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Synergism of plant microbe interactions for remediation of potentially toxic elements

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Abstract: Industrialization and urbanization are important for economic development which makes the human life easy by providing different job opportunities, increasing the production level of cheaper goods and standard of living. Despite its many positive effects, industrialization has had a negative impact on the natural ecosystem through environmental pollution. It is responsible for a greater input of potentially toxic and non-toxic substances into essential environmental components such as air, soil and water. Continuous industrialization has resulted in significant environmental problems due to the release of pollutants and extremely difficult treatment of contaminated areas. This review focuses on the recent literature dealing with the role of Plant Growth Promoting Microbes (PGPMs), i.e. bacteria and Arbuscular mycorrhizal Fungi (AMF) in the remediation of polluted sites.

Keywords: detoxification; hyperaccumulator plants; plant growth promoting rhizobacteria; mycorrhiza; risk elements; synergistic interactions

Industrialization over the last century has led to an elevated release of anthropogenic chemicals into the environment. Heavy metals, pesticides, hydrocarbons, chlorinated solvents and salts are the most common hazardous contaminants in soil, air and water. Heavy metals are the elements in the periodic table with high densities, atomic weights and atomic numbers but this definition does not cover all elements, so potentially toxic elements (PTE) or risk rlements (RE) are the most appropriate terms (Pourret, Hursthouse 2019). The impact of PTE generated by industries is a global concern. The amount of PTE accumulated in soil depends on industrial discharge, transportation from the source to the disposal site, and the retention of these elements (Alloway 2008). Among these PTE or RE the most common are As (arsenic), Zn (zinc), Mn (manganese), Cr (chromium), Cu (copper), Cd (cadmium), Pb (lead), and Hg (mercury) (Emamverdian et al. 2015). PTE such as Hg, Cd, As and Pb are toxic even at very low concentrations of 0.001–0.1 $mg \cdot L^{-1}$ and have no known beneficial role in living organisms (Alkorta et al. 2004). Excess PTE are altering the functionality and sustainabil-

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ity of an ecosystem by inhibiting a variety of physiological and biochemical processes of plants and the soil microbes, which leads to reduced crop yield (Friedlova 2010). After being consumed in contaminated food, these PTE accumulate in the bodies of living organisms, posing a health risk (Singh et al. 2011). These PTE are responsible for the formation of reactive oxygen species (ROS), i.e. oxygen radicals (superoxide and hydroxyl), hydrogen peroxide (H_2O_2) and breakage of the DNA molecule that causes deterioration of antioxidant systems (glutathione, superoxide dismutase, etc.) which protect cells (Chibuike, Obiora 2014). Cd is a common PTE that accumulates in important agricultural crops, impairing homeostasis and nutrient absorption by reducing the root and shoot growth (di Toppi, Gabbrielli 1999).

PTE are non-biodegradable, difficult to remediate, and can persist in soil for long periods of time, resulting in severe soil pollution (Kabata-Pendias 1993). Soil pollution caused by these elements from industrial waste and automobile exhaust is a serious environmental issue, so it is necessary to develop methods for remediation. Excavation, landfill, thermal treatment, leaching, and electro-reclamation are some of the engineering methods used (Tangahu et al. 2011). But all these methods are prohibitively expensive and frequently have a negative impact on the diversity of soil microbial communities (Ma et al. 1993). Biological methods of the cleanup of pollutants from environment are a more effective and expedient solution in comparison with physicochemical technologies which are too costly and harmful for nature. Biological processes like phytoremediation, rhizoremediation, bioremediation are more applicable or acceptable methods to remediate PTE or RE from soil. In addition to these direct remediation techniques, biofortification is an indirect method that also helps in metal uptake.

PHYTOREMEDIATION

The term phytoremediation is an amalgam of the Greek word "*phyto*" meaning "plant" and the Latin word "*remedium*" meaning "restoring balance". In phytoremediation, plants are used for the cost-effective, eco-friendly rehabilitation of soil and groundwater contaminated by toxic elements and organic compounds. Plants play an ecologically important role to remove or stabilize soil pollution in industrially polluted land. The process of phytoremediation relies on hyperaccumulator plants (Visoottiviseth et al. 2002). These are the plants that belong to different families but they have the ability to grow in metalliferous soil and accumulate a high amount of risk elements without suffering phytotoxic effects (Rascio, Navari-Izzo 2011). *Brassicaceae*, *Euphorbiaceae*, *Asteraceae*, *Fabaceae*, *Lamiaceae*, and *Scrophulariaceae* are some of the important families to which these plants belong (Ghosh, Singh 2005). Indian mustard (*Brassica juncea* L.), willow (*Salix* sp.), poplar tree (*Populus* sp.), Indian grass (*Sorghastrum nutans*), sunflower (*Helianthus annuus* L.) are some of the important plants which has a good capacity to extract, sequester or detoxify the PTE from contaminated soils. Different types of phytoremediation strategies are used for the remediation of PTE contaminated soil and water: (*i*) phytostabilization, (*ii*) phytoextraction, (*iii*) phytofiltration, (*iv*) phytovolatilization

