Ju X, Ding Y, Liao S, Song N (2011) Effects of inoculation of a plant growth promoting rhizobacterium *Burkholderia* sp. D54 on plant growth and metal uptake by a hyperaccumulator *Sedum alfredii* Hance grown on multiple metal contaminated soil. *World J Microbiol Biotechnol* 27:2835–2844
- Gürtler V, Stanisich VA (1996) New approaches to typing and identification of bacteria using the 16S-23S rDNA spacer region. *Microbiology* 142:3–16
- Hagmann DF, Goodey NM, Mathieu C, Evans J, Aronson MFJ, Gallagher F, Krumins JA (2015) Effect of metal contamination on microbial enzymatic activity in soil. *Soil Biol Biochem* 91:291–297
- Haslmayr HP, Meißner S, Langella F, Baumgarten A, Geletneky J (2014) Establishing best practice for microbially aided phytoremediation. *Environ Sci Pollut Res* 21:6765–6774
- Hattori H (1989) Influence of cadmium on decomposition of sewage sludge and microbial activities in soils. *Soil Sci Plant Nutr* 35:289–299
- He LY, Chen ZJ, Ren G-D, Zhang Y-F, Qian M, Sheng X-F (2009) Increased cadmium and lead uptake of a cadmium hyperaccumulator tomato by cadmium-resistant bacteria. *Ecotoxicol Environ Saf* 72:1343–1348
- He LY, Zhang YF, Ma HY, LN S, Chen ZJ, Wang QY, Qian M, Sheng XF (2010a) Characterization of copper-resistant bacteria and assessment of bacterial communities in rhizosphere soils of copper-tolerant plants. *Appl Soil Ecol* 44:49–55
- He CQ, Tan G, Liang X, Du W, Chen Y, Zhi G, Zhu Y (2010b) Effect of Zn-tolerant bacterial strains on growth and Zn accumulation in *Orychophragmus violaceus*. *Appl Soil Ecol* 44:1–5
- Herrera A, Héry M, Stach JEM, Jaffré T, Normand P, Navarro E (2007) Species richness and phylogenetic diversity comparisons of soil microbial communities affected by nickel-mining and revegetation efforts in New Caledonia. *Eur J Soil Biol* 43:130–139
- Héry M, Nazaret S, Jaffré T, Normand P, Navarro E (2006) Adaptation to nickel spiking of bacterial communities in neocaledonian soils. *Environ Microbiol* 5:3–12
- Hiltner L (1904) Über neuer Erfahrungen und Probleme auf dem Gebiet der Bodenbakteriologie unter besonderer Berücksichtigung der Gründüngung und Brache. *Arbeiten aus dem Deutschen Landwirtschafts Gesellschaft* 98:59–78
- Hinsinger P, Plassard C, Jaillard B (2006) Rhizosphere: a new frontier for soil biogeochemistry. *J Geochem Explor* 88:210–213
- Hu Q, Qi HY, Zeng JH, Zhang HX (2007) Bacterial diversity in soils around a lead and zinc mine. *J Environ Sci* 19:74–79
- Huang PM, Wang MC, Wang MK (2004) Mineral–organic–microbial interactions. In: Hillel D, Rosenzweig C, Powlson DS, Scow KM, Singer MJ, Sparks DL, Hatfield J (eds) *Encyclopedia of soils in the environment*. Elsevier, Amsterdam, pp 486–499
- Hussein H (2008) Optimization of plant-bacteria complex for phytoremediation of contaminated soils. *Int J Bot* 4:437–443
- Idris R, Trifonova R, Puschenreiter M, Wenzel WW, Sessitsch A (2004) Bacterial communities associated with flowering plants of the Ni hyperaccumulator *Thlaspi goesingense*. *Appl Environ Microbiol* 70:2667–2677
- Jacobs H, Boswell GP, Ritz K, Davidson FA, Gadd GM (2002) Solubilization of metal phosphates by *Rhizoctonia solani*. *Mycol Res* 106:1468–1479
- Janssen J, Weyens N, Croes S, Beckers B, Meiresonne L, Van Peteghem P, Carleer R, Vangronsveld J (2015) Phytoremediation of metal contaminated soil using willow: exploiting plant associated bacteria to improve biomass production and metal uptake. *Int J Phytoremediation* 17:1123–1136
