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Available Approaches of Remediation and Stabilisation of Metal Contamination in Soil: A Review

Tania Rahman[1*], Md. Ferdous Seraj[2,3]

[1]Department of Biochemistry and Molecular Biology, University of Dhaka, Dhaka, Bangladesh
[2]Department of Environmental Science and Management, North South University, Dhaka, Bangladesh
[3]School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
Email: *tania.rahman@du.ac.bd

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Abstract

Anthropogenic activities, such as mining of natural resources, manufacturing industries, modern agricultural practices and energy production have resulted in the release of heavy metals with resultant harmful impacts in some natural environments. Toxic heavy metals are harmful to living organisms even at low concentrations. Therefore, heavy metal contaminated sites should be remediated as heavy metals do not decompose into less harmful substances and are retained in the soil. Conventional methods are used for remediation of heavy metal contaminated soils such as heavy metal extraction, immobilization and removal of soils to landfill produce large quantities of toxic products including insoluble hydroxides and are rarely cost effective. The advent of bioremediation technologies like biosparging, bioventing and bioaugmentation has provided an alternative to conventional methods for remediating heavy metal contaminated soils. A subset of bacteria found in the rhizosphere has been found to increase the tolerance of plants to heavy metals in soil. These bacteria commonly known as plant growth promoting rhizobacteria or Plant Growth Promoting Rhizobacteria (PGPR) are showing promise as a bioremediation technique for the stabilisation and remediation of heavy metal contaminated sites. PGPR can improve plant growth via a variety of mechanism including fixing atmospheric N to improve N status and making plants more tolerant of heavy metals. Scattered literature is harnessed to review the principles, advantages and disadvantages of the available technologies for remediating heavy metal contaminated soils and is presented.

Keywords

In Situ Bioremediation, *Ex Situ* Bioremediation, Phytoremediation, Rhizoremediation, Plant Growth Promoting Rhizobacteria (PGPR)

1. Introduction

One of the environmental problems caused by industry is an increase in the concentration of heavy metals in the air, land and water. Pollution of the biosphere by heavy metals is a global hazard that has accelerated since the beginning of the industrial revolution [1] by the spillage and disposal of waste materials. Heavy metals released from different sources accumulate in soil and, where bioavailability is high enough; can adversely affect soil biological functioning and other properties, leading to the loss of soil and ecosystem fertility and health.

Heavy metals that are necessary for living organisms at low concentrations can become toxic at higher concentrations [2]. Toxic heavy metals are those which are not essential for life and are thus often toxic at lower concentrations than essential heavy metals [3] [4]. Heavy metals can enter organisms via direct soil ingestion, inhalation, dermal contact and intake through food and water [5]. Accumulation of heavy metals in soil is of concern to the agricultural production sector because of the potential threat to food quality and quantity as a result of increased absorption of heavy metals by plants [6]. Agricultural exports are internationally marketed on the basis of environmental safety and sustainability and so regulating heavy metal contamination is an important issue [7]-[13].

2. Remediation of Metal Contaminated Soils

Soil remediation is described as the use of several procedures to reduce, remove or mitigate the contamination of a certain area or land [14]. Remediation may be done to stabilise the site, reduce movement of contaminants offsite via soil erosion or water flow, to reduce toxicity of the contaminants and/or to protect environmental/human health [15]. With an increase in public awareness regarding the consequences of contaminated soil, many researchers are focussing on developing soil remediation technologies which are cost effective and socially acceptable [15]. A specific contaminated site may necessitate a group of procedures to permit the optimum remediation that reduces the environmental and human health risks to acceptable levels [16]. Conventional techniques for soil clean-up of heavy metals involve heavy metal extraction and immobilization that lead to excavation of the land [17]. Contaminated land can be remediated by physical, chemical or biological approaches which may be used in combination with each other to decrease the contamination to a safer and acceptable level [16] [18].

3. Bioremediation

Bioremediation, or biological remediation, is a cost effective and eco-friendly biotechnology that involves the use of organisms such as plants and/or bacteria to remediate and stabilize contaminated sites [19] [20] [21]. The technology involves biological agents such as plants and microorganisms to transform or degrade contaminants into nonhazardous or less-hazardous substances [22] [23]. Various organisms like bacteria, fungi, algae and plants have been reported to efficiently bioremediate pollutants [24]. The technology of bioremediation offers an alternative pathway to more traditional techniques for the remediation of contaminated sites.

