Rhizoremediation of Heavy Metal- and Xenobiotic-Contaminated Soil: An Eco-Friendly Approach

Pramila Verma and Seema Rawat

Abstract

In the last few decades, staggeredly increasing human population, indiscriminate use of pesticides, polycyclic aromatic hydrocarbons, and discharge of effluents containing toxic heavy metals, dyes, etc. have negatively impacted the soil fertility and biodiversity to the extent of converting the agricultural land into barren land. These pollutants can be removed or altered by conventional and physical methods. However, these methods are neither cost-effective nor eco-friendly as they generate large amount of toxic intermediates. The most powerful eco-friendly approach is bioremediation. Microorganisms play a pivotal role in the maintenance and sustainability of any ecosystem. They are versatile and capable to adapt to any challenges posed by the environment. The biotic activities of a diverse group of bacterial populations residing in rhizosphere affect the dynamics of soil which in turn affect the crop productivity. They stimulate plant growth by making soil nutrients available to them, stimulating the production of various plant growth hormones, protecting the plants from pathogens by their antagonistic activity and remediation of the pollutants by sequestering toxic heavy metals, and degrading xenobiotic compounds such as pesticides, PAHs, etc. This chapter highlights the role of PGPR in remediation of heavy metal- and xenobiotic-contaminated soil for sustainable crop production.

P. Verma
Department of Botany and Microbiology, H.N.B. Garhwal University, Srinagar, Uttarakhand, India

S. Rawat (✉)
Microbiology Lab, School of Life Sciences, Central University of Gujarat, Gandhinagar, Gujarat, India
e-mail: seema.rawat@cug.ac.in

M. P. Shah (ed.), *Removal of Emerging Contaminants Through Microbial Processes*,
https://doi.org/10.1007/978-981-15-5901-3_5

Keywords

Bioremediation · Pesticides · Polycyclic aromatic hydrocarbons · Rhizosphere · PGPR

1 Introduction

The soil fertility and biodiversity have been adversely affected, in the last few decades, due to continuously increasing human population, indiscriminate use of pesticides, polycyclic aromatic hydrocarbons, and discharge of effluents containing toxic heavy metals, dyes, etc. Industries such as plating, mining, petroleum, paint, automotive, and battery manufacturing industries, printing circuits and chemical manufacturing industries, etc. are the major sources of pollutants in the environment. As per 2009 estimates, approximately 33,900 million liter per day (MLD) urban waste water and 23,500 MLD industrial waste water were produced in India which contaminated the water and soil resources (Saha et al. 2017). According to CEPI (Comprehensive Environmental Pollution Index) rating, 43 critically polluted industrial areas or clusters or zones have been declared in 16 states by CPCB (Central Pollution Control Board) that have more than 70 CEPI rating. Among the 43 zones, 21 sites have been reported in four states, i.e., Gujarat, Uttar Pradesh, Maharashtra, and Tamil Nadu (Saha et al. 2017).

These pollutants have adversely affected human health, plants, and associated soil microorganisms. These toxic compounds accumulate in the agricultural soils in which they are applied, threaten food security, and pose health risks to living organisms by their transfer within the food chain. These pollutants accumulate in different parts of the body such as the muscle, bones, brain, and kidney and cause several harmful diseases like headache, nausea, vomiting, gastrointestinal tract disorders, asthma, allergy, cancer, heart attack, renal failure, nervous disorder, liver toxicity, Alzheimer's diseases, and muscle weakness.

These toxic pollutants can be removed or altered by conventional and physical methods such as membrane separation, chemical precipitation, reverse osmosis, solvent extraction, filtration, flocculation, electrodialysis, electrochemical treatments, ion-exchange, advanced oxidation process, and adsorption by using nanocomposite materials (Saravanan et al. 2019). However, the conventional (physical and chemical) methods are complicated and expensive, require large energy consumption, and generate large amount of toxic intermediates responsible for secondary pollution. Moreover some techniques are not useful in removing the high concentration of contaminants. This has led to search for a cost-effective alternative method. Bioremediation is the most powerful eco-friendly approach. It is the biological process that detoxifies, removes, and immobilizes the hazardous pollutants from the environment by the use of naturally occurring bacteria, fungi, or plants. It is a very useful technique for restoration of contaminated soil. The concept of using plants for the treatment of pollutants has emerged a few years ago. When plants remove, destroy, and stabilize the contaminants from soil, it is referred to as phytoremediation. This is a cost-effective and eco-friendly method, firstly investigated by Chaney (1983). This process removes the pollutants from soil by plants without affecting their biological activity, fertility, and structure of soil. It is also known as green remediation and agro-remediation (Pivetz 2001). The process of phytoremediation includes phytoextraction, phytoaccumulation, phytostabilization, phytostimulation/rhizostimulation, phytovolatilization, and rhizofiltration (Akpor and Muchie 2010).

Though phytoremediation reduces the contamination of many hazardous pollutants, the large-scale field application requires long time period. It suffers serious limitations by pollutant-induced stress which affects seed germination, plant development, and plant biomass. The use of rhizospheric microbes is the alternative way for reducing deleterious effect of pollutants to plants (Burd et al. 2000). The remediation of pollutants by rhizospheric microbes is called rhizoremediation (Kuiper et al. 2004). The rhizospheric bacteria have the extraordinary ability to promote the growth of plant by various mechanisms such as nitrogen fixation, solubilization of minerals, production of plant growth regulators and siderophores, and transformation of nutrient elements. Generally, the plant is not directly involved in the bioremediation process. The rhizobacteria can directly carry out the remediation process. Both endophytic and rhizospheric microbes have the potential to carry out the remediation of pollutants. Thus, among the various methods for the removal of pollutants, rhizoremediation is the most potential eco-friendly approach in which pollutants are removed and degraded by the interaction of microbes and plant roots. Plants provide the essential nutrients to microbes, while microbes convert the toxic compound into nontoxic minerals and make them available for plants. So, microbes enhance the soil health by addition of nutrients. These rhizobacteria play an important role in biological restoration and reclamation of contaminated sites. This process completely destroys pollutants and converts hazardous compounds into harmless products, which also eliminates the possibility of future liability associated with the treatment and disposal of contaminated materials (Abtenh 2017). A consortium of microbes detoxifies the pollutants more efficiently rather than single strain or species. This chapter focuses upon the rhizoremediation of heavy metals and xenobiotics from environment.

2 Phytoremediation

It is a Latin word in which *phyto* means plant and the *remedium* means restoring balance which maintains a permissible concentration of toxic material in the environment. It is a promising and emerging area of interest because it is an environmentally safe method for restoration of barren land. 0.2% of angiosperms tolerate and accumulated high concentration of metals referred as hyperaccumulaters (Baker and Brooks 1989). There are several examples of plants which act as hyperaccumulaters like *Alyssum* species, *Arabidopsis halleri*, *Astragalus racemosus*, *Brassica juncea*, *Noccaea* sp., and *Viola calaminaria* (Ganesan 2012). Plants use various mechanisms to remove pollutants from soil (Table 1, Fig. 1).

