# Chapter 16
# Role of Endophytic Microorganisms in Phosphate Solubilization and Phytoremediation of Degraded Soils

**Dipita Ghosh, B. S. Manisha Singh, Manish Kumar, Subodh Kumar Maiti, and Nabin Kumar Dhal**

**Abstract** Phosphorus (P) is considered as the second most important element in plant nutrient profile after nitrogen. It primarily exists incorporated in organic compounds or as mineral salts in soil. Despite these, phosphorus compounds are disbursed abundantly in agricultural soil, and the majority of them are of insoluble form. With the assistance of plant-associated bacteria, the inorganic phosphate solubilization is one of the significant mechanisms for plant growth promotion. The mechanism involves the solubilization of phosphate complexes into more available forms such as orthophosphate ions by organic acid secreted by microbes. The employment of plant growth promoting P bacterial inoculants as biofertilizers can provide favourable alternative to replace chemical fertilizer to some extent. Some examples of phosphate solubilizer are *Bacillus*, *Pseudomonas* and *Aspergillus,* while the phosphate absorber includes arbuscular mycorrhizal fungi (e.g. Glomus). Phytoremediation of heavy metals in association with phosphate-solubilizing bacteria are known to overcome metal stress on plants due to the contaminated substrate. In case of mine-degraded soils, endophyte assisted P-solubilization enhances the bioavailability of insoluble P to plants which in turn enhances the plant growth. Therefore, this chapter covers endophytes assisted

---

D. Ghosh · S. K. Maiti
Ecological Restoration Laboratory, Department of Environmental Science & Engineering,
Indian Institute of Technology (ISM), Dhanbad, Jharkhand, India

B. S. M. Singh
Environment Sustainability Department, CSIR-Institute of Minerals and Materials Technology,
Bhubaneswar, Odisha, India

Academy of Scientific and Innovative Research (AcSIR), CSIR-Human Resource Development
Centre, (CSIR-HRDC) Campus, Ghaziabad, Uttar Pradesh, India

M. Kumar · N. K. Dhal (✉)
Environment Sustainability Department, CSIR-Institute of Minerals and Materials Technology,
Bhubaneswar, Odisha, India
e-mail: nkdhal@immt.res.in

S. Chhabra et al. (eds.), *Plant Microbiome for Plant Productivity and Sustainable Agriculture*, Microorganisms for Sustainability 37,
https://doi.org/10.1007/978-981-19-5029-2_16

sustainable in-situ remediation of contaminated site which stimulates plant growth, defence against metal toxicity and soil fertility.

**Keywords** Biofertilizers · Soil · Heavy metals · Amendment · Phytoremediation · Microbes

## 16.1 Introduction

Mining activity causes complete loss of soil profile, vegetation and the biodiversity of a land. It also causes air and water pollution, disturbs drainage and permanently affects a landform (Ghosh and Maiti 2020; Mohapatra et al. 2020). Mine spoil is characterized by impoverished nutrient content, low organic content and cation exchange capacity and disturbed ambient soil physicochemical and biological properties (Basu et al. 2015; Ahirwal et al. 2021; Ghosh and Maiti 2021a). A degraded mine spoil is devoid of soil organic matter, microbial activity and the enzymatic activities associated with the soil fauna (Maiti 2013; Ghosh and Maiti 2021b). A mine spoil is devoid of essential soil nutrients and often the storehouse of potentially toxic elements (Ahirwal and Maiti 2017; Ghosh and Maiti 2021c). Phosphorous (P) is a crucial component for overall plant development and productivity (Rawat et al. 2021). Its properties constrain its free accessibility and make it a restraining nutrient for vegetation development (Mehta et al. 2017). Thus, an efficient amendment technique is required for mitigation of phosphate deficiency and heavy metal contaminations in mine spoils/tailings and technosol. Some common restoration practices for post-mining coal mine degraded land are forestry, agricultural practices, grass-legume seeding, fly ash amended plantation and biochar aided plantation (Šebelíková et al. 2019; Shukla and Lal 2005; Kumari et al. 2022; Świątek et al. 2019; Fellet et al. 2011; Ghosh et al. 2020).

In a natural soil ecosystem, plants interact with a number of symbiotic microorganisms (Domka et al. 2019). The plant–soil interaction includes synergy of plants with rhizobacteria and endophytic fungi (Maiti 2013; Domka et al. 2019; Varma et al. 2019a, b). Actinomycetes, bacterial and fungal endophytes perforate the plant through root zones along with flower, leaf, stem and cotyledon (Li et al. 2012). The microbiomes are such integral part of plants that they can be used as proxy to study the phenotypic variation of the plant genotype. The knowledge of plant–microbiome interactions can help improving the economic and environmental sustainability of mine spoil restoration through agriculture and forestry. A reduction in inputs, in terms of fertilizer, water, or chemical pesticides, would lead to significant cost savings (Prasad 2017, 2018; Prasad et al. 2021).