Bioremediation uses natural processes and relies upon organisms to alter contaminants and environmental conditions as these organisms undergo their normal life functions [25]. Their metabolic processes are capable of using chemical contaminants as an energy source, rendering the contaminants harmless by reducing their bioavailability or producing less toxic products [25] [26]. Bioremediation is being used as an effective means of mitigating hydrocarbons, organic solvents and organic compounds, pesticides and herbicides, nitrogenous compounds and heavy metals [23].

By definition, bioremediation provides techniques for purging up pollution by augmenting the same biodegradation processes that take place in nature [27]. Despite bioremediation occurs naturally over time, environmentalists have established myriads of ways to speed up the whole bioremediation process. The technology uses naturally occurring bacteria and fungi or plants or fertilizers to degrade or detoxify substances hazardous to human health and/or the environment. The microorganisms may be indigenous to a contaminated area or they may be isolated from somewhere else and transported to the contaminated site [24]. For bioremediation to be operative, microorganisms should enzymatically attack the pollutants and convert them to innocuous products [28]. These belong to the groups of oxidoreductases, hydrolases, lyases, transferases, isomerases and ligases. Many enzymes have remarkably varied degradation ability due to their specific as well as nonspecific substrate affinity. Bioremediation technology is principally based on biodegradation. It refers to thorough removal of organic toxic pollutants in to innocuous or naturally occurring compounds including carbon dioxide, water, inorganic compounds which are safe for human, animal, plant and aquatic life [29]. Numerous mechanisms and pathways have been elucidated for the biodegradation of a wide variety of organic compounds; for instance, it is completed in the presence and absence oxygen.

Microorganisms used to perform the function of bioremediation are known as bioremediators [21]. Typically, microbes like bacteria, archaea and fungi are the leading bioremediators [24]. There are lots of different types, they grow very rapidly and they can be easily modified genetically. Examples of this type of bioremediators include *Aspergillus niger, Pseudomonas aeruginosa*, *Penicillium chrysogenum*, *Pseudomonas putida*, *Bacillus subtilis* and *Rhizobium* sp.

These bioremediators are grouped into two broad categories: aerobic and anaerobic. Aerobic microorganisms work in presence of oxygen and can degrade pesticides and hydrocarbons with many of these microbes use the pollutant as the source of energy [21]. Anaerobic microorganisms work in absence of oxygen and are less frequently used in comparison to aerobic ones [21]. Bioremediation involves two different strategies: *in situ* and *ex situ*.

3.1. *In Situ* Bioremediation

In situ bioremediation is remediation without excavation of contaminated land [18]. Often, it is applied to the breakdown of contaminants in saturated soils. It uses beneficial micro-organisms to degrade the chemicals in the contaminated environment and costs less than conventional remediation technologies [29]. *In situ* bioremediation includes techniques like biosparging, bioventing and bio-augmentation [21].

Biosparging is injecting oxygen under pressure in to the saturated zone to transfer volatile compounds to the unsaturated zone for biological breakdown by naturally occurring microorganisms [21]. Biosparging is relatively cheap, easy to install and quickly distributes oxygen across the site to maximise microbial functioning [30]. Bioventing involves using a low flow of air to provide adequate oxygen for sustaining microbial activity [31]. Bioventing is typically used to treat contaminants that are biodegradable under aerobic conditions. Bioventing accelerates natural processes as it provides a low flow of air, which augments the growth of microorganisms naturally present in soil [32]. Bioaugmentation involves naturally occurring microbial strains or genetically engineered variants to treat contaminated soil [33]. This approach is commonly used in municipal wastewater treatment [34]. Maintenance of this system is difficult as it requires monitoring to ensure the complete degradation of the contaminants [21]. Also optimising the efficiency of the microorganisms in an uncontrolled external environment is difficult to achieve and assess [35].

3.2. *Ex Situ* Bioremediation

Ex situ bioremediation involves removing contaminated soils from the ground for treatment that can occur in another location either on or off site [18]. It is often considered to be less advantageous than *in situ* remediation because the contamination is moved elsewhere and has the possibility to create significant risks in the excavation and transport of harmful material [29]. *Ex situ* bioremediation includes techniques such as land farming, composting and biopiling [21] [29].