Table 1 Mechanisms used for bioremediation of for heavy metals and xenobiotics

Mechanism	Pollutants	Plants	References
Phytovolatization	Hg	*Chara canescens* (musk grass) and *Arabidopsis thaliana*	Ghosh and Singh (2005)
Phytoextraction	Pb As	*Glycine max* L. *Pteris vittata*	Aransiola et al. (2013), Xie et al. (2009)
Phytodegradation/ phytotransformation	Total Petrolium carbon (TPH)	*Scirpus grossus*	Al-Baldawi et al. (2015)
Phytostimulation/ rhizodegradation	Biodiesel Phenanthrene and pyrene	*Pisum sativum* Kandelia candel	Hawrot-Paw et al. (2019) Zhang et al. (2011)
Phytostabilization	As	*Piricum sativum*	Jonnalagadda and Nenzou (1997)
Rhizoremediation	Cr Lindane PHCs	*Helianthus annuus* *Withania somnifera* *Lolium perenne*	Gupta et al. (2018) Abhilash et al. (2011) Kukla et al. (2014)

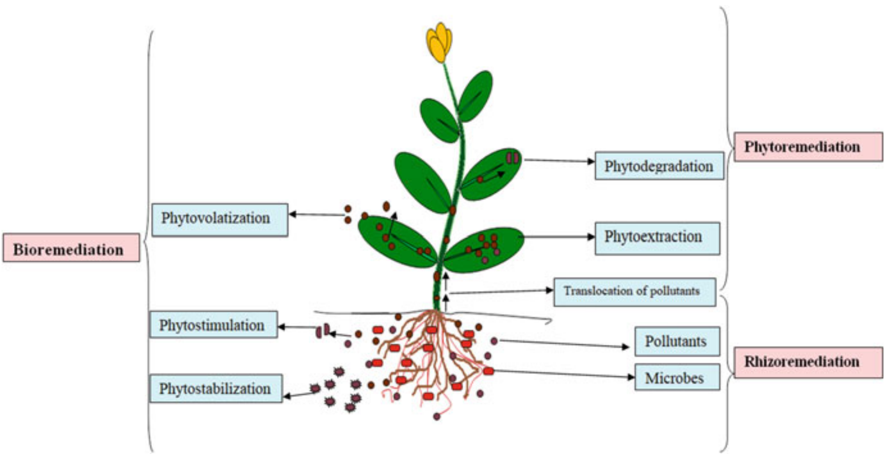

Fig. 1 Bioremediation of pollutants

These are the following. (1) Phytoremediation—It is the uptake of pollutants from soil by root system which are then converted into volatile form and released out in the atmosphere. (2) Phytoextraction—It is the translocation of pollutant by root from soil which gets accumulates in as hyperaccumulaters, and once the pollutant has reached the saturation limit, then plants are cut and disposed of. (3) Phytostabilization—It is the immobilization of pollutant in soil by absorption and precipitation. (4) Phytodegradation—It is the degradation and mineralization of pollutants via the metabolic processes of plants after uptake from the soils.

(5) Phytostimulation—It is the degradation of contaminants by microbial activity. Various types of xenobiotics are degraded by the process of phytoremediation. Although phytoremediation is a promising approach, it has some limitations which include the following: (1) long time period is required for remediation; (2) rate of plant growth and accumulation should be fast for reduction of time period; and (3) efficiency of phytoextraction is dependent upon translocation and bioconcentration; some plants do not allow translocation; and (4) the accumulation of higher concentration of pollutants by plant affects the growth and development of plants. The transgenic plants have been used to improve remediation, but they inhibit the growth of native plants by absorbing excess nutrients from soil.

3 Rhizoremediation

The word, "rhizoremediation" is composed of two words, *rhizo* (a latin word which means roots) and remediation (which means the process of removal of pollutants). It is a natural process and cost-effective and highly efficient method in which pollutants of soil are remediated by rhizospheric bacteria (Kala 2014). Rhizoremediation is a mutual relation between plant roots and soil microbes in the rhizosphere in which plants provide essential nutrients in the form of root exudates to microbes, and in return plants get protection from pathogens and help in nitrogen fixation. The plant roots secrete some substances such as sugars, organic acids, sterols, and amino acids which are utilized by the microbes for degradation of pollutants (Kuiper et al. 2004; Saravanan et al. 2019). These root exudates make a nutrient-rich environment in the rhizosphere where microbial metabolic activity and number are too high. The root exudates play an important role in rhizoremediation because these root exudates attract a specific microbial group. Rhizoremediation is enhanced by expanded root system of plants which provide large surface area for microbes which help in effective uptake and removal of contaminants (Praveen et al. 2019). This process is the combination of bioaugumentation and phytoremediation, which solves the problems that arise during the use of individual methods (Bhatia and Malik 2011). Thus, this process benefits the plants to enhance plant growth by making soil nutrients available to them, stimulating the production of various plant growth hormones, and protecting the plants from pathogens by their antagonistic activity and remediation of the pollutants by sequestering toxic heavy metals and degrading xenobiotic compounds such as pesticides, PAHs, etc. In the process of rhizoremediation, the rhizospheric microbes change the bioavailability of metals by changing the pH of soil, secretion of chelating agents (organic acids, siderophores, etc.), and oxidation/reduction reactions (Rajkumar et al. 2012). Plant growth-promoting rhizobacteria (PGPR) along with mycorrhizal and arbuscular mycorrhizal fungi (AMF) carry out remediation. The fungi spread around the plant roots increase competition for uptake of pollutants and reduce the uptake of pollutants by plants (Praveen et al. 2019). The microbial diversity and activity in the rhizosphere of plants are much more than that in bulk soil. Microbes residing in the rhizosphere of plant are more potent to degrade or transform pollutants than the microbes of bulk soil (Kamaludeen and Ramasamy 2008). The microbes of rhizosphere form a mutual association with root which has potential for detoxification of hazardous pollutants (De Souza et al. 1999).

Thus, there are many advantages of rhizoremediation like it is a cost-effective and eco-friendly approach, no need to add any chemical for degradation, and negligible side effects while chemical degradation adversely affect the environment. The efficient microbial strain and consortium has to be provided, and no investment is required (Saravanan et al. 2019). In addition to phytoremediation, rhizoremediation can be a better alternative for the removal of pollutants such as heavy metals, pesticides, polycyclic aromatic hydrocarbons (PAHs), etc.

3.1 Heavy Metals

Metals are the natural components of soil. Some of them are essential and required for various metabolic activities. Zn, Fe, Mg, Mn, Cu, Cr, Ni, Na, and Ca are essential micronutrients. Fe^{3+} is essential for all bacteria, while Fe^{2+} is required for only anaerobic bacteria and other metals such as Cd, Hg, Au, and Ag are nonessential and very toxic to soil microbes and other organisms. Heavy metals occur in soil as free cations in the form of complex with organic/inorganic ligands and soil colloids. Now pollution of heavy metals has become a severe problem for the environment. The increasing anthropogenic activities like industrial waste disposal, waste incineration, vehicle exhausts, energy and fuel production, mining and smelting of metals, long-term application of urban sewage *sludge*, and excessive use of agrochemicals and pesticides, etc. are the major source of heavy metal contamination which poses serious threat to soil ecosystem and human health (Khan 2005).