Endophytic microbes have the ability to grow throughout the host plant tissues and releases phytochemicals that provide resistance to disease and help in nutrient mineralization for host plant (Maiti 2013). Some endophytic fungi can also solubilize P and supply it to their non-mycorrhizal counterparts, encouraging its growth under nutrient environment (Mehta et al. 2017; Rawat et al. 2021). Thus, they help in improving the overall plant growth under stressed environmental conditions (Maiti 2013). *Curvularia geniculata* isolated from *Parthenium hysterophorus* roots is a dark septate root endophytic fungus which can improve plant growth by promoting P-solubilization and certain phytohormone secretion (Priyadharsini and Muthukumar 2017). Another important role played by endophytes includes resistance to heavy metals and assistance in phytoremediation of a metal contaminated site. Endophyte-assisted phytoremediation technology has been reported to be an efficient technique for in situ remediation of potentially toxic elements contaminated soils (Mastretta et al. 2009; Domka et al. 2019; Guerrero-Zúñiga et al. 2020). During the phytoremediation of polluted sites, heavy-metal contamination enduring endophytes can also improve plant growth, reduce metal phytotoxicity and influence translocation and accumulation of metal. Thus, this chapter focuses on the beneficial role of endophytes for phosphate solubilization and heavy metal remediation. In conclusion, this chapter provides an insight on how endophytes-assisted phytoremediation enhances soil properties.

## 16.2 Role of Endophytes for Mine Spoil Reclamation

### *16.2.1 Phytostimulation and Nutrient Cycling*

Essential nutrients such as C, N, H, O and P are absolutely necessary for plant growth and development. These nutrients are in chemical form through atmosphere, soil, water and organic matter. Endophyte facilitates the uptake of nutrients by the roots of the plants (Nair and Padmavathy 2014). They have been reported to elicit different modes of actions for plant adaptation in P-deficient soil and facilitation of N uptake (Arachevaleta et al. 1989). Certain endophytic bacteria have been reported to produce phytohormones such as cytokinins, auxins and gibberellic acids which are essential plant growth regulators (Xin et al. 2009). Endophytes play vital role in biodegradation of the debris of its host flora (Mehta et al. 2017).

### *16.2.2 Enzyme Production, Antimicrobial Activity and Source of Bioactive*

Soil micro-organisms are the source of a number of commercially important enzymes. This quest for alternative source of enzyme production has led to the discovery of certain endophytes which can produce vital enzymes. Endophytic fungi such as *Aspergillus japonicas*, *Cladosporium sphaerospermum*, *Nigrospora sphaerica*, *Penicillium aurantiogriseum, P. glandicola* and *Xylaria* sp. have been reported to produce enzymes such as pectinases, cellulases, xylanases and proteases (Nair and Padmavathy 2014). *Acremonium zeae*, isolated from maize, has also been reported to produce the enzyme hemicellulase (Bischoff et al. 2009). A number of isolated endophytes from plants have been reported to possess antimicrobial activity (He et al. 2020). Most endophytes show antimicrobial activity; however, the ones obtained from medicinal plants affects a broad spectrum of pathogenic microbes (Nair and Padmavathy 2014).

### *16.2.3 Bioremediation*

Bioaccumulation, bio-stimulation, bio-deterioration, bio-leaching, bio-reduction and bio-sorption are some common bioremediation techniques used for heavy metal contamination. Endophytes possess the ability to breakdown complex compounds. Mastretta et al. (2009) reported that the inoculation of *Nicotiana tabacum* with endophytes resulted in improved plant growth under Cd toxicity and the phytoavailable Cd concentration was high in comparison with the one having no endophytic growth. According to Basu et al. (2015), a number of microorganisms catalyse the reduction of Cr (VI) to Cr (V) or Cr (III) in various environmental conditions. Cr (VI) reduction is shown to be metabolic in some species of bacteria but can also be dissimilatory/respiratory when exposed to anaerobic conditions. Although, most microbes are sensitive to Cr (VI), some microbes are highly resistant and can tolerate Cr (VI) toxicity in the soil. Metal reductase genes found on plasmids and chromosomes impart the resistance to these microbes for growth in Cr (VI) environment (Patra et al. 2017). Some common endophytes that have the potential for Cr remediation include *Acinetobacter*, *Arthrobacter*, *Bacillus* spp., *Cellulomonas* spp., *Escherichia coli*, *Enterobacter cloacae, Pseudomonas* and *Ochrobactrum* (Hossan et al. 2020). A review conducted by Pushkar et al. (2021) reported that major bacterial communities found at chromium contaminated sites are *Gammaproteobacteria*. Other bacteria reported to inhabit chromite contaminated sites includes *Serratia marcescens, Pseudomonas aeruginosa, Alcaligenes faecal* and *Klebsiella oxytoca.*