Land farming is a technique where contaminated soil is taken and spread in a thin layer over a ground surface of a treatment site until the contaminants are degraded by aerobic microorganisms [36]. Microorganisms are frequently added to the soil to achieve rapid degradation and the soil must be well mixed in order to increase the contact between the contaminants and microorganisms [16]. Large areas of land are required for land farming, which is a limitation to the suitability of this technology [16].

Composting is a controlled process by which organic materials are degraded by microorganisms under elevated temperature, resulting in the production of organic and/or inorganic by-products [37]. The increased temperature results from the heat released by microorganisms during the degradation of the organic materials in the waste. Typical compost temperatures are in the range of 55˚ to 65˚C [38]. The volume of material often increases after composting due to the addition of amendment agents, which is a limitation of this technology [39]. Nevertheless this is a cost-effective technology [21].

Biopiling is a technology where excavated soils are piled and get mixed with microorganisms by using applied aeration. The piles should be covered to prevent overflow, evaporation and to advance solar heating [40]. The contaminants are often condensed to carbon dioxide and water [41]. Biopiling is similar to land farming but in the latter the soil is aerated artificially.

4. Phytoremediation

Phytoremediation involves using plants to remediate contaminated land. [42] [43] [44] [45]. Phytoremediation is a rising technology, that remediates a broad range of environmental pollutants *in situ* [21]. Growing and harvesting plants in contaminated sites is seen as an inexpensive, solar-energy driven and ecologically friendly method of remediation that can be used to remediate these sites [44]. A number of heavy metal accumulating plants have been used for removing toxic metals from soil [46], which in addition, also provide the vegetation cover, to control soil erosion on contaminated sites, and thus, the movement of contaminants offsite [47]. For example, high Ni accumulation and tolerance has been reported in 7 genera and 72 species of the family Brassicaceae [48]. It is established that certain species of this family exhibit a strong ability to gather and translocate heavy metals, such as Cd, Cr, Pb, Zn and Ni through the roots to the shoot [49]. Phytoremediation has several subcategories including Phytoextraction, Phytotransformation, Phytodegradation, Phytostabilisation and Rhizoremediation [1] [21] [50].

Phytoextraction or phytoaccumulation is the process that is used to accumulate contaminants into the roots and shoots of plants [46]. It is rather less expensive but more time consuming than many other soil clean-up process [21]. Phytotransformation or phytodegradation is the uptake of organic pollutants from soil or water and their transformation into lower risk forms [21]. Rhizofiltration is the remediation of contaminated groundwater. Pollutants maybe absorbed by roots or adsorbed onto the surface of the roots [49]. Phytostabilisation is a technique where plants reduce the bioavailability and/or mobility of contaminants in the soil or reduce the relocation of contaminated soil, e.g. via erosion, thus immobilising contaminants within the soil profile [21] [50]. Elements that are adsorbed and bound into the structure of plants form a stable mass within the plant and do not again enter the environment [21]. Rhizoremediation is phytoremediation that uses rhizobacteria, where combinations of plant and the bacteria work together within the plant rhizosphere to remediate the soil [1] [51].

Approximately, 400 species of terrestrial plants have been identified as hyper-accumulators of various heavy metals [52] which may serve as potentially useful bioagents for phytoextraction of heavy metals. Generally, the threshold for hyper-accumulation of Ni by plants is set at 1000 mg/kg (0.1%) dry mass [53]. Efficiency of phytoaccumulation depends upon the rate of heavy metal uptake and enhanced production of biomass with minimal phytotoxicity [54]. Still, it has been speculated that most of the known hyperaccumulators are not suitable for phytoextraction due to their slow growth and low biomass in heavy metal contaminated soil [49]. These limitations have led to the exploration of the possibilities of enhancing the biomass of heavy metal accumulators using rhizobacteria as plant growth promoting bioinoculants. Considerable attention is being paid to using plants as well as plant-microbe interactions for the removal or immobilisation of heavy metals and other toxic wastes in soil [55].

5. Rhizoremediation

Rhizoremediation is the remediation of soil by rhizobacteria *i.e.* bacteria that inhabit the rhizosphere of plants [56]. Combining the benefits of microbe-plant symbiosis within the plant rhizosphere into an effective remediating technology is a relatively new approach that has the potential to provide practical remediation outcomes [1].