According to the report of Central Pollution Control Board (CPCB), in India, the states of Gujarat, Maharashtra, and Andhra Pradesh have 80% contribution in the generation of toxic pollutants including heavy metals. The report of Ministry of Mines, Government of India (2018), suggested that India is the major source of different types of metallic and nonmetallic minerals. Maximum numbers of mines are present in Tamil Nadu and Madhya Pradesh (Kumar et al. 2019). High concentration of heavy metal in soil are absorbed and accumulated by plant which ultimately reaches into the human body (Mishra et al. 2017) via food chain. The nonbiodegradable nature of these toxic heavy metals results in their persistence for long period in the environment. Even a very low concentration of these metals enters into the human body via contaminated food and contaminated drinking water and gets accumulated in animals and plants which can have lethal effects.

Various physical and chemical methods such as excavation and stabilization or solidification are used for removal of heavy metals, but these technologies have some demerits like less cost-effective, generation of hazardous products, difficult to operate, and cannot remove heavy metals permanently (Akshata et al. 2014). The remediation of heavy metals by phytoremediation takes a long time period while the addition of suitable microbes increases the rate of remediation. Microbes reduce the toxicity of metals by converting the metals from toxic to nontoxic form, by stabilizing the metal in rhizosphere so that pollutants cannot be used by plants and enhance the degradation of metals by increasing bioavailability.

The rhizosphere region of plants which is growing in heavy metal-contaminated soil harbors a large population of microbes (Idris et al. 2004) which are able to tolerate high concentration of metals. They convert toxic metals into bioavailable form in soil by mechanisms like precipitation, chelation, acidification, redox reactions, and complexation (Ma et al. 2016). These microbes have developed various resistance mechanisms for survival in the presence of heavy metal-contaminated soil such as bioabsorption, bioaccumulation, bioleaching, biotransformation, biomineralization, and plant-microbe interaction. Besides this PGPRs also act as biofertilizer which enhance the yield of crops by efficient way of heavy metals remediation in soil (Ganesan 2012).

Madhaiyan et al. (2007) reported that *Methylobacterium oryzae* strain CBMB20 and *Burkholderia* sp. strain CBMB40 reduce the toxicity of nickel (Ni) and cadmium (Cd) in tomato by reducing uptake and translocation of heavy metals to shoot in plant and also promote the plant growth in contaminated soil. Fatnassi et al. (2015) reported that at high concentration of copper (Cu), the growth of plant *Vicia faba* (fava bean) was inhibited, but when plant was inoculated with *Rhizobium* and *Pseudomonas*, the inhibitory effect was decreased. Wu et al. (2006) observed that *Azotobacter chroococcum* HKN-5 promoted the growth of *Brassica juncea* by phytoextraction from the soil which was highly contaminated by lead (Pb). Dary et al. (2010) reported that the consortium of *Bradyrhizobium* sp.750, *Ochrobactrum cytisi*, and *Pseudomonas* sp. protected and promoted the growth of *Lupinus luteus* in multi-metal-contaminated soil Cu, Cd, and Pb by the process of phytostabilization and also helped in the reclamation of soil. The rhizobacteria *Pseudomonas aeruginosa* and *Burkholderia gladioli* were reported to facilitate the plant growth of *Lycopersicon esculentum* seedlings by reducing the accumulation of Cd metal due to immobilization of metal on the root that prevented the translocation of metal towards shoot and reduce the toxicity of Cd by decreasing bioavailability (Khanna et al. 2019). Wani et al. (2008) reported that *Bacillus* sp. PSB10 improved the growth, nodulation, chlorophyll seed yield, etc. of chickpea grown in chromium-contaminated soil by reducing the uptake and toxicity of contaminant from soil. Another study was performed by Gupta et al. (2018) on sunflower (*Helianthus annuus* L.) in which inoculation of strain *Pseudomonas* sp. CPSB21 reduced the $Cr6+$ toxicity and enhanced the plant growth and nutrient uptake. Some examples of microbes involved in rhizoremediation of heavy metals are listed in Table 2.

3.2 Pesticides

Pesticides are organic chemical which were introduced in agriculture for increasing agricultural yield and soil productivity, to protect agricultural products from crop pests, and to control insect vectors for prevention of outbreaks of human and animal epidemics. Pesticides are used for many purposes such as livestock farming,

Table 2 Remediation of heavy metals by rhizobacteria

Plant	Pollutant	Microbes	References
Brassica juncea	Pb	*Azotobacter chroococcum* HKN-5	Wu et al. (2006)
Glycine max	Mn	*Glomus etunicatum* or *G. macrocarpum*	Nogueira et al. (2007)
Pteris vittata	As	*Pseudomonas*	Huang et al. (2007)
Zea mays	Pb, Zn, cu	*Brevibacterium haloterans*	Abou-Shanab et al. (2008)
Brassica juncea	Ni	*Pseudomonas* sp., *Bacillus megaterium*	Rajkumar and Freitas (2008)
Brassica juncea	Cu	*Achromobacter xylosoxidans* strain Ax10	Ma et al. (2009)
Cicer arietinum	Cr	*Bacillus* sp. PSB10	Wani and Khan (2010)
Helianthus annuus, *Ricinus communis*	Ni	*Psychrobacter* sp. SRS8	Ma et al. (2010)
Lupinus luteus	Cu, cd, Pb	*Bradyrhizobium* sp.750, *Pseudomonas* sp., and *Ochrobactrum cytisi*	Dary et al. (2010)
Orychophragmus violaceus	Zn	*Bacillus subtilis*, *Bacillus cereus*, *Flavobacterium* sp., *Pseudomonas aeruginosa*	He et al. (2010)
Crotalaria juncea	Cd	*Achromobacter* sp. AO22	Stanbrough et al. (2013)
Oryza sativa	Ni	*Bacillus licheniformis* NCCP-59	Jamil et al. (2014)
Triticum aestivum (wheat)	Zn	*Pseudomonas fluorescens*	Sirohi et al. (2015)
Vicia faba	Cu	*Rhizobium*, Enterobacter *cloacae*, and *Pseudomonas* sp.	Fatnassi et al. (2015)
Brassica nigra	Cu	*Kocuria* sp. *CRB15*	Hansda et al. (2017)
Leucaena leucocephala	Zn, cd	Rhizobia	Rangel et al. (2017)
Suaeda nudiflora	Zn, Pb	*Bacillus megaterium*, *Pseudomonas aeruginosa*	Jha et al. (2017)
Helianthus annuus	Cr	*Pseudomonas* sp. CPSB21	Gupta et al. (2018)

cropping, horticulture, forestry, home gardening, homes, hospitals, kitchens, roadsides, and industrial areas. Pesticides are a cost-effective method to control pest and increase agriculture productivity. But now the use of pesticides has become a serious threat as they cause many adverse effects upon environment and the human health. Residues of pesticides remain in the environment (air, soil, groundwater, and surface water) for long periods. Pesticides pollute the rivers, ponds, and lakes and also cause acid rain, which is hazardous to animals and especially amphibians

