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Review

Unveiling the potential of plant growth promoting rhizobacteria (PGPR) in phytoremediation of heavy metal

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Abstract
Rapid industrialization, modern farming practices, and other human activities are contributing significant amounts of harmful heavy metals to the environment. These metals can accumulate and magnify through food chains, posing substantial risks to human health. Recognizing the global environmental threat and its health implications, researchers have developed cutting-edge methods to address heavy metal contamination. Phytoremediation stands out as the foremost method, offering effectiveness and environmental suitability. Combining plant growth-promoting rhizobacteria (PGPR) with phytoremediation can be a viable option for minimizing contamination. PGPR enhances plant growth and aids in metal cleanup through chemical synthesis, the secretion of chelating agents, redox reactions, and acidification. This review conducted a comprehensive online search across peer-reviewed electronic databases using specific keywords related to PGPR in heavy metal phytoremediation. This review included 129 relevant articles out of the initially identified 187 articles and outcomes were represented with schematic sketches and in-depth tables. The articles selected were focused on the potential of PGPR in phytoremediation, with emphasis on the contribution of rhizo and endophytic bacteria in accelerating the benefits of phytoremediation. There is little information available about the mechanisms involved in plant-PGPR relationships for metal accumulation. The causes and effects of heavy metal toxicity in the environment were examined in this review, along with the usage of PGPR as a different biological strategy to reduce metal contamination and prevent metals from migrating into edible plant parts. Finally, these prospects will provide some perspectives for future studies on these bacteria in agriculture and offer the possibility of major breakthroughs through knowledge expansion and the allocation of trial sites for the transfer of phytoremediation technology to the farmers in a better way.

Article highlights

- A systematic review of the use of PGPR as an alternative biological approach to reduce metal pressure and its translocation into the edible parts of plants.
- A basis for developing an integrated approach to phytoremediation of heavy metals.
- A guideline for future studies on these bacteria in agriculture and offer the possibility of major breakthroughs in phytoremediation technology so that we can offer this to farmers in a better way.

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1 Introduction

It is foreseen that by 2050, the global total population will be approximately 9 billion [1]. Because of the projected increase, providing food to the entire population during the next decade will be a significant challenge. In recent years, industrialization is increasing the amount of heavy metal contamination in the ecosystem, which poses possible ecological hazards. Unfixed heavy metals are abundant in wastewater produced by businesses (paint, fertilizer, textile, electrochemical, etc.) and are released partially or untreated, which allows them to penetrate the aquatic and terrestrial environments [2, 3]. The non-degradable nature of heavy metal pollutants in sewage leads to their progressive build up in the ecosystem [4, 5]. Heavy metals such as mercury (Hg), nickel (Ni), lead (Pb), arsenic (As), zinc (Zn), chromium (Cr), cadmium (Cd), cobalt (Co) and copper (Cu) pose a significant health risk due to their cytotoxic, mutagenic, and carcinogenic nature [6, 7]. Such elements enter the soil through both anthropogenic and geological sources, such as agrochemical usage, industrial and domestic wastewater, mining activities, and atmospheric deposition [8–10].

The excessive use of biosolids, livestock manure, composts, and sewage sludge as fertilizers also leads to elevated levels of heavy metals in soil, which can further leach into groundwater [11, 12]. Micronutrient-deficient soils are often supplemented with heavy metals like Fe, Co, Cu), Zn, Mn, and Ni for plant growth [13]. Moreover, the excessive use of potassium, phosphorus, and nitrogen fertilizers, particularly phosphate fertilizers, can lead to an increase in the levels of heavy metals such as Hg, Cd, and Pb in the soil. Pesticides that are commonly employed in agriculture contain heavy metals, including substances like copper sulfate and lead arsenate, which are used for pest management [10]. Additionally, the long-term application of wastewater effluents for irrigation purposes, even when they contain low levels of heavy metals, contributes to elevated accumulation in the soil [14, 15]. The magnitude of heavy metal contamination in the soil is dependent on the specific type and location of the compounds, ranging from minimal traces to high concentrations [16].

Based on the United States Environmental Protection Agency (USEPA) [17] estimates, soil heavy metal contamination has affected the health of approximately 10 million people worldwide. Hence, to address this issue, remediation measures are necessary to prevent heavy metal contamination in terrestrial, aquatic, and atmospheric environments and to mitigate the impact on polluted land [18]. Various remediation approaches, including physio-chemical and mechanical techniques like soil excavation, washing, incineration, and to some extent solidification, landfilling, and electric field application, have been developed. Nevertheless, these approaches have limitations, such as high cost, irreversible changes to soil properties, inefficiency at low contaminant concentrations, and the potential for introducing secondary pollution [19]. As an alternative, phytoremediation, a plant-based approach, offers a promising solution. This method involves the use of plants to extract and reduce the bioavailability of elemental contaminants in soil [19]. Plants can take up ionic compounds, even at low concentrations, and translocate them through their root systems. They establish a rhizosphere ecosystem by extending their roots into the soil matrix, facilitating the accumulation of heavy metals and modulating their bioavailability [20]. Whereas, bioremediation that uses living organisms, mainly microorganisms (bacteria, fungi and microalgae) or their processes to degrade or detoxify environmental contaminants, which leads to decontaminate polluted soil and water [21]. Recently, it has become increasingly evident that soil microbes, principally plant growth promoting rhizobacteria (PGPR), have a profound effect on soil remediation of natural and metallic toxins and plant growth through a range of strategies [22]. Metals are mobilized by the PGPR in a variety of ways, including acidifying rhizospheric conditions, solubilizing metallic minerals, improving the discharge of root exudates, and increasing the root surface for uptake of the metals [23].