- Jiang CY, Sheng XF, Qian M, Wang QY (2008) Isolation and characterization of a heavy metal resistant *Burkholderia* sp. from heavy metal-contaminated paddy field soil and its potential in promoting plant growth and heavy metal accumulation in metal-polluted soil. *Chemosphere* 72:157–164
- Kandeler E, Tschirko D, Bruce KD, Stemmer M, Hobbs PJ, Bardgett RD, Amelung W (2000) The structure and function of the soil microbial community in microhabitats of a heavy metal polluted soil. *Biol Fertil Soils* 32:390–400
- Kapulnik Y, Douds D (2000) *Arbuscular Mycorrhizas: physiology and function*. Kluwer Academic, Dordrecht, The Netherlands, 384 pp
- Khan S, El-Latif Hesham A, Qiao M, Rehman S, He JZ (2010) Effects of Cd and Pb on soil microbial community structure and activities. *Environ Sci Pollut Res* 17:288–296
- Kidd P, Barceló J, Bernal MP, Navari-Izzo F, Poschenrieder C, Shilev S, Clemente R, Monterroso C (2009) Trace element behaviour at the root–soil interface: implications in phytoremediation. *Environ Exp Bot* 67:243–259
- Kinnersley AM (1993) The role of phytochelates in plant growth and productivity. *Plant Growth Regul* 12:207–218
- Kirk JL, Beaudette LA, Hart M, Moutoglis P, Klironomos JN, Lee H, Trevors JT (2004) Methods of studying soil microbial diversity. *J Microbiol Methods* 58:169–188
- Knight BP, McGrath SP, Chaudri AM (1997) Biomass carbon measurements and substrate utilization patterns of microbial populations from soils amended

- with cadmium, copper, or zinc. *Appl Environ Microbiol* 63:39–43
- Kohler J, Caravaca F, Azcón R, Díaz G, Roldán A (2015) The combination of compost addition and arbuscular mycorrhizal inoculation produced positive and synergistic effects on the phytomanagement of a semiarid mine tailing. *Sci Total Environ* 514:42–48
- Kozdrój J, van Elsas JD (2001a) Structural diversity of microorganisms in chemically perturbed soil assessed by molecular and cytochemical approaches. *J Microbiol Methods* 43:197–212
- Kozdrój J, van Elsas JD (2001b) Structural diversity of microbial communities in arable soils of a heavily industrialised area determined by PCR-DGGE fingerprinting and FAME profiling. *Appl Soil Ecol* 17:31–42
- Krumins JA, Goodey NM, Gallagher FJ (2015) Plant-soil interactions in metal contaminated soils. *Soil Biol Biochem* 80:224–231
- Kuffner M, Puschenreiter M, Wieshammer G, Gorfer M, Sessitsch A (2008) Rhizosphere bacteria affect growth and metal uptake of heavy metal accumulating willows. *Plant Soil* 304:35–44
- Kuffner M, De Maria S, Puschenreiter M, Fallmann K, Wieshammer G, Gorfer M, Strauss J, Rivelli AR, Sessitsch A (2010) Culturable bacteria from Zn- and Cd-accumulating *Salix caprea* with differential effects on plant growth and heavy metal availability. *J Appl Microbiol* 108:1471–1484
- Kumar KV, Singh N, Behl H, Srivastava S (2008) Influence of plant growth promoting bacteria and its mutant on heavy metal toxicity in *Brassica juncea* grown in fly ash amended soil. *Chemosphere* 72:678–683
- Kumar KV, Srivastava S, Singh N, Behl HM (2009) Role of metal resistant plant growth promoting bacteria in ameliorating fly ash to the growth of *Brassica juncea*. *J Hazard Mater* 170:51–57