(Gilden et al. 2010). Every year around two million tonnes of pesticides are consumed worldwide, of which 24% is consumed by the United States, 45% in Europe, and the remaining 25% in the world (Abhilash and Singh 2009). Thus, three quarters of the total pesticide used worldwide (USEPA 2009) are consumed by the developed countries such as North America, Western Europe, and Japan (Yadav et al. 2015). In India, the use of pesticides started from 1948 where dichloro diphenyl trichloroethane (DDT) was used for the control of malaria and benzene hexachloride (BHC) for locusts. Now, India accounts for 3% of the world consumption of pesticide. After China, India is the second largest pesticide manufacturing country in Asia. The most common pesticides used in India are organophosphates, organochlorine, neonicotinoids, etc. The pesticides which are mostly used in India include monocrotophos, endosulfan, phorate, chlorpyrifos, methyl parathion, quinalphos, mancozeb, paraquat, butachlor, isoproturon, and phosphamidon (Bhushan et al. 2013). Ideally, according to definition a pesticide should be lethal only for targeted pests, but unfortunately, it has become lethal for nontargeted species including humans also. The persistent nature of pesticides is making the agriculture land barren.

Phytoremediation is a cost-effective technology that removes organic and inorganic contaminants used in polluted areas. But it is not an efficient technology without the contribution of rhizobacteria. Plant microbial interaction is very useful in remediation of contaminants. Romeh and Hendawi (2014) reported the degradation of organophosphorus insecticides, chlorpyrifos, chlorpyrifos-methyl, cyanophos, and malathion degraded by some phosphate-solubilizing bacteria like *Azospirillum lipoferum* and *Paenibacillus polymyxa* on mineral salt media as a carbon and phosphorus source. Various pesticides like acibenzolar-*S*-methyl, metribuzin, napropamide, propamocarb hydrochloride, and thiamethoxam have been reported to be degraded by *Bacillus subtilis* GB03, *Bacillus subtilis* FZB24, *Bacillus amyloliquefaciens* IN937a, and *Bacillus pumilus* SE34 in liquid culture and soil microcosm (Myresiotis et al. 2012). Some examples of microbes involved in rhizoremediation of pesticides are listed in Table 3.

The bacterial strain *Achromobacter xylosoxidans JCp4 and Ochrobactrum sp. FCp1* was found to increase crop productivity by degrading chlorpyrifos from soil and promote the plant growth of *Vigna unguiculata* (Akbar and Sultan 2016). *Fulekar (2014) studied the effect of consortium Stenotrophomonas maltophilia* MHF ENV20, *Stenotrophomonas maltophilia* MHF ENV22, and *Sphingobacterium thalpophilum* MHF ENV23 on plant growth of *Pennisetum pedicellatum* and *Cenchrus setigerus*. The consortium was found to degrade pesticides chlorpyrifos, cypermethrin, and fenvalerate in soil. Jacobsen (1997) suggested that colonization of the plant roots by the herbicide-degrading *Burkholderia cepacia* DBO1 (pRO101) can protect the plant *Hordeum vulgare* by degradation of the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) in the rhizosphere soil. Abhilash et al. (2011) reported that the integrated use of pesticide-tolerant plant *Withania somnifera* and rhizospheric microbe *Staphylococcus cohnii* decreases the concentration of lindane from soil and has practical application for in situ remediation of contaminated soils.

Table 3 Remediation of pesticides by rhizobacteria

Plant	Pollutant	Microbes	References
Zinnia angustifolia	Mefenoxam	*Pseudomonas fluorescens* and *Chryseobacterium indologenes*	Pai et al. (2001)
Greengram (*Vigna radiata*)	Fipronil and pyriproxyfen	*Pseudomonas aeruginosa* PS1	Ahemad and Khan (2011)
Withania somnifera	Lindane	*Staphylococcus cohnii*	Abhilash et al. (2011)
Grapevines (*Vitis vinifera*)	Profenofos	*Bacillus subtilis*	Salunkhe et al. (2013)
Cauliflower (*Brassica oleracea*)	Cypermethrin	*Serratia nematodiphila*	Tyagi and Prashar (2015)
Maize (*Zea mays*)	Thiamethoxam	*Bacillus subtilis* GB03) and *B. subtilis* FZB24	Myresiotis et al. (2015)
Vigna unguiculata	Chlorpyrifos	*Achromobacter xylosoxidans* JCp4, *Ochrobactrum* sp. FCp1	Akbar and Sultan (2016)

3.3 Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous environmental pollutants generated from both natural and anthropogenic processes and pose a serious concern to the health of aquatic life and humans. They are released naturally in the environment due to incomplete combustion of organic material. Due their toxic, carcinogenic, and mutagenic effects on human health, 16 PAHs have been identified as priority pollutants by USEPA (United States Environmental Protection Agency) and monitored regularly in industrial wastes (Bisht et al. 2015; Gupte et al. 2016). Out of 16, seven priority pollutants are considered as probable human carcinogens by USEPA and IARC (International Agency for Research on Cancer) (Wang et al. 2018). There are various types of chemical methods used for removal of PAHs; however as mentioned earlier, due to their various demerits, phytoremediation and rhizoremediation are the most preferred method. Bisht et al. (2010, 2014) reported the rhizoremediation of PAHs by rhizospheric and endophytic bacteria in *Populus* sp. Some examples of microbes involved in PAH rhizoremediation are listed in Table 4.

Golubev et al. (2009) reported that *Sinorhizobium meliloti* was quite effective in degradation of PAHs besides its ability to produce surfactant and indole acetic acid (IAA). Kukla et al. (2014) reported that *Rhodococcus fascians* strain (L11) was able to degrade petroleum hydrocarbon and promoted the growth of ryegrass (*Lolium perenne* L.). Khan et al. (2014) reported that inoculation of *Pseudomonas putida* PD 1 to willow plant and ryegrass protected the plant from toxic effect by degrading phenanthrene and promoted plant growth. *Burkholderia fungorum* DBT1 along with hybrid poplar plant was reported to degrade PAHs from contaminated soil by the process of phytoextraction or rhizodegradation (Andreolli et al. 2013).

Table 4 Remediation of PAHs by rhizobacteria

Plant	Pollutant	Microbes	References
Grasses (*Lolium multiflorum*)	Napthalene	*Pseudomonas putida* PCL1444	Kuiper et al. (2001)
Festuca arundinacea	PAHs	*Pseudomonas fluorescens*	Ho et al. (2007)
Zea mays	Phenanthrene	*Pseudomonas putida* MUB1	Chouychai et al. (2009)
Populus deltoides	Naphthalene and anthracene	*Kurthia* sp. SBA4, *Micrococcus varians* SBA8, *Bacillus circulans* SBA12	Bisht et al. (2010)
Populus deltoides	PAHs	*Bacillus* sp. SBER3	Bisht et al. (2014)
Oryza sativa	Phenanthrene	*Phomopsis liquidambaris*	Fu et al. (2020)

3.4 Factors Affecting Rhizoremediation

The physicochemical properties of soil play an important role in successful rhizoremediation. The microbial activity as well as diffusion of the chemicals in the soil is affected by moisture, redox conditions, temperature, pH, organic matter, nutrients and nature, and amount of clay. The effect of soil moisture on microbial mineralization of three aerobically degradable pesticides (benzolin-ethyl, isoproturon, and glyphosate) was quantified by Schroll et al. (2006). They observed a linear correlation ($p < 0.0001$). The increasing soil moisture (within a soil water potential range of -20 and $-$ 0.015 MPa) was found to increase the mineralization of pesticides.