Phytostabilization. It is a strategy to prevent PTE dispersion and reduce their outflow into groundwater by using metal-tolerant plant species to prevent their migration into the ecosystem (Marques et al. 2009; Mench et al. 2010). As plant roots play an important role to immobilize RE and prevent soil erosion by stabilizing the soil structure, plants should have dense rooting systems, and be able to produce a large amount of biomass (Berti, Cunningham 2000). In spite of the selection of suitable plant species (*Atriplex halimus, Brassica juncea, Ricinus communis, Populus deltoides*), some organic or inorganic changes to the contaminated soil can also improve the phytostabilization by increasing PTE solubility and bioavailability. These bioavailable PTE are readily absorbed from the root surface and become fixed inside the root cells, thereby reducing off-site contamination. Furthermore, rhizospheric microorganisms such as bacteria and mycorrhiza improve phytostabilization by producing chelators such as siderophores and increasing the root surface and depth to enhance immobilization of PTE (Gohre, Paszkowski 2006; Ma et al. 2011).

Phytoextraction. It is an important phytoremediation technique which uses hyperaccumulator plants for translocation and accumulation of RE in their aboveground parts through a hyperaccumulation mechanism (Jutsz, Gnida 2015; Jacob et al. 2018). Like in phytostabilization, selection of plant species is important for effectual phytoextraction. The plant species should be highly

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tolerant to the toxicity of RE, fast-growing, highly resistant to pathogens, pests and repulsive to herbivores to avoid the flow of RE in the ecosystem (Seth 2012; Ali et al. 2013). Plant species which have all these characteristics are known as hyperaccumulators (van der Ent et al. 2013). *Helianthus annuus, Cannabis sativa, Nicotiana tobacum* and *Zea mays* are some biomass high-producing crops (Vangronsveld et al. 2009; Herzig et al. 2014) and grasses like *Trifolium alexandrinum* (Ali et al. 2012) have been reported for the removal of RE from contaminated soil because these plant species are highly tolerable to abiotic stress, and they have a short life span with high growth rate (Malik et al. 2010). Phytoextraction is one of the most preferred methods used by plants for remediation of polluted environments as it is enhanced by PGPMs associated with the plant roots.

Phytofiltration. It is a phytoremediation strategy which removes contaminants from polluted surface water by the use of either roots, shoots or seedlings (Mesjasz-Przybyłowicz et al. 2004). In rhizofiltration, plant roots either absorb the RE or minimize the movement to underground water by changing the pH of rhizosphere, which leads to the precipitation of RE on plant roots (Javed et al. 2019). Plants with dense root systems are grown hydroponically, they are acclimatised with polluted water and then transferred to the contaminated site for