- Kuperman RG, Carreiro MM (1997) Soil heavy metal concentrations, microbial biomass and enzyme activities in a contaminated grassland ecosystem. *Soil Biol Biochem* 29:179–190
- Kurek E, Jaroszuk-Scisel J (2003) Rye (*Secale cereale*) growth promotion by *Pseudomonas fluorescens* strains and their interactions with *Fusarium culmorum* under various soil conditions. *Biol Control* 26:48–56
- Lebeau T, Braud A, Jezequel K (2008) Performance of bioaugmentation-assisted phytoextraction applied to metal contaminated soils: a review. *Environ Pollut* 153:497–522
- Lemanceau P, Maurhofer M, Défago G (2007) Contribution of studies on suppressive soils to the identification of bacterial biocontrol agents and to the knowledge of their modes of action. In: Gnanamanickam SS (ed) - Plant-associated bacteria. Springer, The Netherlands, pp 231–267
- Leung HM, Ye ZH, Wong MH (2007) Survival strategies of plants associated with arbuscular mycorrhizal fungi on toxic mine tailings. *Chemosphere* 66:905–915
- Leyval C, Turnau K, Haselwandter K (1997) Effect of heavy metal pollution on mycorrhizal colonization and function: physiological, ecological and applied aspects. *Mycorrhiza* 7:139–153
- Li Z, Xu J, Tang C, Wu J, Muhammad A, Wan H (2006) Application of 16S rDNA-PCR amplification and DGGE fingerprinting for detection of shift in microbial community diversity in Cu-, Zn-, and Cd-contaminated paddy soils. *Chemosphere* 62:1374–1380
- Li WC, Ye ZH, Wong MH (2007) Effects of bacteria on enhanced metal uptake of the Cd/Zn-hyperaccumulating plant, *Sedum alfredii*. *J Exp Bot* 58:4173–4182
- Lian B, Chen Y, Zhu L, Yang R (2008) Effect of microbial weathering on carbonate rocks. *Earth Sci Front* 15:90–99
- Liang CN, Tabatabai MA (1978) Effects of trace elements on nitrification in soils. *J Environ Qual* 7:291–293
- Lipman CB (1926) The bacterial flora of serpentine soils. *J Bacteriol* 12:315–318
- Lloyd JR (2003) Microbial reduction of metals and radionuclides. *FEMS Microbiol Rev* 27:411–425
- Lodewyckx C, Mergeay M, Vangronsveld J, Clijsters H, Van der Lelie D (2002) Isolation, characterization, and identification of bacteria associated with the zinc hyperaccumulator *Thlaspi caerulescens* subsp. *calaminaria*. *Int J Phytoremediation* 4:101–115
- Lucisine P, Echevarria G, Sterckeman T, Vallance J, Rey P, Benizri E (2014) Effect of hyperaccumulating plant cover composition and rhizosphere-associated bacteria on the efficiency of nickel extraction from soil. *Appl Soil Ecol* 81:30–36
- Lugtenberg BJJ, Dekkers LC (1999) What makes *Pseudomonas* bacteria rhizosphere competent? *Environ Microbiol* 1:9–13
- Ma Y, Rajkumar M, Freitas H (2009a) Improvement of plant growth and nickel uptake by nickel resistant-plant-growth promoting bacteria. *J Hazard Mater* 166:1154–1161
- Ma Y, Rajkumar M, Freitas H (2009b) Isolation and characterization of Ni mobilizing PGPB from serpentine soils and their potential in promoting plant growth and Ni accumulation by *Brassica*. *Chemosphere* 75:719–725
- Ma Y, Rajkumar M, Freitas H (2009c) Inoculation of plant growth promoting bacterium *Achromobacter xylosoxidans* strain Ax10 for the improvement of copper phytoextraction by *Brassica juncea*. *J Environ Manag* 90:831–837
- Ma Y, Prasad MNV, Rajkumar M, Freitas H (2011) Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils. *Biotechnol Adv* 29:248–258