To tolerate heavy metal stress in contaminated soils, some microbes have developed certain mechanisms that they apply to withstand the uptake of heavy metals (**Figure 1**). These mechanisms comprise; 1) exclusion: pumping heavy metal ions outside to the cell, here the metal ions are kept at bay and away from the target sites; 2) extrusion: where the metals are pushed out from the cell through plasmid/ chromosomal mediated events; 3) accommodation: where metals form complex with different cell components including metal binding proteins, that is gathering and sequestration of the metal ions inside the cell; 4) biotransformation: where the toxic metal is reduced to a less toxic form by conversion; 5) methylation and demethylation and 6) desorption/adsorption of heavy metals [1]. These defence mechanisms enable tolerant microorganisms to function metabolically in heavy metal polluted environments.

6. Plant Growth Promoting Rhizobacteria

Plant growth promoting rhizobacteria or PGPR are a number of species of soil bacteria that grow in the rhizosphere of plants and stimulate plant growth by a variety of mechanisms [57]. The roots of plants interact with large number of diverse microorganisms and these interactions together with soil conditions impact on plant growth. The colonization of the rhizosphere by bacteria is known to be helpful for bacteria but their presence can also be beneficial to plants [55]. Plant growth promoting rhizobacteria are used in some agricultural systems to improve crop yield and quality [58] [59] [60]. For example, the legume-rhizobium symbiosis turns atmospheric N into forms plants can use and is