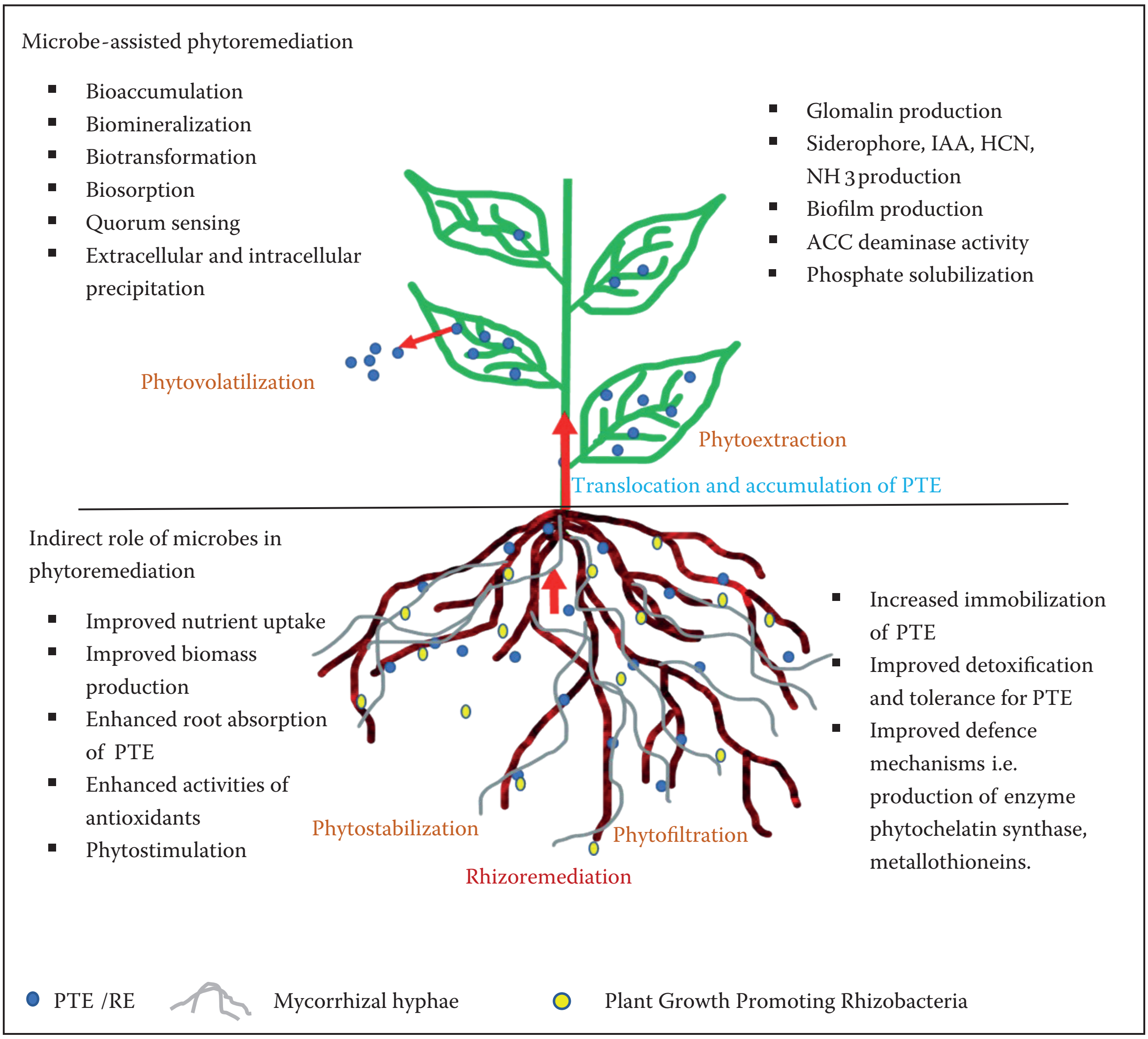

Figure 1. Summary of various mechanisms for PTE/RE mitigation in microbe-assisted phytoremediation

PTE – potentially toxic elements; RE – risk elements; IAA – indole-3-acetic acid; ACC – 1-aminocyclopropane-1-carboxylate

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removal of PTE or RE (Wuana, Okieimen 2011). Both terrestrial (Indian mustard and sunflower) and aquatic (hyacinth, azolla, duckweed) plants can be used for rhizofiltration. But terrestrial plants have highly developed or advanced (longer and hairy) root systems compared with aquatic plants for the accumulation of PTE in high concentration (Tome et al. 2008; Dhanwal et al. 2017).

Phytovolatilization. It is the process of removal of soil contaminants by plants which convert highly toxic elements into less toxic volatile forms and release them into the atmosphere by the process of transpiration (Rahman et al. 2016). This strategy is useful in detoxification of some PTE like Se, Hg and As (Mahar et al. 2016). Tobacco plants have the ability to transform the highly toxic methyl mercury form to the less toxic volatile form of Hg (Rayu et al. 2012) and Indian mustard is a good volatilizer of Se (Banuelos et al. 1993). However, it is a useful strategy of phytoremediation but it does not completely remove the pollutants. It is simply a transfer of pollutants from soil to atmosphere that contaminates the air, then again they enter into the soil in the form of precipitation (Vangronsveld et al. 2009).

Phytoremediation is the best alternative method for the removal of pollutants from soil that does not affect soil biological activity, structure and fertility (Raskin et al. 1997). But sometimes high concentrations of contaminants tend to inhibit plant growth, including root growth due to oxidative stress which limits the rate of phytoremediation in *in situ* conditions (Huang et al. 2005). Although it is a time-consuming process due to the slow growth of plants and climate change, the interaction between plant roots and naturally occurring rhizospheric microorganisms increases the growth and bioremediation potential of plants (Wenzel 2009). Rhizospheric microorganisms play an important role in the management of contaminants by accumulating, transforming, or detoxifying PTE (Figure 1).

BIOFORTIFICATION

It is a method of increasing the absorption and accumulation of mineral nutrients (Fe, I, Cu, Zn, Mn, Co, Cr, Se, Mo, Ni, Si, and V) in various agricultural crops (Yin et al. 2012). Although these metals are essential plant micronutrients and are beneficial for plant growth and development, high contents and continuing presence of some PTE in soil are usually considered a matter of concern to society as they may adversely affect the quality of soil and water, and compromise sustainable food production (Kabata-Pendias, Mukherjee 2007). Iodine (I) biofortification of *Brassica napus* L. and *Amaranthus retroflexus* L. (Ligowe et al. 2021), PGPR (Plant Growth Promoting Rhizobacteria) assisted Zn biofortification (Hussain et al. 2018; Upadhayay et al. 2022), Se and Fe biofortification of wheat (Yasin et al. 2015) are some of the recent studies showing the importance of biofortification in reducing health risks due to deficiencies of important micronutrients. The primary goal of biofortification is to combat the nutritional deficiencies of a growing population by producing nutrient-rich crops, but in addition, it also helps in remediation of PTE (Sharma, Yeh 2020). Xie et al. (2022) studied the effect of biofortification on soil Cd remediation using *Sedum alfredii* under crop rotation and relay cropping mode. The increased concentration of PTE, i.e. Cd, Pb, As, Hg that do not even act as micronutrients in agricultural soils, is an increasing and serious challenge, hence, this concept of indirect remediation requires further study (Sohail et al. 2022).