- Ma Y, Rajkumar M, Luo Y, Freitas H (2013) Phytoextraction of heavy metal polluted soils using *Sedum plumbizincicola* inoculated with metal mobilizing *Phyllobacterium myrsinacearum* RC6b. *Chemosphere* 93:1386–1392

- Maltz MR, Treseder KK (2015) Sources of inocula influence mycorrhizal colonization of plants in restoration projects: a meta-analysis. *Restor Ecol* 23:625–634
- Mastretta C, Taghavi S, van der Lelie D, Mengoni A, Galardi F, Gonnelli C, Barac T, Boulet J, Weyens N, Vangronsveld J (2009) Endophytic bacteria from seeds of *Nicotiana tabacum* can reduce cadmium phytotoxicity. *Int J Phytoremediation* 11:251–267
- Mengoni A, Barzanti R, Gonnelli C, Gabbriellini R, Bazzicalupo M (2001) Characterization of nickel-resistant bacteria isolated from serpentine soil. *Environ Microbiol* 3:691–698
- Mengoni A, Grassi E, Barzanti R, Biondi EG, Gonnelli C, Kim CK, Bazzicalupo M (2004) Genetic diversity of bacterial communities of serpentine soil and of rhizosphere of the nickel-hyperaccumulator plant *Alyssum bertolonii*. *Microb Ecol* 48:209–217
- Moreira H, Pereira SIA, Marques APGC, Rangel AOSS, Castro PML (2016) Mine land valorization through energy maize production enhanced by the application of plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi. *Environ Sci Pollut Res* 23:6940–6950
- Muehe EM, Weigold P, Adaktylou IJ, Planer-Friedrich B, Kraemer U, Kappler A, Behrens S (2015) Rhizosphere microbial community composition affects cadmium and zinc uptake by the metal-hyperaccumulating plant *Arabidopsis halleri*. *Appl Environ Microbiol* 81:2173–2181
- Muyzer G (1999) Genetic fingerprinting of microbial communities—present status and future perspectives. *Methods of microbial community analysis. Proceedings of the 8th international symposium on microbial ecology*. Atlantic Canada Society for Microbial Ecology, Halifax, Canada
- Nannipieri P, Giagnoni L, Renella G, Puglisi E, Ceccanti B, Masciandaro G, Fornasier F, Moscatelli MC, Marinari S (2012) Soil enzymology: classical and molecular approaches. *Biol Fertil Soils* 48:743–762
- Naseby DC, Lynch JM (2002) Enzymes and microbes in the rhizosphere. In: Burns RG, Dick RP (eds) *Enzymes in the environment*. Marcel Dekker, New York, pp 109–123
- Nguyen C (2003) Rhizodeposition of organic C by plants: mechanisms and controls. *Agronomie* 23:375–396
- Niklinska M, Chodak M, Laskowski R (2006) Pollution-induced community tolerance of microorganisms from forest soil organic layers polluted with Zn or Cu. *Appl Soil Ecol* 32:265–272
- Oline DK (2006) Phylogenetic comparisons of bacterial communities from serpentine and nonserpentine soils. *Appl Environ Microbiol* 72:6965–6971
- Orłowska E, Orłowski D, Mesjasz-Przybyłowicz J, Turnau K (2011) Role of mycorrhizal colonization in plant establishment on an alkaline gold mine tailing. *Int J Phytoremediation* 13:185–205
- Pal A, Dutta S, Mukherjee PK, Paul AK (2005) Occurrence of heavy metal-resistance in microflora from serpentine soil of Andaman. *J Basic Microbiol* 45:207–218
- Pal A, Wauters G, Paul AK (2007) Nickel tolerance and accumulation by bacteria from rhizosphere of nickel hyperaccumulators in serpentine soil ecosystem of Andaman, India. *Plant Soil* 1:37–48
- Pawlowska TE, Chaney RL, Chin M, Charvat I (2000) Effects of metal phytoextraction practices on the indigenous community of arbuscular mycorrhizal fungi at a metal contaminated landfill. *Appl Environ Microbiol* 66:2526–2530