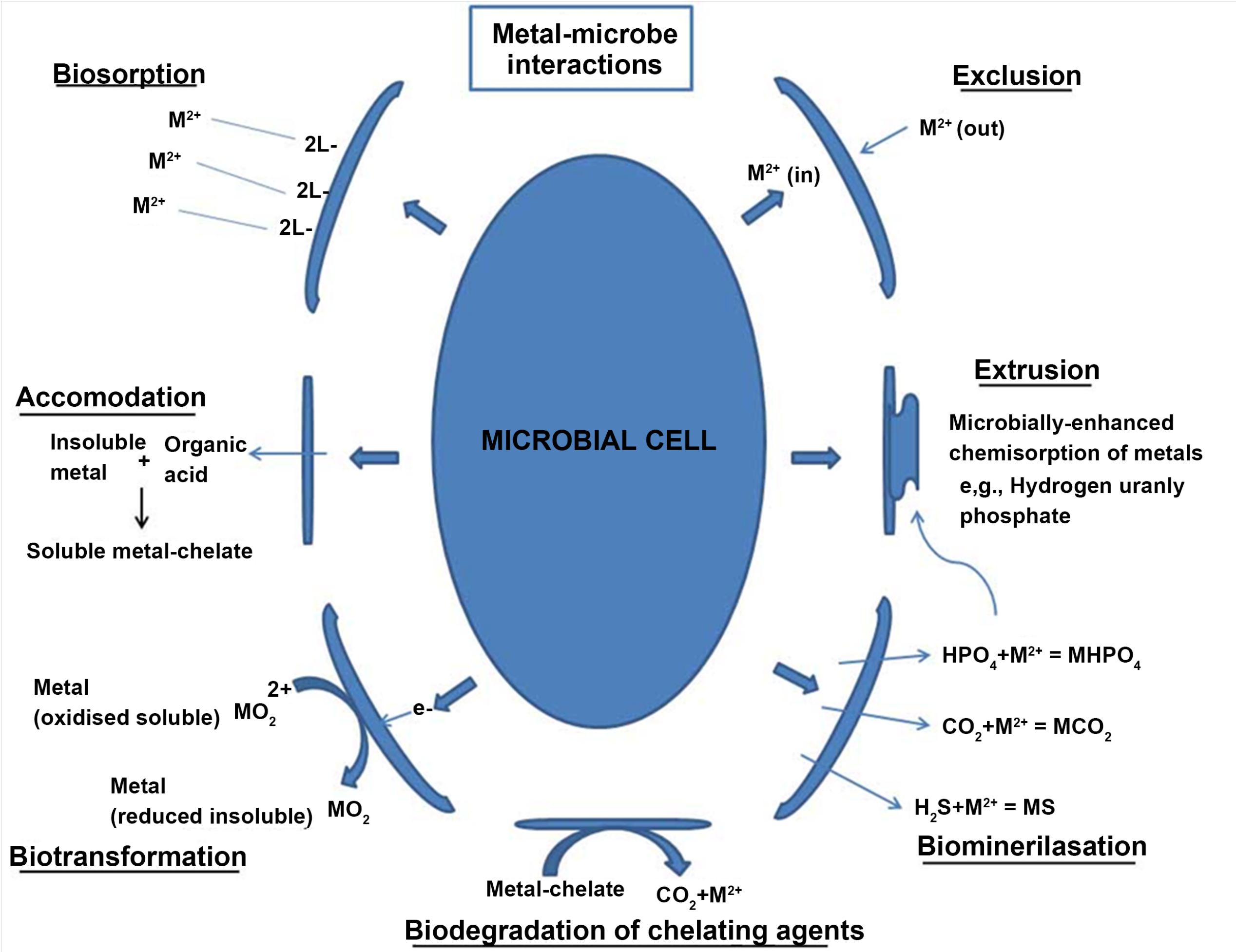

Figure 1. Metal tolerance mechanisms developed by soil microbes (partially adapted from [1]).

a vital part of the N cycle [61]. As leguminous plants are important sources of protein for humans and the animal world, the use of rhizobial inoculants for legumes to ensure efficient N fixation has been occurring for over 100 years [62]. Simultaneously inoculant markets were also developed in Myanmar [63], Thailand [64] [65] and Bangladesh [66].

In addition to use in agricultural systems, there is the potential for utilising the properties of PGPR in other systems such as to use PGPR in the remediation and stabilisation of contaminated land [67]. Some PGPR have also been shown to protect their host plant from pathogenic microorganisms [68] and heavy metals [69]. The effectiveness of various bioremediation strategies are summarized in Table 1.

6.1. Mechanism of Action of PGPR

Plant growth promoting rhizobacteria are usually applied to plants for the purpose of growth enhancement, including increased seed germination, plant weight, and harvest yields [68]. The general mechanisms of plant growth promotion by PGPR includes resource acquisition from the atmosphere (e.g.

Table 1. The effectiveness of different types of bioremediation strategies of metal contaminated soils.

Mode of Bioremediation	Examples	Advantages/Effectiveness	Disadvantages	Ref.
In situ	Biosparging Bioventing Bioaugmentation	Most Cost effective; Natural attenuation process; Relatively passive; Treats soil and water;	Extended treatment time; Monitoring difficulties; Environmental constraints;	[21] [24]
Ex situ	Land farming Composting Biopiling	Low cost; Can be done on site;	Space requirement; Extended treatment time; Bioavailability limitation;	[24] [29]
Phytoremediation	Phytoextraction Phytotransformation Phytodegradation Phytostabilisation Rhizoremediation	Cost of the phytoremediation lower than that of traditional processes both in-situ and ex-situ; Can be easily monitored; Uses naturally occurring organisms and preserves the natural state of the environment;	The toxicity and bioavailability of biodegradation products are not permanently known; Too high concentration of contaminants can result in plants death;	[50] [70] [71]
Rhizoremediation	Exclusion Extrusion Accommodation Biotransformation Methylation Demethylation Desorption/adsorption of heavy metals	Uptake of metals in plant roots; Roots absorb Zn, Pb, Cd, As; Groundwater adsorb pollutants, mainly metals, from water and aqueous waste streams;	May require a longer period than other remedial approaches; Phytoremediation is limited to the depth that the plant roots can reach and to sites with low contaminants concentrations because concentrations that are too high can be toxic to plants;	[21] [72] [73]
	Plant Growth promoting Rhizobacteria	resource acquisition including assimilation of N from atmosphere, protection of host plant from pathogenic microorganisms and heavy metals		[74] [75]

atmospheric N) [74] [75], producing particular compounds used by plants (e.g. siderophores and phytohormones) [76] [77], solubilising nutrients (e.g. P, Fe), facilitating uptake of nutrients from soil (e.g. P, Fe) [78] [79] [80], protecting plants from possible microbial attack [81] [82], and decreasing the toxicity of heavy metals [25]. Nevertheless the mechanisms of PGPR-mediated expansion of plant development are not entirely understood [83]. For instance, the production of siderophores effect plant growth promotion in multiple ways such as bio-control, providing plants with micronutrients like Fe and protecting plants from heavy metal intoxication by chelating heavy metals and reducing their bioavailability [55] [70]. Plant growth promoting rhizobacteria strains can promote plant growth and development either directly or indirectly [84].