Bioremediation: Use of PGPMs. Bioremediation refers to the use of microorganisms to remove contaminants such as PTE, dyes, xenobiotics, and hydrocarbons. The basic principle of bioremediation involves reducing the solubility of environmental contaminants by changing pH, redox reactions and adsorption of contaminants from polluted environment (Jain, Arnepalli 2019). Bioremediation depends on the nature of the microorganisms utilized, environmental factors at the contaminated site, degree of pollution (Azubuike et al. 2016) and metabolic potential of the microorganisms (Jan et al. 2014). Bioremediation is of two types, *in situ* or *ex situ*. *In situ* bioremediation is an onsite clean-up process which involves addition of nutrients (biostimulation), introduction of new microorganisms for degradation of contaminants (bioventing) and improvement in indigenous microorganisms by genetic engineering (Rayu et al. 2012). In *ex situ* bioremediation, contaminated media are taken to different location based on the cost of treatment, contamination, types of pollutant, geographical locality and geology of site (Azubuike et al. 2016). The use of indigenous microorganisms which are capable of degrading PTE and genetically engineered microorganisms is a cost effective way to treat polluted environment by removing toxic elements (Gupta et al. 2016). Microorganisms present in the

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rhizosphere of plants enhance the plant growth and development directly or indirectly through different mechanisms, i.e. biochemical (PTE detoxification, mobilization, immobilization, transformation, transport, and distribution) and molecular (PTE resistance genes and proteins) (Ianeva 2009; Ma et al. 2016). Archaea, bacteria, and fungi are major bioremediators in rhizospheric soil that degrade or transform pollutants into less toxic forms to facilitate plant growth (Strong, Burgess 2008). These microorganisms improve the plant phytoremediation ability directly or indirectly through synergism (Figure 1). Rhizospheric bacteria play an important role in the management of soil fertility by accumulating, transforming or detoxifying PTE. Bioaccumulation, biomineralization, biotransformation and biosorption are different mechanisms used by rhizospheric bacteria in bioremediation of PTE (Ali et al. 2017; Niamat et al. 2019; Haider et al. 2021). This review mainly focuses on the synergistic approach of plant-associated microorganisms, such as PGPR and mycorrhizae, their interactions in the phytobiome, and their mechanisms for mitigating PTE stress.

PGPR mediated bioremediation. Microorganisms present in the rhizospheric soil help in growth promotion by facilitating the uptake of nutrients, by secreting phytohormones (auxins and cytokinins), by inhibiting ethylene accumulation via the expression of aminocyclopropane deaminase activity (Glick 2014). Plants help in establishing a symbiotic association with these rhizobacteria to diminish the abiotic stress by secreting a number of root exudates which act as attractants for these microbes (Bharti et al. 2016; Olanrewaju et al. 2017; Ramakrishna et al. 2020). As the name indicates, PGPR assist plants in their growth by nitrogen fixation, phosphorus and potassium solubilization, siderophore production or stress-relieving enzyme production (Olanrewaju et al. 2017). *Rhizobium* species (symbiotic) and *Azospirillum, Pseudomonas, Azotobacter, Acetobacter* (non-symbiotic) are some widely reported nitrogen-fixing PGPR (Bhattacharyya, Jha 2012; Umar et al. 2020). Similarly, *Bacillus, Pseudomonas, Enterobacter, Microbacterium, Serratia, Burkholderia,* and *Beijerinckia* are some most significant phosphate-solubilizing bacteria (PSB) (Kalayu 2019) and *Bacillus mucilaginosus, B. edaphicus,* and *B. circulans* are effective potassium solubilizers (Saiyad et al. 2015). With significant effects on plant growth promotion, PGPR also have various abilities to detoxify and degrade toxins which make them more common for bioremediation (Ali et al. 2020; Haider et al. 2021).

PGPR sequester PTE by cell wall components or intracellular metal binding proteins, e.g. metallothioneins (MT) and phytochelatins, alter biochemical pathways to block metal uptake and also reduce the intracellular concentration of PTE by an efflux system (Gupta et al. 2016; Gupta, Diwan 2017). PGPR have multiple plant health and development enhancing traits, as well as the excellent potential to reduce PTE stress in soil. Bacterial strains isolated from polluted environments become tolerant to higher concentrations of PTE than those isolated from unpolluted areas (Rajkumar et al. 2006). PGPR are used as bioinoculants or biofertilizers to improve plant growth in contaminated soil by using these metal stress evading mechanisms (Madhaiyan et al. 2007; Wani, Khan 2010) and also protect the plants from pathogen attack by the production of antibiotics, HCN and phenazines, etc. (Cazorla et al. 2007; Saravana Kumar et al. 2007). These metal-tolerant rhizospheric bacteria with plant growth promoting factors have the potential to be used in soil remediation. Consortium of bacterial strains is more useful in bioremediation than a single strain culture. Wang and Chen (2009) studied the synergistic effect of bacterial mixtures by using four strains *Viridi bacillus arenosi* B-21, *Sporosarcina soli* B-22, *Enterobacter cloacae* KJ-46 and *E. cloacae* KJ-47 for bioremediation of Pb, Cd and Cu from contaminated soil. Quorum sensing is another type of mechanism that helps in establishing the plant microbe interaction in the rhizosphere by sporulation, antibiotic and biofilm production which enhances the development of plants and bacterial remediation potential (Thomas, Cebron 2016). A summary of the remediation of PTE contaminants by some PGPR using different mechanisms is presented in Table 1.