- Pereira SIA, Barbosa L, Castro PML (2015) Rhizobacteria isolated from a metal-polluted area enhance plant growth in zinc and cadmium-contaminated soil. *Int J Environ Sci Technol* 12:2127–2142
- Pessoa-Filho M, Barreto CC, dos Reis Junior FB, Fragozo RR, Costa FS, Carvalho Mendes I, Rovênia Miranda de Andrade L (2015) Microbiological functioning, diversity, and structure of bacterial communities in ultramafic soils from a tropical savanna. *Antonie Van Leeuwenhoek* 107:935–949
- Puschenreiter M, Schnepf A, Millán MI, Fitz WJ, Horak O, Klepp J, Schrefl T, Lombi E, Wenzel WW (2005) Changes of Ni biogeochemistry in the rhizosphere of the hyperaccumulator *Thlaspi goesingense*. *Plant Soil* 271:205–218
- Quantin C, Becquer T, Rouiller JH, Berthelin J (2002) Redistribution of metals in a New Caledonia ferralsol after microbial weathering. *Soil Sci Soc Am J* 66:1797–1804
- Raaijmakers JM, Vlami M, de Souza JT (2002) Antibiotic production by bacterial biocontrol agents. *Antonie Van Leeuwenhoek* 81:537–547
- Rajkumar M, Freitas H (2008a) Effects of inoculation of plant-growth promoting bacteria on Ni uptake by Indian mustard. *Bioresour Technol* 99:3491–3498
- Rajkumar M, Freitas H (2008b) Influence of metal resistant-plant growth-promoting bacteria on the growth of *Ricinus communis* in soil contaminated with heavy metals. *Chemosphere* 71:834–842
- Rajkumar M, Nagendran R, Lee KJ, Lee WH, Kim SZ (2006) Influence of plant growth promoting bacteria and Cr^{6+} on the growth of Indian mustard. *Chemosphere* 62:741–748
- Rajkumar M, Ma Y, Freitas H (2008) Characterization of metal-resistant plant-growth promoting *Bacillus weihenstephanensis* isolated from serpentine soil in Portugal. *J Basic Microbiol* 48:500–508
- Rajkumar M, Sandhya S, Prasad MNV, Freitas H (2012) Perspectives of plant-associated microbes in heavy metal phytoremediation. *Biotechnol Adv* 30:1562–1574
- Ranjard L, Poly F, Nazaret S (2000) Monitoring complex bacterial communities using culture-independent molecular techniques: application to soil environment. *Microbiology* 151:167–177
- Ranjard L, Echairi A, Nowak V, Lejon DPH, Nouaïm R, Chaussod R (2006) Field and microcosm experiments

- to evaluate the effects of agricultural copper treatment on the density and genetic structure of microbial communities in two different soils. *FEMS Microbiol Ecol* 58:303–315
- Rastogi G, Sani RK (2011) Molecular techniques to assess microbial community structure, function, and dynamics in the environment. In: Ahmad I et al (eds) *Microbes and microbial technology, agricultural and environmental applications*. Springer, New York, pp 29–57
- Renella G, Egamberdiyeva D, Landi L, Mench M, Nannipieri P (2006) Soil microbial activity and hydrolase activity during decomposition of model root exudates released by a model root surface in Cd-contaminated soils. *Soil Biol Biochem* 38:702–708
- Renella G, Zornoza R, Landi L, Mench M, Nannipieri P (2011) Arylesterase activity in trace element contaminated soils. *Eur J Soil Sci* 62:590–597
- Richardson AE, Simpson RJ (2011) Soil microorganisms mediating phosphorus availability update on microbial phosphorus. *Plant Physiol* 156:989–996