3.4.1 Soil pH

pH of soil is an important factor that control the microbial growth and activity. Most of the microbes have optimum pH at 6.5–7.5. At particular pH, microbes secrete enzymes and organic acids that enhance the removal of pollutants. The catalytic activity of enzymes is dependent upon pH. The degradation process takes more time at acidic pH rather than alkaline and neutral pH. Singh et al. (2006) reported the biodegradation of organophosphate pesticide was found to be slow at low pH soil as compared to neutral and high pH soils.

3.4.2 Temperature

The removal and degradation rate of pollutants are affected by soil as the metabolic activity of microbes depends on temperature. Bioavailability of pollutants is increased with increasing temperature of soil. However the native microbes of low temperature soil like Arctic and Antarctic soils will degrade pollutants at low temperature. *Rhodococcus* isolated from an Antarctic soil was found to degrade various alkanes at -2 °C, while its activity was inhibited at high temperature (Oberai and Khanna 2018).

3.4.3 Soil Organic Matter

The soil organic matter is a rich source of nutrients which enhance microbial growth and thus affect the degradation of pollutants. The soil organic matters control the adsorption and desorption process. Sewage sludge which is a source of organic matter increases the biodegradation of isoproturon herbicide (Perrin-Ganier et al. 2001).

3.4.4 Plant Root Exudates

Rhizoremediation is mainly dependent on the quality of root exudates. The age of plants and presence of pollutants affect the quality and nature of root exudates which determine the microflora of the rhizosphere. It is a mixture of soluble organic compounds including sugars, amino acids, organic acids, and enzymes that influence the colonization of specific microbial community which promote the plant growth and protect the plant from soil pollutants, and microbes use root exudates for their growth and development.

3.4.5 Microbial Population

The composition of microbial community of rhizosphere can affect the rate and efficiency of rhizoremediation. There are many microbes like *Azotobacter*, *Bacillus* sp., *Pseudomonas* sp., etc. which are active colonizers of rhizosphere and have been reported to be efficient degraders of pollutants.

3.4.6 Pollutants

The nature of pollutants in soil can affect the composition of microbial population. The hydrophobic pollutants are degraded in aqueous medium such as the biodegradation of phenanthrene (Bouchez et al. 1995). The type and concentration of pollutants affect the process of rhizoremediation.

3.5 Methods to Improve Rhizoremediation

There are several limiting factors such as pH, temperature, organic matter, pollutant type, soil properties, source of energy, and microbes which slow the process of rhizoremediation. This process also depends on the capacity of plants to tolerate the maximum limit of pollutants which can be accumulated in the plants without any adverse effects to them. The efficiency of rhizoremediation can be enhanced by several techniques.

3.5.1 Biostimulation

It is a remediation method that refers to the addition of rate-limiting nutrients such as phosphorous, nitrogen, oxygen, carbon, and electron donors in the polluted soils to stimulate existing bacteria for degradation of pollutants (Tribedi et al. 2018). The activity of rhizobacteria is enhanced by the addition of fertilizers or minerals (N, P, and K) and compost in soil as they improve the root exudates. Biosurfactants improve the physicochemical property of soil and increase the bioavailability of pollutants in soil. The use of additive such as biochar, cattle manure, and fly ash enhances the soil fertility. Biochar is known as a universal sorbent due to its strong ability to bind pollutants and has long been used as a sorbent for both organic and inorganic pollutants (Ahmad et al. 2014). Biochar increases soil fertility moisture content and nutrient retention and remediate heavy metals from soil by surface adsorption, precipitation, partitioning, and sequestration (Tang et al. 2013; Saravanan et al. 2019). Recently, biochar has been implemented to enhance phytoremediation efficiency by improving plant growth, water holding capacity, and soil structure. Qin et al. (2013) observed the total petroleum hydrocarbon (TPH) removal after applying biochar as a soil amendment.

3.5.2 Bioaugumentation

Bioaugumentation is the addition of bacterial culture to increase the rate of degradation of pollutants. The native microbes of contaminated sites are able to detoxify the contaminants. The process of rhizoremediation is also enhanced by introducing specific pollutant-degrading microbes or consortium in the soil by various methods such as seed coating, root dipping, and soil drenching. The ability of microbe to remove contaminants is limited because the catabolic pathway for some pollutants like polychlorinated biphenyls (PCBs) has not evolved in microbes. To combat this problem, genetically modified microbes are used to increase efficiency of rhizoremediation by modification of a gene (Lorito et al. 1998). The genes of siderophore receptor introduced into *Pseudomonas* sp. made it more useful in rhizosphere region (Praveen et al. 2019). The selection of suitable plant-microbe combination for efficient rhizoremediation is also quite important (Kuiper et al. 2004).

3.5.3 Transgenic Plants

For efficient rhizoremediation, transgenic plants are now used. Transgenic plants have increased ability to uptake, transport, and degrade pollutants. The plant is improved by either gene transfer or breeding. Janssen et al. (2015) have improved *Salix* sp. (Willow tree) into *S. viminalis* and *S. alba* by metal extraction. Both species have improved ability to accumulate Cd and Zn. Plants are genetically modified to improve stabilization and accumulation of the pollutants. Doty et al. (2000) reported enhanced degradation of the halogenated hydrocarbons by the introduction of cytochrome P450 2E1 gene into plants.

3.5.4 Rhizoengineering

The use of transgenic plants increases the root exudates that improve the rhizoremediation, but they are not effective for soil which is contaminated by multiple contaminants. Wu et al. (2006) utilized the advantages of plant-microbe symbiosis within the plant rhizosphere for effective cleanup technology. They demonstrated the expression of a metal-binding peptide (EC20) in *Pseudomonas putida* 06909 that not only improved cadmium binding but also decreased the cellular toxicity of cadmium and also improved the plant growth. Thus rhizoengineering becomes very important to reclaim the soil.

3.5.5 Nanotechnology

Nanotechnology is characterized by the use of very small manufactured particles (<100 nm) called as nanoparticles. The use of nanoparticles for the removal of pollutants for environment cleanup is an emerging technique that has gained attention recently. Bacteria have the ability to mobilize and immobilize the metals, and they can reduce the metals by precipitation. The removal of environmental pollutants such as heavy metals, organic and inorganic, from polluted sites by using nanoparticles/nanomaterial produced by plants, fungi, and bacteria is called nanobioremediation which has been reported to enhance the efficiency of phytoremediation or rhizoremediation (Yadav et al. 2017). Recently some studies have reported the degradation of organic contaminants such as atrazine, molinate, and chlorpyrifos by nanosized zerovalent ions (Zhang 2003; Ghormade et al. 2011). Liu and Zhao (2007) used iron phosphate (vivianite) nanoparticles for in situ immobilization of Pb^{+2} in soils and reported the reduction of bioavailability and mobility of Pb^{+2} from soil effectively. Some organic pollutants like hydrocarbons and organochlorines cannot be degraded by plant as well as microbes, but the combined use of nanotechnology and biotechnology solved this problem (Yadav et al. 2017).