Fungi mediated bioremediation: Mycoremediation. Fungi are pivotal to the biosphere because they are the primary decomposers of waste matter and complex plant debris components such as cellulose and lignin (Rhodes 2012). They play an important role in the development of a healthy ecosystem by recycling nutrients in all terrestrial habitats (Kendrick 2011) and act as plant growth promoting microorganisms. These are either free living or in symbiotic association with different plant hosts. AMF are ubiquitous soil microflora that

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Table 1. Summary of few pot experiments on PGPRs assisted phytoremediation of PTE/RE contaminated soils

PTE/RE	Plant growth promoting rhizobacteria	Host plants	Mechanisms of PTE/RE mitigation	Effect of PGPRs on phytoremediation	References
As	*Sporosarcina ginsengisoli*	–	biomineralization	reduction in As exchange by microbially induced calcite precipitation	Achal et al. (2012)
Cd	*Bacillus mycoides* and *Micrococcus roseus*	*Zea mays*	phytoextraction and phytostabilization	increase in shoot and root Cd content at the levels of 100 mg(Cd)·kg^{-1} and 200 mg(Cd)·kg^{-1}	Malekzadeh et al. (2012)
Pb	*Pseudomonas aeruginosa* WI-1	*Pisum sativum* L	bioaccumulation, IAA and siderophore production	accumulation of high amount of Pb (26.5 mg·g^{-1})	Naik et al. (2012)
Pb	*Bacillus* sp. MN3–4	*Alnus firma*	extracellular sequestration and intracellular accumulation	reduction in PTE phytotoxicity and increment in Pb accumulation	Shin et al. (2012)
Cd, Pb and As	*Ochrobactrum* sp. and *Bacillus* spp.	*Oryza sativa*	ACC deaminase activity and siderophore production	inoculation decreases the superoxide dismutase (SOD) activity and malondialdehyde (MDA) level	Pandey et al. (2013)
As	*Pseudomonas* sp. P1III2 *and Delftia* sp. P2III5 (A), *Bacillus* sp. MPV12, *Variovorax* sp. P4III4, and *Pseudoxanthomonas* sp. P4V6 (B)	*Pteris vittata*	IAA and siderophore production	As removal efficiency increased from 13% to 35%	Lampis et al. (2015)
Zn and Pb	*Pseudomonas aeruginosa* and *P. fluorescens*	–	biofilm formation	no direct evidence	Meliani et al. (2016)
Cr, Cd, and Ni	*Pseudomonas aeruginosa* KP717554, *Alcaligenes feacalis* KP717561, *and Bacillus subtilis* KP717559	*Brassica juncea*	bioaccumulation, production of IAA, HCN, NH_3 and phosphate solubilization	significant increment in growth and metal accumulation of plants	Ndeddy Aka and Babalola (2016)
Cu	*Pseudomonas brassicacearum* strain Zy-2-1 and *Sinorhizobium meliloti*	*Medicago lupulina*	IAA, siderophores and ACC deaminase activities	increased Cu accumulation and translocation in both shoots and roots	Kong et al. (2017)
Cd	*Bacillus safensis* and *Kocuria rosea*	*Helianthus annus*	siderophore production, increase precipitation and immobilization of PTE	increased Cd uptake in shoot and total biomass by 30% and 25%	Mohammadzadeh et al. (2017)
Cr and Cd	*Azotobacter* sp.	*Lepidium sativum*	–	no clear evidence	Sobariu et al. (2017)
Cr	*Burkholderia vietnamiensis*	Zea mays	bioaccumulation	bioaccumulation and translocation factor of Cr increased by 50% and 31%	Ali et al. (2018)