- Rue M, Vallance J, Echevarria G, Rey P, Benizri E (2015) Phytoextraction of nickel and rhizosphere microbial communities under mono- or multispecies hyperaccumulator plant cover in a serpentine soil. *Aust J Bot* 63:92–102
- Ryu CM, Farag MA, CH H, Reddy MS, Wei HX, Pare PW, Kloepper JW (2003) Bacterial volatiles promote growth in *Arabidopsis*. *Proc Natl Acad Sci U S A* 100:4927–4932
- Sanger F, Nicklen S, Coulson AR (1977) DNA sequencing with chain-terminating inhibitors. *Proc Natl Acad Sci U S A* 74:5463–5467
- Schalk IJ, Hannauer M, Braud A (2011) Minireview new roles for bacterial siderophores in metal transport and tolerance. *Environ Microbiol* 13:2844–2854
- Schlegel HG, Cosson JP, Baker AJM (1991) Nickel-hyperaccumulating plants provide a niche for nickel-resistant bacteria. *Bot Acta* 104:18–25
- Schmidt W (1999) Mechanisms and regulation of reduction-based iron uptake in plants. *New Phytol* 141:1–26
- Sessitsch A, Kuffner M, Kidd P, Vangronsveld J, Wenzel WW, Fallmann K, Puschenreiter M (2013) The role of plant-associated bacteria in the mobilization and phytoextraction of trace elements in contaminated soils. *Soil Biol Biochem* 60:182–194
- Sheng XF, Xia JJ (2006) Improvement of rape (*Brassica napus*) plant growth and cadmium uptake by cadmium-resistant bacteria. *Chemosphere* 64:1036–1042
- Sheng XF, He L, Wang Q, Ye H, Jiang C (2008a) Effects of inoculation of biosurfactant-producing *Bacillus* sp. J119 on plant growth and cadmium uptake in a cadmium amended soil. *J Hazard Mater* 155:17–22
- Sheng XF, Xia J-J, Jiang C-Y, He L-Y, Qian M (2008b) Characterization of heavy metal resistant endophytic bacteria from rape (*Brassica napus*) roots and their potential in promoting the growth and lead accumulation of rape. *Environ Pollut* 156:1164–1170
- Shilev S, Fernández A, Benlloch M, Sancho E (2006) Sunflower growth and tolerance to arsenic is increased by the rhizospheric bacteria *Pseudomonas fluorescens*. In: Morel JL (ed) *Phytoremediation of metal contaminated soils*. Springer, The Netherlands, pp 315–326
- Smith SE, Read DJ (1996) *Mycorrhizal symbiosis*, 2nd edn. Academic Press, 605 pp
- Sowerby A, Emmett B, Beier C, Tietema A, Penuelas J, Estiarte M, Van Meeteren JMM, Hughes S, Freeman C (2005) Microbial community changes in heathland soil communities along a geographical gradient: interaction with climate change manipulations. *Soil Biol Biochem* 37:1805–1813
- Strasser H, Burgstaller W, Schinner F (1994) High yield production of oxalic acid for metal leaching purposes by *Aspergillus niger*. *FEMS Microbiol Lett* 119:365–370
- Sun LN, Zhang Y-F, He L-Y, Chen Z-J, Wang Q-Y, Qian M, Sheng X-F (2010) Genetic diversity and characterization of heavy metal-resistant-endophytic bacteria from two copper-tolerant plant species on copper mine wasteland. *Bioresour Technol* 101:501–509
- Tabatabai MA (1994) Soil enzymes. In: Weaver RW, Angle S, Bottomley P (eds) *Methods of soil analysis. Part 2, Microbiological and biochemical properties*. Soil Science Society of America, Madison, pp 775–833
- Tate RL (2002) Microbiology and enzymology of carbon and nitrogen cycling. In: Burns RG, Dick RP (eds) *Enzymes in the environment*. Marcel Dekker, New York, pp 227–248
- Thangavelu R, Palaniswami A, Ramakrishnan G, Doraiswamy S, Muthukrishana S, Velazhahan R (2001) Involvement of fusaric acid detoxification by *Pseudomonas fluorescens* strain Pf10 in the biological control of *Fusarium* wilt of banana caused by *Fusarium oxysporum* f. sp. *cubense*. *Z. Pflanzenkr. Pflanzenschutz* 108:433–445