## 16.3 Role of Endophytes for Phosphate Solubilization

Phosphorus is an essential macronutrient for the proper metabolism, growth and plant development. Phosphorus is abundantly available in both inorganic and organic forms in soil; however, due to the complex formation with metal ions in soil, it is unavailable for plant uptake. Phosphate-solubilizing endophytes have the ability to solubilize the complex phosphates in the soil by various mechanisms. Some commonly used mechanisms used by these microbes include production of enzymes, organic acids and siderophores that have the ability to chelate the heavy metal ions and form complexes, making bioavailable phosphates for vegetation uptake (Rawat et al. 2021). These endophytes also produce certain phytohormones such as auxins, cytokinins and gibberellins which promote plant growth. 1-aminocyclopropane-1-carboxylic acid deaminase produced by endophytes has been reported to improve plant growth under stressful environment which improves its resistance to heavy metal toxicity (Fig. 16.1). A few examples of endophytes, their host plant and the role they play are given in Table 16.1.

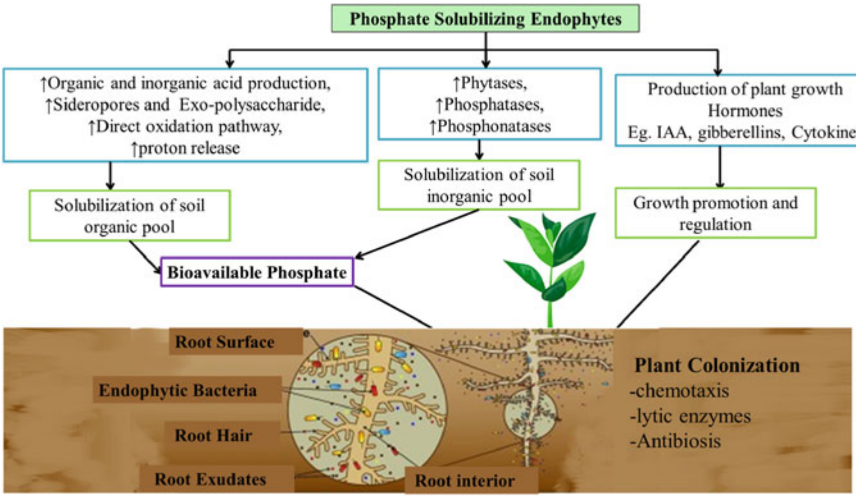

**Fig. 16.1** Mechanism by which endophytes promotes plant growth and phosphate solubilization

## 16.4 Role of Endophytes for Phytoremediation

A number of endophytes have been reported to be heavy metals resistant. Endophyte-assisted phytoremediation is an effective technique for in situ remediation of contaminated soils (Prasad 2022). Microbes develop symbiotic relationships with their plant hosts and promote phytoremediation. Some common hyperaccumulating plants such as *Brassica juncea* (L.) Czern., *Pteris vittata*, *Sedum alfredii* and non-hyper-accumulators, such as *Arabidopsis thaliana, Brassica napus* and *Glycine max* have been reported to house a number of important endophytes (He et al. 2020). During pollutant phytoremediation association of heavy-metal-resistant endophytes can result in enhancement of plant development followed by decrease in metal phytotoxicity and affect translocation of metals in plants. They even produce certain enzymes which help in the degradation of contaminants that reduces the phytotoxicity of the potentially toxic elements. Application of endophytes for phytoremediation and their significance for the host plant growth has been given in Table 16.2.

## 16.5 Case Studies

### *16.5.1 Fungal Root Endophytes in Metal-Polluted Tailings*

Flores-Torres et al. (2021) conducted a research identifying and assessing the plant and fungal root endophytes in bioremediation of polymetallic polluted tailings. The study revealed the significant role of native plants such as *Tagetes lunulata, Cerdia*