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Table 1 to be continued

PTE/RE	Plant growth promoting rhizobacteria	Host plants	Mechanisms of PTE/RE mitigation	Effect of PGPRs on phytoremediation	References
Cd and Pb	*Pseudomonas aeruginosa* and *Bacillus cereus*	*Oryza sativa*	bioaugmentation	*P. aeruginosa* strains were significantly reduced the negative impact of Cd and Pb	Nath et al. (2018)
Cr and Ni	*Pseudomonas aeruginosa*	*Cicer arietinum*	exopolysaccharides, siderophore production and proline accumulation	increase in seed yield (81%) and grain protein (16%) at 660 mg(Ni)·kg^{-1} and 144 mg(Cr)·kg^{-1}	Saif and Khan (2018)
Cd	*Raoultella* sp. strain X13	*Brassica chinensis* L.	phosphate solubilization, IAA and siderophore production	substantial reduction in the Cd^{2+} bioavailability for *B. chinensis* L.	Xu et al. (2019a)
Cd	*Serratia marcescens* S2I7	*Oryza sativa*	phosphate solubilization, IAA, HCN, siderophore production and Glutathione S-transferase (GST) mechanism for detoxification of Cd	significant increase in germination and growth of seedlings due to reduction in amount of residual Cd in soil	Kotoky et al. (2019)
Cr	*Klebsiella* sp. and *Enterobacter* sp.	*Solanum lycopersicum* L.	bioaccumulation, increase in the amount of anti-oxidative enzymes and non-enzymatic anti-oxidants	more Cr accumulation in roots with poor translocation in shoot	Gupta et al. (2020)
Zn	*Serratia* sp. (zinc tolerant bacterial strains)	*Zea mays*	biosorption, exopolysaccharide, IAA, siderophores production and ACC deaminase activity	improvement in plant growth parameters due to elimination of Zn toxicity	Jain et al. (2020)
Cr	*Stenotrophomonas maltophilia*, *Bacillus thuringiensis*, *B. cereus* and *B. subtilis*	*Cicer arietinum*	IAA and siderophore production, phosphate and potassium solublization, bioaccumulation, phytostabilization	improvement in root and shoot length by 6.25–60.41% and 11.3–59.6%	Shreya et al. (2020)
Cr, Cd, and Pb	*Klebsiella* sp. TIU20	*Vigna radiata* L.	extracellular polymeric substances (EPS), bio-sorption, bioaccumulation, biofilm formation, volatile organic compounds, phosphate solubilization, production of IAA and ammonia	adsorption of PTE by EPS secretion 54.6 µg·mL^{-1} for Cr, 50 µg·mL^{-1} for Pb and 46 µg·mL^{-1} for Cd	Chakraborty et al. (2021)
Cd and Zn	*Streptomyces pactum* and *Bacillus* sp. (*B. subtilis* and *B. licheniformis*)	*Brassica juncea*	bioaccumulation and phytoextraction	improvement in level of enzymes, bioavailability and mobilization of metals	Jeyasundar et al. (2021)

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Table 1 to be continued

PTE/RE	Plant growth promoting rhizobacteria	Host plants	Mechanisms of PTE/RE mitigation	Effect of PGPRs on phytoremediation	References
Cd and Cr	*Bacillus gibsonii* and *B. xiamenensis*	*Sesbania sesban*	IAA, ACC deaminase and exopolysaccharides production	improvement in plant growth, enzymatic activities and PTE accumulation	Zainab et al. (2021)
Cd	*Enterococcus faecium*	*Oryza sativa*	bioaccumulation and bio-sorption	significant reduction in extractable and soluble Cd concentrations in soil	Cheng et al. (2022)
Pb and Cd	*Pantoea* sp. PP4	*Lolium multiflorum*	bio-sorption, bioprecipitation, phosphate solubilization and IAA production	increased accumulation of Pb and Cd in *L. multiforum* by 28.9% and 95.5%	WeiXie et al. (2022)

PGPR – Plant Growth Promoting Rhizobacteria; PTE – potentially toxic elements; RE – risk elements; IAA – indole-3-acetic acid; ACC – 1-aminocyclopropane-1-carboxylate

form symbiotic relationships with roots of 80–90% land plants in natural, agricultural, and forest ecosystems (Brundrett 2002). Plant Growth Promoting Fungi (PGPF) are used as bioinoculants or biofertilizers to improve the plant growth under stress and to protect plants from pathogens through a variety of mechanisms that include solubilizing and mineralizing nutrients for easy uptake by plants, regulating hormonal balance, producing volatile organic compounds, and microbial enzymes (Hossain, Sultana 2020). Despite the fact that they act as plant growth promoters and biocontrol agents, these microorganisms appear to be good bioremediation agents for PTE polluted soil and water. Fungi have been found to have significant resistance to PTE and to be dominant organisms in polluted habitats (Mishra, Malik 2012). A number of fungal species (*Penicillium, Aspergillus, Trichoderma, Fusarium, Rhizopus, etc.*) have been reported with different types of PTE removal capacity (Iskandar et al. 2011; Mumtaz et al. 2013; Fomina et al. 2017). Some basidiomycetes members (Pleurotus, Ganoderma, Cantharellus, etc.) have also been reported to bioremediate PTE from contaminated soil (Kaewdoung et al. 2016; Drewnowska et al. 2017; Li et al. 2017). Some of the important mechanisms used by different fungal species for PTE tolerance and removal include bioabsorption, biosynthesis, bioaccumulation, biomineralisation, biological oxidation-reduction, precipitation, etc. (Kumar, Dwivedi 2021).