Direct stimulation involves resource acquisition, which includes assimilation of N from atmosphere, solubilising nutrients particularly mineral phosphate, sequestering Fe, modulating phytohormone levels, producing cytokinins, gibberellins, indoleacetic acid (IAA) [85] [86]. Indirect stimulation is related to the ability of the bacteria to prevent the proliferation of plant pathogens by producing antibiotics and lytic enzymes [87] [88], producing siderophores which can prevent some phytopathogens from acquiring a sufficient amount of Fe thereby limiting their ability to proliferate [89], the ability of bacteria to compete with pathogenic microbes for available nutrients in soil, lowering inhibitory levels of stress ethylene by producing ACC deaminase and thereby increasing root growth [90], enhanced resistance to drought [91] [92], salinity [93], waterlogging [94] oxidative stress [95] and heavy metals [69] [96].

6.2. PGPR in Heavy Metal Contaminated Soil

The potential of using beneficial bacteria to increase plant growth has shown considerable promise in laboratory and greenhouse studies, but responses have been variable in the field [97]. The use of PGPR has been extended to remediate contaminated soils in association with plants [25]. Research has found that PGPR play an active role in plants grown in heavy metal contaminated soils by improving plant growth and tolerance to heavy metals [55] [67] [70] [98] [99] [100] [101]. As an example, the heavy metal tolerant PGPR *Bacillus subtilis* strain SJ-101 improved the growth of Indian mustard (*Brassica juncea*) in Ni contaminated soil [55] [101].

Several rhizobial species are known to increase the nutrient status of plants grown on contaminated soils but most importantly some PGPR are both heavy metal tolerant and improve plant growth under exposure to excess heavy metals [67]. For example, *Bradyrhizobium* strain RM8 is tolerant to Ni and Zn; *Rhizobium* sp. RL9, isolated from lentil nodules is tolerant of Zn; and *Rhizobium* sp. RP5, isolated from pea nodules is tolerant of Zn and Ni and produces substantial amounts of IAA. A variety of PGPR strains aid in heavy metal induced toxicity in plants (**Table 2**).

A range of rhizobacterial strains help in amending heavy metal induced plant toxicity [108]. For instance, PGPR strains, pseudomonads and *Acinetobacter* enhance uptake of Fe, Zn, Mg, Ca, K and P by crop plants [112]. Studies on certain rhizobacteria in heavy metal uptake indicated that this group of bacteria for example, *Pseudomonas* are able to grow and produce siderophores in presence of heavy metals in chickpea plants grown in Ni contaminated soil [55].

Numerous strains of plant growth promoting rhizobacteria possessing heavy metal reducing ability have been identified. As an example, certain rhizobacteria are able to tolerate arsenic accumulated by the silverback fern (*Pityrogramma calomelanos*) [113]. Rhizosphere microbes that were collected from roots of *P. calomelanos* increased the biomass and as concentration of plants significantly suggesting that rhizosphere bacteria improved phytoextraction of as [114]. In similar studies, it was found that fern *Pteris vittata* is an as hyper accumulator and adding as reducing bacteria plant biomass increased by 53% and as uptake by 44% [115]. In another study, the growth promoting effect of *Bradyrhizobium japonicum CB*1809 with soybean plants grown in as contaminated growing medium was investigated [69]. In this study, however, the bacteria improved plant growth of soybean but the plant uptake of as was not increased by inoculation with the *Bradyrhizobium* and thus the bacteria has potential for use in site phytostabilisation.

Recently, plant growth promoting rhizobacteria *Arthrobacter mysorens* 7, *Azospirillum lipoferum* 137, *Agrobacterium radiobacter* 10 were isolated from

Table 2. Examples of plant growth promoting rhizobacteria able to tolerate a variety of heavy metals in plants.