**Table 16.1** Phosphate-solubilizing endophytes, their respective host, phosphate-solubilizing ability and their significance

| Endophyte | Host | Isolation of endophytes and colonization | Phosphorous solubilized (μg $mL^{-1}$) | Significance | References |
|---|---|---|---|---|---|
| *Serratia plymuthica* BMA1 | *Vicia faba* L. | • Strain isolated from the extracted rock phosphate (RP) stockpiles (operated by the company of phosphate of Gafsa: CPG Tunisia).<br>• Direct strain inoculation in plant at a cell concentration of approximately $3 \times 10^6$ CFU $g^{-1}$ of soil | 450 | • Phosphorus uptake improved<br>• Improved plant biomass and height | Borgi et al. (2020) |
| *Pseudomonas* sp. | *Triticum aestivum* | – | 101 | • Production of Siderophore<br>• Improved biomass and dry matter | Liu et al. (2019) |
| *Bacillus megaterium* | *Brassica napus* | – | 119 | Phosphorus content and biomass production increased | Zheng et al. (2019) |
| *Staphylococcus sciuri, Bacillus pumilus,* | *Oryza sativa* L. | • From fresh soil (attached to roots of *O. sativa*)<br>• Colonization of PSB in glucose based N-free medium for Azotobacter type free living $N_2$ fixers | 192 | Enhanced phosphorus uptake in shoot, root, grains | Rajapaksha and Senanayake (2011) |
| *Enterobacter asburiae*<br>*Acinetobacter rhizosphaerae* | *Zea mays* L. | • Rhizosphere of *Hippophae rhamnoides*<br>• Charcoal based bacterial inoculants (CFU of approx. $10^7$/g) | 750 | • Plant height and root shoot length increased<br>• Available ca and P content high in soil with endophytes. | Gulati et al. (2010) |
| *Penicillium* spp. | *Triticum aestivum* | • From disinfected wheat roots (3-7 mm root segments) | – | Plant fertility improved | Wakelin et al. (2004) |

| | | | | | |
|---|---|---|---|---|---|
| | | • Cultured in semiselective medium for Penicillium spp. (Dichloran, rose bengal, chloramphenicol agar) | | | |
| *Bacillus* sp. | *Cicer arietinum* | • Pre isolated bacterial strain | 753 | • Improved phytohormones<br>• Dry weight of nodules, root shoot biomass increment | Ditta et al. (2018) |
| *Pseudomonas putida* | *Pisum sativum* | N-fixer isolation from nodules of pea plants<br>Isolated and colonized in yeast extract mannitol medium +2.5% Congo red dye | 319 | • Shoot biomass increased<br>• High seed protein content and increased phosphorus in shoots | Ahmad et al. (2013) |
| *Penicillium oxalicum* | *Triticum aestivum, Zea mays* L. | • Rhizospheric soil from *Jatropha curcas* (rock phosphate landfills of Rajasthan state mines and minerals Ltd)<br>• Fungi isolated in PVK agar +50 mg $P_2O_5$/100 ml medium | 586 | • Shoot height enhanced 1.5 times compared to control<br>• 42% increase in yield of wheat compared to control<br>• 82% increase in root shoot biomass compared to control | Singh and Reddy (2011) |
| *Streptomyces laurentii* | *Sorghum bicolour* L | Aerobic bacteria isolated from rhizospheric soil (Amaranthus, buckwheat, millets and maize soil attached to roots) by serial dilution method in growth medium | 206 | Siderophore production, enzymatic activity potassium solubilization | Kour et al. (2020) |
| *Pantoea vagans, Pseudomonas psychrotolerans, Bacillus subtilis, Bacillus safensis* and *Pantoea agglomerans* | *Festuca arundinacea; Solanum lycopersicum and Capsicum annuum* | • Endophytes isolated from plants grown in the foothills of Appalachian Mountains of USA (37.125372, 79.298415) unfertilized soil.<br>• Sterilized random plants were sectioned in root leaf and | 274–372 | • Promoted *Festuca arundinacea* growth in vitro<br>• Promoted pepper and tomato growth<br>• The extracellular enzymes such as acid phosphatase and phytase secreted by the | Mei et al. (2021) |

(continued)

**Table 16.1** (continued)

| Endophyte | Host | Isolation of endophytes and colonization | Phosphorous solubilized (μg mL$^{-1}$) | Significance | References |
|---|---|---|---|---|---|
| | | stem and they were individually grounded followed by centrifugation then 50 μL aliquot spreader on Luria agar | | bacteria helped in decomposition and nutrient cycling | |
| *Enterobacter* sp. J49 *or Serratia* sp. *S119* | *Zea mays, Glycine max and Arachis hypogaea L.* | Isolated from cultivated peanut plants<br>Two endophytic strains colonization was analysed by isolating bacterial cells from internal tissues of stem, leaves and roots of peanut, soybean and maize plants from the microcosm assay. | – | • Promoted the growth of maize and soybean plants and contributed significantly P to their tissues<br>• Root exudates of the three produced changes in pectinase and cellulase activities<br>• Potential sources for the formulation of biofertilizers | Lucero et al. (2021) |