For the degradation of inorganic and organic impurities, PGPR employ numerous mechanisms, such as transformation, volatilization, and rhizodegradation [24]. By enzymatic detoxification, metal complexation, toxic metal efflux, and volatilization of metals, these PGPR can counterattack the toxicity of metals [64]. Furthermore, PGPR can resist and detoxify metalloids and metals, such as Co^{2+}, Ag^{2+}, Cu^{2+}, Hg^{2+}, Zn^{2+}, Ni^{2+} Cd^{2+}, and Sb^{2+} [25]. There is significant evidence that PGPR assuage the integration of metals by plants (immobilization) [23]. Many physiochemical methods have been used in the past to remove metal pollution. The majority of these methods are expensive, change the biological makeup of the soil, and create secondary pollutants. Consequently, it is vitally desirable to adopt an alternate and environmentally beneficial technique. In this case, employing biological resources to remediate heavy metal contamination is a viable and economical method with benefits over traditional physicochemical procedures. Because it is both environmentally friendly and economically viable, phytoremediation is one of the most extensively used biological techniques to bioremediation. However, a number of issues, including the plants' inadequate shallow root structure, sensitivity to several metals, low biomass production at higher metal concentrations, and so on, hampered the plant's ability to perform phytoremediation. Therefore, using PGPR to increase the plant's phytoremediation efficacy at greater metal concentrations is a potential strategy. Utilizing PGPR as a bioinoculant enhanced the plant's biomass and root development by recycling nutrients, stabilizing the soil's structure, and adjusting the toxicity and bioavailability of heavy metals. The mechanisms employed in plants-PGPR associations on the buildup of metals are scantly documented. In this review, we reviewed the sources and impacts of heavy metal toxicity in the environment; besides, we have discussed the use of PGPR as an alternative biological approach to reduce the metal pressure and their translocation into the edible parts of the plants.

2 A recurring change in the research studies

We conducted a comprehensive online search using reputable sources such as PubMed, Scopus, Google Scholar, Web of Science, ResearchGate and Science Direct for the literature survey. Other government sources such as the USEPA are also utilized for this study. The search employed specific key terms, including "phytoremediation", "hyperaccumulator plants", "heavy metal toxicity and decontamination", "plant growth promoting rhizobacteria or PGPR", "microbial strains for bioremediation", "phytostabilization", "phytoextraction" and "future prospects". The articles included in this review were primarily chosen based on the relevance of their titles and abstracts of the research topic.

The inclusion criteria for this review encompassed studies that specifically investigated the role of PGPR in heavy metal decontamination through plants to maintain environmental sustainability. Papers that did not have importance of PGPR in phytoremediation in their abstract, introduction or conclusion were eliminated in the eligibility stage. Conversely, the exclusion criteria entailed articles that provided other use of PGPR in reducing environmental pollution rather than main focus on phytoremediation, articles not in the English language, those with irrelevant or insufficient data, and articles for which full-text access was unattainable.

We conducted a comprehensive literature search to identify studies that elucidate the potential of PGPR to accelerate the process of phytoremediation. This work presents extensive research on the latest application of PGPR in phytoremediation to maintain agricultural and environmental sustainability. Out of the initially identified 187 articles, a total of 129 relevant articles were included in this review. The objective of this review is to consolidate and present all available information on the discussed topic in one accessible article, facilitating future research efforts by other scholars. To address the existing knowledge gap in this field, we included studies spanning from 1994 to 2024, encompassing both recent and historical research.

3 Heavy metals and their properties

Generally speaking, metals with atomic weights higher than iron are referred to as heavy metals. Heavy metals are defined as metallic elements with a density > 5 g/cm^3, which have a relatively high density compared with water. In addition, some other heavy metals, including lead (Pb), mercury (Hg), and cadmium (Cd), which are called non-essential elements, are considered exogenous, and they are able to induce toxicity at low levels of exposure. In the natural world, heavy metals are classified into two classes and are typically non-biodegradable. The first category includes toxic metals, such as Pb, Cd, and As, among others, which are harmful in all quantities and undesirable. They also don't have any biological advantages for human health. The second category consists of important metals, such as Cu, Zn, Mn, Fe, Ni, and Cr, among others. Properties of heavy metal are given in Table 1. These elements are beneficial to human health biologically at low concentrations, but turn hazardous at large ones [26].