4 Conclusions

The rhizoremediation is a cost-effective and eco-friendly approach that is the emerging technique for remediation of pollutants. It is the mutual interaction of microbes and plant roots that enhances the degradation of contaminants. The versatility and adaptability of microbes to any challenges posed by the environment make them perfect for remediation of environmental pollutants. In rhizoremediation the degradation of pollutant is higher than that of phytoremediation in plant and microbe alone. So rhizoremediation is the best research topic for understanding the interaction of soil-root-microbe for bioremediation of pollutants. Plants and microbes can be genetically modified for improvement of degradation ability. Thus, rhizoremediation can be an environment-friendly cleaning technique.

References

Abhilash PC, Singh N (2009) Pesticide use and application: an Indian scenario. J Hazard Mater 165 (1–3):1–12

Abhilash PC, Srivastava S, Srivastava P, Singh B, Jafri A, Singh N (2011) Influence of rhizospheric microbial inoculation and tolerant plant species on the rhizoremediation of lindane. Environ Exp Bot 74:127–130

Abou-Shanab RA, Ghanem K, Ghanem N, Al-Kolaibe A (2008) The role of bacteria on heavy-metal extraction and uptake by plants growing on multi-metal-contaminated soils. World J Microbiol Biotechnol 24(2):253–262

Abtenh EG (2017) Application of microorganisms in bioremediation-review. J Environ Microbiol 1 (1):2–9

Ahemad M, Khan MS (2011) Pseudomonas aeruginosa strain PS1 enhances growth parameters of greengram [Vignaradiata (L.) Wilczek] in insecticide-stressed soils. J Pest Sci 84(1):123–131

Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, Ok YS (2014) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19–33

Akbar S, Sultan S (2016) Soil bacteria showing a potential of chlorpyrifos degradation and plant growth enhancement. Braz J Microbiol 47(3):563–570

Akpor OB, Muchie M (2010) Remediation of heavy metals in drinking water and wastewater treatment systems: processes and applications. Int J Phys Sci 5(12):1807–1817

Akshata JN, Udayashankara TH, Lokesh K (2014) Review on bioremediation of heavy metals with microbial isolates and amendments on soil residue. Int J Sci Res 3:118–123

Al-Baldawi IA, Abdullah SRS, Anuar N, Suja F, Mushrifah I (2015) Phytodegradation of total petroleum hydrocarbon (TPH) in diesel-contaminated water using *Scirpus grossus*. Ecol Eng 74:463–473

Andreolli M, Lampis S, Poli M, Gullner G, Biro B, Vallini G (2013) Endophytic *Burkholderia fungorum* DBT1 can improve phytoremediation efficiency of polycyclic aromatic hydrocarbons. Chemosphere 92(6):688–694

Aransiola SA, UJJ I, Abioye OP (2013) Phytoremediation of lead polluted soil by *Glycine max* L. Appl Environ Soil Sci 2013:1–7

Baker AJM, Brooks RR (1989) Terrestrial higher plants which hyperaccumulate metallic elements-a review of their distribution, ecology and phytochemistry. Biorecovery 1:81–126

Bhatia D, Malik DK (2011) Plant-microbe interaction with enhanced bioremediation. Res J Biotechnol 6(4):72–79

Bhushan C, Bhardwaj A, Misra SS (2013) State of pesticide regulations in India. Centre for Science and Environment, New Delhi

Bisht S, Pandey P, Sood A, Sharma S, Bisht NS (2010) Biodegradation of naphthalene and anthracene by chemo-tactically active rhizobacteria of *Populus deltoides*. Braz J Microbiol 41 (4):922–930

Bisht S, Pandey P, Kaur G, Aggarwal H, Sood A, Sharma S, Bisht NS (2014) Utilization of endophytic strain Bacillus sp. SBER3 for biodegradation of polyaromatic hydrocarbons (PAH) in soil model system. Eur J Soil Biol 60:67–76

Bisht S, Pandey P, Bhargava B, Sharma S, Kumar V, Sharma KD (2015) Bioremediation of polyaromatic hydrocarbons (PAHs) using rhizosphere technology. Braz J Microbiol 46(1):7–21

Bouchez M, Blanchet D, Vandecasteele JP (1995) Substrate availability in phenanthrene biodegradation: transfer mechanism and influence on metabolism. Appl Microbiol Biotechnol 43 (5):952–960

Burd GI, Dixon DG, Glick BR (2000) Plant growth-promoting bacteria that decrease heavy metal toxicity in plants. Can J Microbiol 46(3):237–245

Chaney RL (1983) Plant uptake of inorganic waste constituents. In: Parr JF, Marsh PB, Kla JM (eds) Land treatment of hazardous wastes. Noyes Data Corporation, Park Ridge, pp 50–76

Chouychai W, Thongkukiatkul A, Upatham S, Lee H, Pokethitiyook P, Kruatrachue M (2009) Plant-enhanced phenanthrene and pyrene biodegradation in acidic soil. J Environ Biol 30 (1):139–144

Dary M, Chamber-Pérez MA, Palomares AJ, Pajuelo E (2010) "In situ" phytostabilisation of heavy metal polluted soils using *Lupinus luteus* inoculated with metal resistant plant-growth promoting rhizobacteria. J Hazard Mater 177(1–3):323–330

De Souza MP, Huang CPA, Chee N, Terry N (1999) Rhizosphere bacteria enhance the accumulation of selenium and mercury in wetland plants. Planta 209(2):259–263

Doty SL, Shang TQ, Wilson AM, Tangen J, Westergreen AD, Newman LA, Gordon MP (2000) Enhanced metabolism of halogenated hydrocarbons in transgenic plants containing mammalian cytochrome P450 2E1. Proc Natl Acad Sci 97(12):6287–6291

Fatnassi IC, Chiboub M, Saadani O, Jebara M, Jebara SH (2015) Impact of dual inoculation with rhizobium and PGPR on growth and antioxidant status of *Vicia faba* L. under copper stress. C R Biol 338(4):241–254

Fu WQ, Xu M, Sun K, Chen XL, Dai CC, Jia Y (2020) Remediation mechanism of endophytic fungus *Phomopsis liquidambaris* on phenanthrene *in vivo*. Chemosphere 243:125305

Fulekar MH (2014) Rhizosphere bioremediation of pesticides by microbial consortium and potential microorganism. Int J Curr Microbiol Appl Sci 3(7):235–248

Ganesan V (2012) Rhizoremediation: a pragmatic approach for remediation of heavy metal-contaminated soil. In: Toxicity of heavy metals to legumes and bioremediation. Springer, Vienna, pp 147–161