In case of fungi, Ascomycota and Basidiomycota are the most commonly reported from PTE/RE contaminated soils (Narendrula-Kotha, Nkongolo 2017), but AMF are the first to primarily colonize the nutrient poor and PTE contaminated soils (Khan et al. 2000). AMF act as a mediator between metals and plant roots, and provide protection to roots from RE toxicity (Leyval et al.1997). AMF also play a significant role in the revegetation of PTE polluted soils and increase the efficiency of bioremediation with PGPR.

AMF assisted phytoremediation of PTE/RE from contaminated sites through various mechanisms such as increase of nutrient uptake, activation of enzymatic and non-enzymatic defence systems, root morphological and rhizospheric changes, accumulation and sequestration of PTE by fungal structures and glomalin (Riaz et al. 2021). Several studies have revealed that AMF can reduce RE toxicity in a variety of plants and show promising results; some of the recent studies are listed in Table 2.

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Table 2. Summary of few studies on mycorrhizal effects on phytoremediation of PTE/RE contaminated soils

PTE/RE	Mycorrhizal species	Host plant	Mechanisms of PTE/RE mitigation	Effect of mycorrhiza on phytoremediation	References
Al and Mn	*Scutellospora reticulata* and *Glomus pansihalos*	*Vigna unguiculata*	phyto-rhizoremediation by increasing immobilization of PTE	significant reduction in the Al and Mn content of polluted soil	Alori et al. (2012)
As	*Rhizophagus clarus, R. intraradices, Funneliformis geosporum* and *Glomus* sp.	*Plantago lanceolata* L.	phytostabilization	increase in shoot and root biomass with low concentration of As in roots	Orlowska et al. (2012)
Cd	*Glomus intraradices*	*Medicago sativa* L.	accumulation of Cd in roots and decreased Cd concentrations in shoots	increased total Cd in roots but decreased Cd concentration in shoots	Wang et al. (2012)
Cd, Co and Pb	*Glomus mosseae, G. etunicatum, G. intraradices, Gigaspora hartiga,* and *G. fasciculatum*	*Medicago sativa* L.	mycorrhizoremediation and PTE sequestration by increasing phosphorus uptake	increased translocation of Pb and Co to plants	Zaefarian et al. (2013)
Zn, Cu, Fe, and Mn	*Glomus mossea, G. fasiculatum* and *G. intraradices*	*Triticum aestivum* L.	phytostabilization	increased root yield, plant height, spike length and hundred grains weight with metal tolerance and accumulation	Khan et al. (2014)
Cd	*Glomus versiforme*	*Solanum nigrum*	phosphatase activity, phytoextraction	improvement in total Cd uptake in all plant tissues at different Cd levels	Liu et al. (2015)
Pb and Cd	*Glomus mossea* and *G. intraradices*	*Calendula officinalis* L.	increased root and shoot accumulation of Pb and especially of Cd	greater accumulation of Pb and Cd, especially 833.3 mg and 1 585.8 mg Cd in shoots and roots at 80 $mg \cdot kg^{-1}$ Cd soil	Tabrizi et al. (2015)
Cd	*Glomus mossea, G. intraradices* and *G. etunicatum*	*Cassia italica*	enhanced activities of antioxidants and increased accumulation of osmolytes	improvement in chlorophyll, protein, proline and phenol content, reduction in lipid peroxidation	Hashem et al. (2016)
Cd and Pb	*Claroideoglomus claroideum* and *Funneliformis mosseae*	*Calendula officinalis* L.	accumulation of important secondary metabolites enhanced the antioxidant capacity	no direct evidence	Hristozkova et al. (2016)
Zn	*Glomus* spp.	*Triticum aestivum* L.	phytostabilization	Zn content were lower in shoot as compared to roots at the highest applied Zn levels (900 $mg \cdot kg^{-1}$)	Kanwal et al. (2016)
Fe	*Glomus, Acaulospora* and *Scutellospora*	*Pennisetum glaucum* and *Sorghum bicolor*	–	increased amount of iron absorption due to siderophore production	Mishra et al. (2016)
Cu	*Claroideoglomus claroideum*	*Oenothera picensis*	high Bradford-reactive soil protein (glomalin) accumulation	high Cu concentration in roots	Cornejo et al. (2017)