**Table 16.2** Application of endophytes for phytoremediation and their significance for the host plant growth

| Endophytes | Heavy metals (mg kg$^{-1}$) | Host plant | Isolation of endophytes | Significance | References |
|---|---|---|---|---|---|
| Enterobacter sp. CBSB1 (OGM – gene) | Cd (45.2);<br>Pb (876.7) | *Brassica juncea* | • Strain was isolated from the surface-sterilized *B. juncea* roots | Improved shoot length. A decrease in Cd and Pb concentration was observed in shoot biomass. | Qiu et al. 2014 |
| Bacillus sp. | Cd (5.9),<br>Zn (1236)<br>Pb (153) | *Sedum plumbizincicola* | Isolated from the rhizospheric soil of *S. plumbizincicola* by serial dilution method | Plant biomass and chlorophyll content increased. Increased Cd, Pb and Zn soil bioavailability | Ma et al. 2015 |
| *Pseudomonas azotoformans* | Cd (400)<br>Ni (350)<br>Zn (500) | *Trifolium arvense* | Strain isolated from the leaves of Ni hyperaccumulator plant *Alyssum serpyllifolium* (subsp. malacitanum) | Improved plant biomass and increased [Cd], [Ni] and [Zn] in shoots | Ma et al. 2017 |
| Pseudomonas koreensis AGB-1 | As (827)<br>Cd (103)<br>Cu (396)<br>Pb (2431)<br>Zn (3991) | *Miscanthus sinensis* | Isolated from fine roots of *M. Sinensis* growing in the mine site soil following Sun et al. (2010) | Improved shoot and root biomass, increased chlorophyll, protein content. Decrease in plant stress and increase in [As] and [Cd] in roots | Babu et al. 2015 |

*congestiflora* and *Lupinus campestris* as well as the exotic plant species *Asphodelus fistulosus*, and *Cortaderia selloana* in phytoextraction and/or phytostabilization of Zn, Pb and Cd. Molecular studies of fourteen endophytic fungi isolated from root inner zones of *Pennisetum villosum* and *T. lunulata* showed the prevalence of *Alternaria* and other *Pleosporales*. The dominance of endophytes in several plant root systems indicates the interaction and functioning of mycorrhiza in mine tailings. Exotic invasive plants *A. Fistulosus* and *P. villosum* showed more than 50% root colonization intensity by endophytes, which could ascertain its invasive capacity. The study reported that these endophytes could facilitate the advancement of *Ambrosia artemisiifolia* growing at polluted sites; therefore, mycorrhizal interactions can help in promoting local adaptation and/or reducing environmental stress. Thus, the study indicated that the employment of native endophytic fungi could emphasize the establishment of plants for reclamation of mine waste in semi-arid climate in biologically sustainable manner. Also, high efforts are needed to enhance the vegetation practice of mine wastes under study, which can efficiently reduce, in turn, their potential ecotoxicological impact on organisms, human populations and agricultural areas.

### *16.5.2 Root Colonizing Endophytes for Succession in a Mine Degraded Land*

Kolaříková et al. (2017) studied the fungal community assembly during spontaneous primary succession in Sokolov brown-coal mining in Czech Republic. The fungal communities associated with the roots of *Betula pendula* and *Salix caprea* were studied in a mine spoil chronosequence (12–50 years old sites) site. The study showed that the fungal root endophytes, fungal plant pathogens and ectomycorrhizal fungi changed significantly along the age of reclamation. Ectomycorrhizal fungi and fungal plant pathogens communities have a direct impact on the development of the vegetation cover and the properties of the reclaimed mine spoil. Thus, the study concluded that plant community structure changed along the various stages of succession which was directly impacted by the endophyte and pathogen communities of the soil. The study provided a better understanding of community assembly of root-associated fungi and provided insight of fungal ecology in various stages of succession.

## 16.6 Conclusion

Phytoremediation with endophyte assistance can be a promising technique for the restoration of a degraded and contaminated soil. They are known to improve nutrient uptake, enhance growth, decrease phytotoxicity of heavy metals and effect their assimilation in plants body. These endophytes also solubilize the unavailable phosphorus in soil and restore the deficiency in soil. These endophytes also play a vital role in phytoremediation of heavy metal contaminated sites. Thus, endophytes as a mean to remediate contaminated sites should be explored for eco-friendly and effective remediation of heavy metal contaminated sites. Selection of potent endophytes with multifunctional role is essential for the commercialisation and reduction of coast of restoration of mine-degraded land. Thus, future researches should be done to develop and discover new strains from various ecological niches and for employing in degraded soil restoration.