Ghormade V, Deshpande MV, Paknikar KM (2011) Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnol Adv 29(6):792–803

Ghosh M, Singh SP (2005) A review on phytoremediation of heavy metals and utilization of it's by products. Asian J Energy Environ 6(4):18

Gilden R, Huffling K, Sattler B (2010) Pesticide and health risks. Obstet Gynecol Neonatal Nurs 39:103–110

Golubev SN, Schelud'ko AV, Muratova AY, Makarov OE, Turkovskaya OV (2009) Assessing the potential of rhizobacteria to survive under phenanthrene pollution. Water Air Soil Pollut 198 (1–4):5–16

Gupta P, Rani R, Chandra A, Kumar V (2018) Potential applications of *Pseudomonas* sp. (strain CPSB21) to ameliorate Cr^{6+} stress and phytoremediation of tannery effluent contaminated agricultural soils. Sci Rep 8(1):1–10

Gupte A, Tripathi A, Patel H, Rudakiya D, Gupte S (2016) Bioremediation of polycyclic aromatic hydrocarbon (PAHs): a perspective. Open Biotechnol J 10(1):363

Hansda A, Kumar V, Anshumali (2017) Cu-resistant *Kocuria* sp. CRB15: A potential PGPR isolated from the dry tailing of Rakha copper mine. 3 Biotech 7(2):132

Hawrot-Paw M, Ratomski P, Mikiciuk M, Staniewski J, Koniuszy A, Ptak P, Golimowski W (2019) Pea cultivar Blauwschokker for the phytostimulation of biodiesel degradation in agricultural soil. Environ Sci Pollut Res 26(33):34594–34602

He CQ, Tan GE, Liang X, Du W, Chen YL, Zhi GY, Zhu Y (2010) Effect of Zn-tolerant bacterial strains on growth and Zn accumulation in Orychophragmus violaceus. Appl Soil Ecol 44(1):1–5

Ho CH, Applegate B, Banks MK (2007) Impact of microbial/plant interactions on the transformation of polycyclic aromatic hydrocarbons in rhizosphere of *Festuca arundinacea*. Int J Phytoremediation 9(2):107–114

Huang A, Teplitski M, Rathinasabapathi B, Ma L (2007) Characterization of arsenic-resistant bacteria from the rhizosphere of arsenic hyperaccumulator. Can J Microbiol 56(3):236–246

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(5):2667–2677

Jacobsen CS (1997) Plant protection and rhizosphere colonization of barley by seed inoculated herbicide degrading *Burkholderia* (*Pseudomonas*) *cepacia* DBO1 (pRO101) in 2, 4-D contaminated soil. Plant Soil 189(1):139–144

Jamil M, Zeb S, Anees M, Roohi A, Ahmed I, Rehman S, Rha ES (2014) Role of *Bacillus licheniformis* in phytoremediation of nickel contaminated soil cultivated with rice. Int J Phytoremediation 16(6):554–571

Janssen J, Weyens N, Croes S, Beckers B, Meiresonne L, Van Peteghem P, 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(11):1123–1136

Jha Y, Subrmanian RB, Mishra KK (2017) Role of plant growth promoting rhizobacteria in accumulation of heavy metal in metal contaminated soil. Emergent Life Sci Res 3:48–56

Jonnalagadda SB, Nenzou G (1997) Studies on arsenic rich mine dumps. II The heavy element uptake by vegetation. J Environ Sci Health Part A 32(2):455–464

Kala S (2014) Rhizoremediation: a promising rhizosphere technology. IOSR J Environ Sci Toxicol Food Technol 8:23–27

Kamaludeen SPB, Ramasamy K (2008) Rhizoremediation of metals: harnessing microbial communities. Indian J Microbiol 48(1):80–88

Khan AG (2005) Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. J Trace Elem Med Biol 18:355–364

Khan Z, Roman D, Kintz T, de las Alas M, Yap R, Doty S (2014) Degradation, phytoprotection and phytoremediation of phenanthrene by endophyte Pseudomonas putida, PD1. Environ Sci Technol 48(20):12221–12228

Khanna K, Jamwal VL, Gandhi SG, Ohri P, Bhardwaj R (2019) Metal resistant PGPR lowered cd uptake and expression of metal transporter genes with improved growth and photosynthetic pigments in Lycopersicon esculentum under metal toxicity. Sci Rep 9(1):1–14

Kuiper I, Bloemberg GV, Lugtenberg BJ (2001) Selection of a plant-bacterium pair as a novel tool for rhizostimulation of polycyclic aromatic hydrocarbon-degrading bacteria. Mol Plant-Microbe Interact 14(10):1197–1205

Kuiper I, Lagendijk Ellen L, Bloemberg Guido V, Lugtenberg Ben JJ (2004) Rhizoremediation: a beneficial plant-microbe interaction. Mol Plant Microbe Interact 17:6–15

Kukla M, Płociniczak T, Piotrowska-Seget Z (2014) Diversity of endophytic bacteria in Lolium perenne and their potential to degrade petroleum hydrocarbons and promote plant growth. Chemosphere 117:40–46

Kumar V, Sharma A, Kaur P, Sidhu GPS, Bali AS, Bhardwaj R, Thukral AK, Cerda A (2019) Pollution assessment of heavy metals in soils of India and ecological risk assessment: a state-of-the-art. Chemosphere 216:449–462

Liu R, Zhao D (2007) Reducing leachability and bioaccessibility of lead in soils using a new class of stabilized iron phosphate nanoparticles. Water Res 41(12):2491–2502

Lorito M, Woo SL, Fernandez IG, Colucci G, Harman GE, Pintor-Toro JA, Filippone E, Muccifora S, Lawrence CB, Zoina A, Tuzun S, Scala F (1998) Genes from mycoparasitic fungi as a source for improving plant resistance to fungal pathogens. Proc Natl Acad Sci 95(14):7860–7865

Ma Y, Rajkumar M, Freitas H (2009) Improvement of plant growth and nickel uptake by nickel resistant-plant-growth promoting bacteria. J Hazard Mater 166(2–3):1154–1161

Ma Y, Rajkumar M, Vicente JAF, Freitas H (2010) Inoculation of Ni-resistant plant growth promoting bacterium Psychrobacter sp. strain SRS8 for the improvement of nickel phytoextraction by energy crops. Int J Phytoremediation 13(2):126–139

Ma Y, Oliveira RS, Freitas H, Zhang C (2016) Biochemical and molecular mechanisms of plant-microbe-metal interactions: relevance for phytoremediation. Front Plant Sci 7:918

Madhaiyan M, Poonguzhali S, Sa T (2007) Metal tolerating methylotrophic bacteria reduces nickel and cadmium toxicity and promotes plant growth of tomato (*Lycopersicon esculentum* L.). Chemosphere 69(2):220–228

Mishra J, Singh R, Arora NK (2017) Alleviation of heavy metal stress in plants and remediation of soil by rhizosphere microorganisms. Front Microbiol 8:1706

Myresiotis CK, Vryzas Z, Papadopoulou-Mourkidou E (2012) Biodegradation of soil-applied pesticides by selected strains of plant growth-promoting rhizobacteria (PGPR) and their effects on bacterial growth. Biodegradation 23(2):297–310