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Table 2 to be continued

PTE/RE	Mycorrhizal species	Host plant	Mechanisms of PTE/RE mitigation	Effect of mycorrhiza on phytoremediation	References
Cu, Pb and Zn	*Rhizophagus irregularis*	*Nicotiana tabaccum*	decrease adverse effects of PTE by bio-accumulation	significant increase in concentration of toxic elements in plant	Neagoe et al. (2017)
Cd	*Rhizophagus irregularis*	*Glycine max*	high Cd tolerance in HX3 (soybean genotypes) appeared to be associated with increased root growth and AM colonization	upregulate the expression of GmPTs and GmHMA19 genes and alleviate Cd toxicity	Cui et al. (2019)
Cr, Zn, Al, Pb, Co, Ni, Mn, Fe Cu, Si and Mo	*Glomus mosseae* and *Glomus intraradices*	*Helianthus annuus*	bio-accumulation	rise in metal uptake of the plants and glomalin contents	Sayin et al. (2019)
Cd, Cr, Ni and Pb	*Rhizophagus fasciculatus*, *Rhizophagus intraradices*, *Funneliformis mosseae* and *Glomus aggregatum*	*Zea mays*	phytoextraction, bio-accumulation, translocation, bio-concentration and enzymatic activity	shoot weight and root length increased by 113% and 49%, proline, chlorophyll content, P content of shoot and root was increased by 55%, 43%, 57%, and 64%	Singh et al. (2019)
TiO_2	*Funneliformis mosseae*	*Phragmites australis*	bio-accumulation	significant increase in the plant nutrition, antioxidant enzyme's activities, chlorophyll content, and reduction in the MDA content and ROS	Xu et al. (2019b)
Pb, Zn, and Cd	*Funneliformis mosseae* and *Diversispora spurcum*	*Cynodon dactylon*	translocation and bio-accumulation	significant increase in the soil pH and uptake of P, S, and PTE; reduction in the available Pb and Zn in soil and Pb in shoot	Zhan et al. (2019)
Cr	*Rhizophagus irregularis*	*Brachiaria mutica*	anti-oxidative enzyme activity, bio-accumulation	increase in the chlorophyll, carotenoid, protein, proline contents and activities of antioxidant enzymes	Kullu et al. (2020)
Cd	*Funneliformis mosseae*	*Sphagneticola calendulacea*	bio-accumulation and phytoextraction	accumulation of more than 100 $mg(Cd) \cdot kg^{-1}$ in the aboveground parts of the plant	Lu et al. (2020)
Cd and Pb	*Funneliformis mosseae*, *Glomus versiforme* and *Rhizophagus intraradices*	*Zea mays*	synergistic effect between AMF and biochar on improving maize growth and decreasing Cd/Pb accumulation in the maize	significant reduction in Cd and Pb concentrations in maize and improvement in corn growth, shoot biomass and P content	Zhuo et al. (2020)

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Table 2 to be continued

PTE/RE	Mycorrhizal species	Host plant	Mechanisms of PTE/RE mitigation	Effect of mycorrhiza on phytoremediation	References
Cu, Pb and Zn	*Rhizophagus intraradices*	*Glycine max* L.	bioaccumulation, bioabsorption and translocation	accumulation of PTE in the roots, with lesser translocation to the shoots and seeds	Adeyemi et al. (2021a)
Pb	*Funneliformis mosseae*, *Claroideoglomus etunicatum*, and *Rhizophagus intraradices*	*Glycine max* L.	bioaccumulation and translocation	Pb accumulation in the roots, with less translocation to the shoots, improved plant growth and P uptake	Adeyemi et al. (2021b)

PTE – potentially toxic elements; RE – risk elements; AM – Arbuscular mycorrhiza; AMF – Arbuscular mycorrhizal fungi

FUTURE PROSPECTS AND CHALLENGES

Microorganisms and plants are the important tools required to remediate industrial wastes such as PTE/RE, toxic chemical fertilizers. They are able to take up, transform, remove and restrain PTE from the polluted soils and help to restore PTE contaminated sites. Although PTE are non-biodegradable complex pollutants, the combination of both microorganisms and plants is an attractive bioremediation approach to ensure a more efficient cleanup of contaminated soils (Chibuike, Obiora 2014). Microorganisms like PGPR and mycorrhiza play an important role in influencing the plant activity in contaminated soil by modification of root exudate composition, growth enrichment and other mechanisms shown in Tables 1 and 2. Although the concept of bioremediation is not so new, as the industrialization and urbanization increase day by day, it is the need of time to make advancement in the old techniques of remediation. This review demonstrated that PGPMs synergically interact with plants and enhance the remediation mechanism of PTE/RE. Several studies proposed an effective contribution of PGPMs associated with plants to PTE mitigation via direct or indirect strategies. Synergism of microbes and plants helps to learn about the mechanisms of PTE transportation and detoxification at a molecular level. Some of the studies revealed the role of proteins and molecules in plant metabolism during PTE exposure (Ozyigit et al. 2021) and PTE resistant genes and proteins in microorganisms (Yang et al. 2015).

– It is well known that PGPMs play an important role in nutrient enhancement under PTE/RE stress. However, molecular mechanisms responsible for remediation are scarce and need to be revealed.

– Most of the research on PGPMs has been done with agricultural crops such as *Zea mays, Glycine max, Triticum aestivum*, *Vigna unguiculata* etc. while limited studies have been done on forestry plant species. Therefore, forestry plant species should be tested for the remediation of PTE/RE so that tolerant tree species can be recommended for contaminated areas.

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