## References

Ahirwal J, Maiti SK (2017) Assessment of carbon sequestration potential of revegetated coal mine overburden dumps: a chronosequence study from dry tropical climate. J Environ Manag 201: 369–377. https://doi.org/10.1016/j.jenvman.2017.07.003

Ahirwal J, Kumari S, Singh AK, Kumar A, Maiti SK (2021) Changes in soil properties and carbon fluxes following afforestation and agriculture in tropical forest. Ecol Indic 123:107354. https://doi.org/10.1016/j.ecolind.2021.107354

Ahmad E, Khan M, Zaidi A (2013) ACC deaminase producing *Pseudomonas putida* strain PSE3 and *Rhizobium leguminosarum* strain RP2 in synergism improves growth, nodulation and yield of pea grown in alluvial soils. Symbiosis 61(2):93–104. https://doi.org/10.1007/s13199-013-0259-6

Arachevaleta M, Bacon CW, Hoveland CS, Radcliffe DE (1989) Effect of the tall fescue endophyte on plant response to environmental stress. Agron J 81(1):83–90, Dissertation, Univ. of Georgia, Athens. https://doi.org/10.2134/agronj1989.00021962008100010015x

Babu AG, Shea PJ, Sudhakar D et al (2015) Potential use of Pseudomonas koreensis AGB-1 in association with Miscanthus sinensis to remediate heavy metal (loid)-contaminated mining site soil. J Environ Manag 151:160–166. https://doi.org/10.1016/j.jenvman.2014.12.045

Basu A, Panda SS, Dhal NK (2015) Potential microbial diversity in chromium mining areas: *bulletin of environment*. Pharmacol Life Sci 4:158–169

Bischoff KM, Wicklow DT, Jordan DB et al (2009) Extracellular hemicellulolytic enzymes from the maize endophyte *Acremonium zeae*. Curr Microbiol 58(5):499–503. https://doi.org/10.1007/s00284-008-9353-z

Borgi MA, Saidi I, Moula A et al (2020) The attractive *Serratia plymuthica* BMA1 strain with high rock phosphate-solubilizing activity and its effect on the growth and phosphorus uptake by Vicia faba L. plants. Geomicrobiol J 37(5):437–445. https://doi.org/10.1080/01490451.2020.1716892

Ditta A, Imtiaz M, Mehmood S et al (2018) Rock phosphate-enriched organic fertilizer with phosphate-solubilizing microorganisms improves nodulation, growth, and yield of legumes. Commun Soil Sci Plant Anal 49(21):2715–2725. https://doi.org/10.1080/00103624.2018.1538374

Domka AM, Rozpaądek P, Turnau K (2019) Are fungal endophytes merely mycorrhizal copycats? The role of fungal endophytes in the adaptation of plants to metal toxicity. Front Microbiol 10: 371. https://doi.org/10.3389/fmicb.2019.00371

Fellet G, Marchiol L, Delle Vedove G, Peressotti A (2011) Application of biochar on mine tailings: effects and perspectives for land reclamation. Chemosphere 83(9):1262–1267. https://doi.org/10.1016/j.chemosphere.2011.03.053

Flores-Torres G, Solis-Hernández AP, Vela-Correa G et al (2021) Pioneer plant species and fungal root endophytes in metal-polluted tailings deposited near human populations and agricultural areas in Northern Mexico. Environ Sci Pollut Res 28(39):55072–55088. https://doi.org/10.1007/s11356-021-14716-6

Ghosh D, Maiti SK (2020) Can biochar reclaim coal mine spoil? J Environ Manag 272:111097. https://doi.org/10.1016/j.jenvman.2020.111097

Ghosh D, Maiti SK (2021a) Biochar assisted phytoremediation and biomass disposal in heavy metal contaminated mine soils: a review. Int J Phytoremediation 23(6):559–576. https://doi.org/10.1080/15226514.2020.1840510

Ghosh D, Maiti SK (2021b) Eco-restoration of coal mine spoil: biochar application and carbon sequestration for achieving UN sustainable development goals 13 and 15. Land 10(11):1112. https://doi.org/10.3390/land10111112

Ghosh D, Maiti SK (2021c) Effect of invasive weed biochar amendment on soil enzymatic activity and respiration of coal mine spoil: a laboratory experiment study. Biochar 3(4):519–533. https://doi.org/10.1007/s42773-021-00109-y

Ghosh D, Masto RE, Maiti SK (2020) Ameliorative effect of Lantana camara biochar on coal mine spoil and growth of maize (*Zea mays*). Soil Use Manag 36(4):726–739. https://doi.org/10.1111/sum.12626

Guerrero-Zúñiga AL, López-López E, Rodríguez-Tovar AV, Rodríguez-Dorantes A (2020) Functional diversity of plant endophytes and their role in assisted phytoremediation. In: Bioremediation of industrial waste for environmental safety, pp 237–255. https://doi.org/10.1007/978-981-13-3426-9_10