Myresiotis CK, Vryzas Z, Papadopoulou-Mourkidou E (2015) Effect of specific plant-growth-promoting rhizobacteria (PGPR) on growth and uptake of neonicotinoid insecticide thiamethoxam in corn (Zea mays L.) seedlings. Pest Manag Sci 71(9):1258–1266

Nogueira MA, Nehls U, Hampp R, Poralla K, Cardoso EJBN (2007) Mycorrhiza and soil bacteria influence extractable iron and manganese in soil and uptake by soybean. Plant Soil 298 (1–2):273–284

Oberai M, Khanna V (2018) Rhizoremediation–plant microbe interactions in the removal of pollutants. Int J Curr Microbiol App Sci 7(1):2280–2287

Pai SG, Riley MB, Camper ND (2001) Microbial degradation of mefenoxam in rhizosphere of Zinnia angustifolia. Chemosphere 44(4):577–582

Perrin-Ganier C, Schiavon F, Morel JL, Schiavon M (2001) Effect of sludge-amendment or nutrient addition on the biodegradation of the herbicide isoproturon in soil. Chemosphere 44(4):887–892

Pivetz BE (2001) Phytoremediation of contaminated soil and ground water at hazardous waste sites. US Environmental Protection Agency, Office of Research and Development, Office of Solid Waste and Emergency Response, Washington, DC

Praveen A, Pandey VC, Marwa N, Singh DP (2019) Rhizoremediation of polluted sites: harnessing plant–microbe interactions. In: Phytomanagement of polluted sites. Elsevier, Amsterdam, pp 389–407

Qin G, Gong D, Fan MY (2013) Bioremediation of petroleum-contaminated soil by biostimulation amended with biochar. Int Biodeterior Biodegradation 85:150–155

Rajkumar M, Freitas H (2008) Effects of inoculation of plant-growth promoting bacteria on Ni uptake by Indian mustard. Bioresour Technol 99(9):3491–3498

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

Rangel WM, Thijs S, Janssen J, Oliveira Longatti SM, Bonaldi DS, Ribeiro PRA, Jambon I, Eevers N, Weyens N, Vangronsveld J, Moreira FMS (2017) Native rhizobia from Zn mining soil promote the growth of *Leucaena leucocephala* on contaminated soil. Int J Phytorem 19(2):142–156

Romeh AA, Hendawi MY (2014) Bioremediation of certain organophosphorus pesticides by two biofertilizers, *Paenibacillus* (*Bacillus*) *polymyxa* (Prazmowski) and *Azospirillum lipoferum* (Beijerinck). J Agric Sci Technol 16(2):265–276

Saha JK, Selladurai R, Coumar MV, Dotaniya ML, Kundu S, Patra AK (2017) Status of soil pollution in India. In: Soil pollution-an emerging threat to agriculture. Springer, Singapore, pp 271–315

Salunkhe VP, Sawant IS, Banerjee K, Rajguru YR, Wadkar PN, Oulkar DP, Sawant SD (2013) Biodegradation of profenofos by Bacillus subtilis isolated from grapevines (*Vitis vinifera*). J Agric Food Chem 61(30):7195–7202

Saravanan A, Jeevanantham S, Narayanan VA, Kumar PS, Yaashikaa PR, Muthu CM (2019) Rhizoremediation–a promising tool for the removal of soil contaminants: a review. J Environ Chem Eng 8:103543

Schroll R, Becher HH, Dörfler U, Gayler S, Grundmann S, Hartmann HP, Ruoss J (2006) Quantifying the effect of soil moisture on the aerobic microbial mineralization of selected pesticides in different soils. Environ Sci Technol 40(10):3305–3312

Singh BK, Walker A, Wright DJ (2006) Bioremedial potential of fenamiphos and chlorpyrifos degrading isolates: influence of different environmental conditions. Soil Biol Biochem 38 (9):2682–2693

Sirohi G, Upadhyay A, Srivastava PS, Srivastava S (2015) PGPR mediated zinc biofertilization of soil and its impact on growth and productivity of wheat. J Soil Sci Plant Nutr 15(1):202–216

Stanbrough R, Chuaboonmee S, Palombo EA, Malherbe F, Bhave M (2013) Heavy metal phytoremediation potential of a heavy metal resistant soil bacterial isolate, Achromobacter sp. strain AO22. Apcbee Proc 5:502–507

Tang J, Zhu W, Kookana R, Katayama A (2013) Characteristics of biochar and its application in remediation of contaminated soil. J Biosci Bioeng 116(6):653–659

Tribedi P, Goswami M, Chakraborty P, Mukherjee K, Mitra G, Bhattacharyya P, Dey S (2018) Bioaugmentation and biostimulation: a potential strategy for environmental remediation. J Microbiol Exp 6:223–231

Tyagi H, Prashar P (2015) Isolation and identification of cypermethrin degrading Serratia nematodiphila from cauliflower rhizosphere. Int J Pharm Tech Res 7:64–71

USEPA (2009) The value of country working together to regulate pesticides and food safety—achieving public health and environmental protection through international collaboration. http://www.epa.gov/oppfead1/international/2009/workingtogether.pdf. Accessed 29 July 2014

Wang D, Ma J, Li H, Zhang X (2018) Concentration and potential ecological risk of PAHs in different layers of soil in the petroleum-contaminated areas of the loess plateau, China. Int J Environ Res Public Health 15(8):1785

Wani PA, Khan MS, Zaidi A (2008) Chromium-reducing and plant growth-promoting Mesorhizobium improves chickpea growth in chromium-amended soil. Biotechnol Lett 30 (1):159–163

Wani PA, Khan MS (2010) *Bacillus* species enhance growth parameters of chickpea (*Cicer arietinum* L.) in chromium stressed soils. Food Chem Toxicol 48(11):3262–3267

Wu CH, Wood TK, Mulchandani A, Chen W (2006) Engineering plant-microbe symbiosis for rhizoremediation of heavy metals. Appl Environ Microbiol 72(2):1129–1134

Xie QE, Yan XL, Liao XY, Li X (2009) The arsenic hyperaccumulator fern Pteris vittata L. Environ Sci Technol 43(22):8488–8495

Yadav IC, Devi NL, Syed JH, Cheng Z, Li J, Zhang G, Jones KC (2015) Current status of persistent organic pesticides residues in air, water, and soil, and their possible effect on neighboring countries: a comprehensive review of India. Sci Total Environ 511:123–137

Yadav KK, Singh JK, Gupta N, Kumar V (2017) A review of nanobioremediation technologies for environmental cleanup: a novel biological approach. J Mater Environ Sci 8(2):740–757

Zhang WX (2003) Nanoscale iron particles for environmental remediation: an overview. J Nanopart Res 5(3–4):323–332

Zhang Y, He L, Chen Z, Wang Q, Qian M, Sheng X (2011) Characterization of ACC deaminase-producing endophytic bacteria isolated from copper-tolerant plants and their potential in promoting the growth and copper accumulation of *Brassica napus*. Chemosphere 83(1):57–62