PGPR	Plant	Tolerated metals	Reference
Bacillus subtilis SJ-101	*Brassica juncea* (Indian mustard)	Ni	[101]
Pseudomonas sp.	Chickpea	Ni	[55]
Bradyrhizobium sp. (vigna) RM8	Greengram (*Vigna radiate*)	Ni	[102]
Sinorhizobium sp. Pb002	*Brassica juncea*	Pb	[103]
Brevibacillus	*Trifolium repens*	Zn	[104]
Pseudomonas sp, *Bacillus* sp.	Mustard	Cr	[105]
Bradyrhizobium japonicum CB1809	Glycine max (Soybean)	As	[69]
Pseudomonas putida KNP9	Mung bean	Pb and Cd	[106]
Pseudomonas sp. RJ10, *Bacillus* sp. RJ31	*Brassica napus*	Cd	[107]
Rhizobacteria	*Triticum aestivum* L. (wheat) *Hordeum vulgare* L.(barley)	Cd	[108]
Rhizobium sp. RL9	Lentil	Zn	[109]
Rhizobium sp. RP5	Pea	Zn and Ni	[110]
Rhizobacterium sp. D14	*Populus deltoides* LH05-17	As	[111]

barley plants grown in Cd and Pb-treated soil [111]. In barley plants, that were cultivated in uncontaminated and contaminated soils, the heavy metal resistant bacterial strains colonized the rhizosphere. Inoculated barley had improved uptake of nutrient elements and growth compared to control plants when grown in soil contaminated with Cd and Pb [111]. It was concluded from this study that accumulation of Cd and Pb in barley plants was reduced by the bacteria which accounted for increased growth of inoculated plants. In another study, Cr tolerant rhizobacteria were isolated from the rhizosphere of a Cr contaminated site. These bacteria were used to inoculated *Vigna radiata* in Cr contaminated soil and the inoculated plants were found to have an increase in biomass, root length and shoot length over non-inoculated plants grown in the same soil [108]. Interestingly, the inoculated plants had a significant enrichment in Mn, Fe, Ni, Zn, Cr, Pb, Cd and Cd accumulation ($P < 0.001$) compared to non-inoculated plants despite the inoculated plants having higher biomass [108]. So, improving plant microbe interaction and introducing useful rhizospheric microorganisms are important to increased biomass production and heavy metal tolerance of plants.

6.3. Prospective of Bioremediation

This review comprehensively covers the salient features of bioremediation, its limitations and recent developments in waste management through bioremediation. It is acknowledged that no single specific technology could be considered as a solution for all contaminated site problems. Microorganisms play essential role in bioremediation; therefore, their assortment, opulence and internal structure in polluted environments provide understanding of the fate of any bioremediation techniques. Genomics, metabolomics, proteomics and transcriptomics—all "Omics" molecular technics have contributed towards the better understanding of microbial identification, functions and associated metabolic and catabolic pathways [27]. Genetically engineered microorganisms (GEMs) have exhibited potential for bioremediation applications in soil and groundwater, showing enhanced degradative capabilities including a wide range of chemical contaminants [116]. GEMs can enhance degradative performances using various strategies including modification of enzyme specificity and affinity, pathway construction and regulation, bioprocess development, monitoring, and control, toxicity reduction, and end point analysis. Further, engineering microorganisms with degradative capacity for a specific compound using synthetic biology approach can increase bioremediation efficacy. The use of nanoparticles can diminish the toxicity of pollutants to microorganisms [117]. Nanoparticles enhance surface area and lesser activation energy, thus accumulating the efficiency of microorganisms in degradation of waste and toxic materials, resulting in overall reduction in remediation time and cost.

6.4. Concluding Remarks

Metal contamination issues in plants and soils are becoming increasingly common throughout the world. Metal toxicities are often associated with a range of symptoms and an overall decrease in plant growth [118] [119] [120]. Background knowledge of available different strategies and potential risks of heavy metals is necessary for the selection of appropriate remedial options. Bioremediation technologies including *in situ* and *ex situ* bioremediation are frequently listed provides methods for remediating heavy metal contaminated soils. The environmental benefit of the approach of using beneficial bacteria to increase plant growth and to reduce heavy metal toxicity and/or bioavailability in contaminated lands fits with sustainable management practices [55] [67] [96] [100] [101] [121]. These bacteria have demonstrated a considerable decrease in the toxicity of metals to the host plant and a subsequently improved overall development and yield of plant species [110] [122]. The growth promoting properties of rhizobia to an array of heavy metals for the remediation and stabilisation of contaminated land is an area of research that needs to be further explored.

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Conflict of Interest

The authors declare no conflict of interest.

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