Gulati A, Sharma N, Vyas P et al (2010) Organic acid production and plant growth promotion as a function of phosphate solubilization by *Acinetobacter rhizosphaerae* strain BIHB 723 isolated from the cold deserts of the trans-Himalayas. Arch Microbiol 192(11):975–983. https://doi.org/10.1007/s00203-010-0615-3

He W, Megharaj M, Wu CY et al (2020) Endophyte-assisted phytoremediation: mechanisms and current application strategies for soil mixed pollutants. Crit Rev Biotechnol 40(1):31–45. https://doi.org/10.1080/07388551.2019.1675582

Hossan S, Hossain S, Islam MR et al (2020) Bioremediation of hexavalent chromium by chromium resistant bacteria reduces phytotoxicity. Int J Environ Res Public Health 17(17):6013. https://doi.org/10.3390/ijerph17176013

Kolaříková Z, Kohout P, Krüger C et al (2017) Root-associated fungal communities along a primary succession on a mine spoil: distinct ecological guilds assemble differently. Soil Biol Biochem 113:143–152. https://doi.org/10.1016/j.soilbio.2017.06.004

Kour D, Rana KL, Kaur T et al (2020) Microbe-mediated alleviation of drought stress and acquisition of phosphorus in great millet (*Sorghum bicolour* L.) by drought-adaptive and phosphorus-solubilizing microbes. Biocatal Agric Biotechnol 23:101501. https://doi.org/10.1016/j.bcab.2020.101501

Kumari S, Ahirwal J, Maiti SK (2022) Reclamation of industrial waste dump using grass-legume mixture: an experimental approach to combat land degradation. Ecol Eng 174:106443. https://doi.org/10.1016/j.ecoleng.2021.106443

Li HY, Wei DQ, Shen M, Zhou ZP (2012) Endophytes and their role in phytoremediation. Fungal Divers 54:11–18. https://doi.org/10.1007/s13225-012-0165-x

Liu C, Mou L, Yi J et al (2019) The endogene of *Burkholderia cenocepacia* strain 71-2 is involved in phosphate solubilization. Curr Microbiol 76:495–502. https://doi.org/10.1007/s00284-019-01642-7

Lucero CT, Lorda GS, Anzuay MS et al (2021) Peanut endophytic phosphate solubilizing bacteria increase growth and P content of soybean and maize plants. Curr Microbiol 78(5):1961–1972. https://doi.org/10.1007/s00284-021-02469-x

Ma Y, Oliveira RS, Wu L et al (2015) Inoculation with metal-mobilizing plant-growth-promoting rhizobacterium Bacillus sp. SC2b and its role in rhizoremediation. J Toxic Environ Health A 78(13–14):931–944. https://doi.org/10.1080/15287394.2015.1051205

Ma Y, Rajkumar M, Moreno A et al (2017) Serpentine endophytic bacterium *Pseudomonas azotoformans* ASS1 accelerates phytoremediation of soil metals under drought stress. Chemosphere 185:75–85. https://doi.org/10.1016/j.chemosphere.2017.06.135

Maiti SK (2013) Ecology and ecosystem in mine-degraded land. In: Ecorestoration of the coalmine degraded lands. Springer, India, pp 21–37. https://doi.org/10.1007/978-81-322-0851-8_2

Mastretta C, Taghavi S, Van Der Lelie D et al (2009) Endophytic bacteria from seeds of *Nicotiana tabacum* can reduce cadmium phytotoxicity. Int J Phytoremediation 11(3):251–267. https://doi.org/10.1080/15226510802432678

Mehta P, Sharma R, Putatunada C, Walia A (2017) Endophytic bacteria: role in phosphate solubilization. In: Singh BP (ed) Advances in endophytic fungal research, fungal biology, pp 61–93. https://doi.org/10.1007/978-3-319-66544-3_4

Mei C, Chretien RL, Amaradasa BS et al (2021) Characterization of phosphate solubilizing bacterial endophytes and plant growth promotion in vitro and in greenhouse. Microorganisms 9(9):1935. https://doi.org/10.3390/microorganisms9091935

Mohapatra S, Kumar M, Karim AA, Dhal NK (2020) Biochars evaluation for chromium pollution abatement in chromite mine wastewater and overburden of Sukinda, Odisha, India. Arab J Geosci 13(586). https://doi.org/10.1007/s12517-020-05532-2

Nair DN, Padmavathy S (2014) Impact of endophytic microorganisms on plants, environment and humans. Sci World J 2014:1–11. https://doi.org/10.1155/2014/250693

Patra JM, Panda SS, Dhal NK (2017) Biochar as a low-cost adsorbent for heavy metal removal : a review. Int J Res Biosci 6(1):1–7