- Thijs S, Sillen W, Rineau F, Weyens N, Vangronsveld J (2016) Towards an enhanced understanding of plant-microbiome interactions to improve phytoremediation: engineering the metaorganism. *Front Microbiol* 7:341
- Turgay OC, Görmez A, Bilen S (2012) Isolation and characterization of metal resistant-tolerant rhizosphere bacteria from the serpentine soils in Turkey. *Environ Monit Assess* 184:515–526
- Turnau K, Mesjasz-Przybyłowicz J (2003) Arbuscular mycorrhiza of *Berkheya coddii* and other Ni-hyperaccumulating members of Asteraceae from ultramafic soils in South Africa. *Mycorrhiza* 13:185–190
- Van der Heijden MGA, Sanders IR (2002) *Mycorrhizal ecology*. Springer, Berlin, Germany
- van Loon LC, Bakker HM, Pieterse CMJ (1998) Systemic resistance induced by rhizosphere bacteria. *Annu Rev Phytopathol* 36:453–383

- Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. *Plant Soil* 255:571–586
- Violante A, Huang PM, Gadd GM (eds) (2008) Biophysicochemical processes of heavy metals and metalloids in soil environments. Wiley, Chichester
- Visioli G, D'Egidio S, Sanangelantoni AM (2015) The bacterial rhizobiome of hyperaccumulators: future perspectives based on omics analysis and advanced microscopy. *Front Plant Sci* 5:1–12
- Vogel-Mikus K, Drobne D, Regvar M (2005) Zn, Cd and Pb accumulation and arbuscular mycorrhizal colonisation of pennycress *Thlaspi praecox* Wulf. (Brassicaceae) from the vicinity of a lead mine and smelter in Slovenia. *Environ Pollut* 133:233–242
- Wang Q, Xiong D, Zhao P, Yu X, Tu B, Wang G (2011) Effect of applying an arsenic-resistant and plant growth-promoting rhizobacterium to enhance soil arsenic phytoremediation by *Populus deltoides* LH05-17. *J Appl Microbiol* 111:1065–1074
- Warembourg FR (1997) The “rhizosphere effect”: a plant strategy for plants to exploit and colonize nutrient-limited habitats. *Bocconea* 7:187–194
- Whiting SN, de Souza MP, Terry N (2001) Rhizosphere bacteria mobilize Zn for hyperaccumulation by *Thlaspi caerulescens*. *Environ Sci Technol* 35:3144–3150
- Wu SC, Cheung KC, Luo YM, Wong MH (2006) Effects of inoculation of plant growth-promoting rhizobacteria on metal uptake by *Brassica juncea*. *Environ Pollut* 140:124–135
- Wyszkowska J, Kucharski J, Borowik A, Boros E (2008) Response of bacteria to soil contamination with heavy metals. *J Elem* 13:443–453
- Wyszkowska J, Kucharski M, Kucharski J, Borowik A (2009) Activity of dehydrogenases, catalase and urease in copper polluted soil. *J Elem* 14:605–617
- Xiong J, He Z, Liu D, Mahmood Q, Yang X (2008) The role of bacteria in the heavy metals removal and growth of *Sedum alfredii* Hance in an aqueous medium. *Chemosphere* 70:489–494
- Yang Q, Tu S, Wang G, Liao X, Yan X (2012) Effectiveness of applying arsenate reducing bacteria to enhance arsenic removal from polluted soils by *Pteris vittata* L. *Int J Phytoremediation* 14:89–99
- Zaidi S, Usmani S, Singh BR, Musarrat J (2006) Significance of *Bacillus subtilis* strain SJ-101 as a bioinoculant for concurrent plant growth promotion and nickel accumulation in *Brassica juncea*. *Chemosphere* 64:991–997
- Zeng F, Ali S, Zhang H, Ouyang Y, Qiu B, Wu F, Zhang G (2011) The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. *Environ Pollut* 159:84–91