Prasad R (2017) Mycoremediation and environmental sustainability, vol 1. Springer International Publishing. ISBN 978-3-319-68957-9. https://link.springer.com/book/10.1007/978-3-319-68957-9

Prasad R (2018) Mycoremediation and environmental sustainability, vol 2. Springer International Publishing. ISBN 978-3-319-77386-5. https://www.springer.com/us/book/9783319773858

Prasad R (2022) Phytoremediation for environmental sustainability. Springer, Singapore. ISBN 978-9811656200. https://doi.org/10.1007/978-981-16-5621-7

Prasad R, Nayak SC, Kharwar RN, Dubey NK (2021) Mycoremediation and environmental sustainability, vol 3. Springer International Publishing. ISBN: 978-3-030-54421-8. https://www.springer.com/gp/book/9783030544218

Priyadharsini P, Muthukumar T (2017) The root endophytic fungus *Curvularia geniculata* from *Parthenium hysterophorus* roots improves plant growth through phosphate solubilization and phytohormone production. Fungal Ecol 27:69–77. https://doi.org/10.1016/j.funeco.2017.02.007

Pushkar B, Sevak P, Parab S, Nilkanth N (2021) Chromium pollution and its bioremediation mechanisms in bacteria: a review. J Environ Manag 287(November 2020):112279. https://doi.org/10.1016/j.jenvman.2021.112279

Qiu Z, Tan H, Zhou S, Cao L (2014) Enhanced phytoremediation of toxic metals by inoculating endophytic Enterobacter sp. CBSB1 expressing bifunctional glutathione synthase. J Hazard Mater 267:17–20. https://doi.org/10.1016/j.jhazmat.2013.12.043

Rajapaksha CP, Senanayake AP (2011) Potential use of rock-phosphate- solubilizing bacteria associated with wild rice as inoculants for improved rice (*Oryza sativa*). Arch Agron Soil Sci 57(7):775–788. https://doi.org/10.1080/03650340.2010.493878

Rawat P, Das S, Shankhdhar D, Shankhdhar SC (2021) Phosphate-solubilizing microorganisms: mechanism and their role in phosphate solubilization and uptake. J Soil Sci Plant Nutr 21(1): 49–68. https://doi.org/10.1007/s42729-020-00342-7

Šebelíková L, Csicsek G, Kirmer A et al (2019) Spontaneous revegetation versus forestry reclamation—vegetation development in coal mining spoil heaps across Central Europe. Land Degrad Dev 30(3):348–356. https://doi.org/10.1002/ldr.3233

Shukla MK, Lal R (2005) Soil organic carbon stock for reclaimed mine- soils in northeastern Ohio. Land Degrad Dev 16(4):377–386. https://doi.org/10.1002/ldr.669

Singh H, Reddy MS (2011) Effect of inoculation with phosphate solubilizing fungus on growth and nutrient uptake of wheat and maize plants fertilized with rock phosphate in alkaline soils. Eur J Soil Ecol 47:30–34. https://doi.org/10.1016/j.ejsobi.2010.10.005

Sun LN, Zhang YF, He LY et al (2010) Genetic diversity and characterization of heavy metal-resistant-endophytic bacteria from two copper-tolerant plant species on copper mine wasteland. Bioresour Technol 101:501e509. https://doi.org/10.1016/j.biortech.2009.08.011

Świątek B, Woś B, Chodak M, Kumar S (2019) Geoderma fine root biomass and the associated C and nutrient pool under the alder (*Alnus* spp.) plantings on reclaimed technosols. Geoderma 337: 1021–1027. https://doi.org/10.1016/j.geoderma.2018.11.025

Varma A, Swati T, Prasad R (2019a) Plant biotic interactions: state of art. Springer International Publishing. ISBN 978-3-030-26657-8. https://www.springer.com/gp/book/9783030266561

Varma A, Swati T, Prasad R (2019b) Plant microbe interface. Springer International Publishing. ISBN 978-3-030-19831-2. https://www.springer.com/gp/book/9783030198305

Wakelin SA, Warren RA, Harvey PR et al (2004) Phosphate solubilization by *Penicillium* spp. closely associated with wheat roots. Biol Fertil Soil 40:36–43. https://doi.org/10.1007/s00374-004-0750-6

Xin G, Zhang G, Kang JW et al (2009) A diazotrophic, indole-3-acetic acid-producing endophyte from wild cottonwood. Biol Fertil Soils 45(6):669–674. https://doi.org/10.1007/s00374-009-0377-8

Zheng BX, Ding K, Yang XR (2019) Straw biochar increases the abundance of inorganic phosphate solubilizing bacterial community for better rape (*Brassica napus*) growth and phosphate uptake. Sci Total Environ 647:1113–1120. https://doi.org/10.1016/j.scitotenv.2018.07.454