4 Sources of heavy metals

Several studies have found that anthropogenic activities including fossil refinement burning, mining and smelting, urban waste disposal, irrigation, pesticides, and fertilization all contribute considerably to the increase in soil heavy metal concentrations. Figure 1 displays the main sources of metals [28–31]. Inorganic fertilizers, sludge, liming, and drainage are primarily responsible for the presence of heavy metals in soils [32]. According to Toth et al. [32], inorganic fertilizers, phosphate fertilization, and fungicides contribute to the varied concentrations of Cr, Ni, Pb, Cd, and Zn in soil. Negrete et al. [33] found that contamination by heavy metals is not restricted to one pesticide.

Table 1 Properties of heavy metals (Adopted from Chawla and Chawla [27])

Physical Properties	Heavy metals
Density	Usually higher
Hardness	Most are quite hard
Thermal expansivity	Mostly lower
Melting point	Low to very high
Tensile strength	Mostly higher
Chemical properties	**Heavy metals**
Periodic table location	Nearly all found in group 3 through 16
Abundance in Earth's crust	Less abundant
Source	Lithophiles or chalcophiles (Au is a siderophile)
Reactivity	Less reactive
Sulfides	Extremely insoluble
Hydroxides	Generally insoluble
Salts	Mostly form coloured solutions in water
Complexes	Mostly coloured
Biological role	Include micronutrients

Fig. 1 Sources of heavy metal in terrestrial soil

Farmers are generally not concerned about environmental hazards or benefits but rather are more concerned with exploiting the land to get maximum yield and profits [34]. The concentrations of metals in wastewater discharges are typically low, however, irrigation of farms for long periods with such water can result in the accumulation of heavy metals in the soil [35, 36]. It has been demonstrated that sewage irrigation promotes heavy metal buildup and mobility in soils. The widespread mining and smelting of lead and zinc ore has resulted in severe soil pollution [37]. Aerosols are formed when heavy metal vapors such as Sn, Cu, As, Pb, Zn, and Cd interact with water [31, 32, 38].

Soil contamination is mainly caused by two types of depositing methods; wet depositing (precipitation) and dry depositing (deposited by wind). Smith et al. [39] noted that heavy metals transform into oxides after which they condense as fine particulates in the absence of a reducing atmosphere. Natural air currents frequently disseminate stack emissions across a wide region until they are eliminated from the gas stream by wet and/or dry precipitation processes. Heavy metals are predominantly released by wear on tires, brake linings, road surfaces, and other road-building materials along transportation routes, in addition to exhaust gases [40]. Heavy metal contamination can be found in incinerator effluent, industrial discharges, open pits, landfills, and transportation or traffic emissions [41–44].

5 Toxicity profile of heavy metals on living cells and environment

Ecosystems and the environment are at risk due to the discharge of multiple hazardous substances into natural resources as a result of increased anthropogenic activities. The most significant cause of environmental pollution is heavy metal ions, which are extremely toxic, non-degradable, and have a propensity to bioaccumulate and biomagnify. There are almost always toxic contaminants in the environment, whether they come from manmade industries like mining or unsustainable farming practices, or from natural events like storms, earthquakes, and volcanoes. These days, one of the biggest environmental risks is heavy metal contamination [45].

Contamination of soil with heavy metals would lead to two major problems: a decrease in soil value and an increase in health risks for people living near the affected areas. Soil poisoned by heavy metals loses at least part of its function. If the concentration of heavy metals is within the permissible limits, the soil can continue to function. However, more attention should be paid to the absence of heavy metals in the soil and the target values. Considering the phytotoxicity and biological importance of metal species regulating various plant processes, the term "heavy metal" was introduced. Few metals like Zn, Fe, Cu, Mn, Ni and Co are essential trace elements for plants but others like Hg, Al, Cd, Pb, As, Ga, Ag and Cr are unnecessary for plants and unknown. physiological function. HM critical thresholds and responses at the cellular and whole plant levels are summarized. The overall visual toxicity response varies between heavy metals due to their different sites of action within the plant. The most common visual sign of heavy metal toxicity is impairment of plant development, including leaf chlorosis, necrosis, loss of turgidity, reduced seed germination rate and damage to the photosynthetic machinery, usually associated with senescence or plant disease. The concentration of this element in food varies depending on where it comes from, how it is stored and how it is processed. These metals have several special properties, including (1) they do not degrade over time, (2) they may be necessary or beneficial to plants in certain amounts but may be toxic if levels exceed a certain threshold, (3) they are always present at background levels of non-anthropogenic origin and their entry into soil is related to weathering and pedogenesis of source rocks, and (4) soil heavy metals can become mobile as a result of changing environmental conditions, since they are often cations that interact strongly with soil [45, 46].

They do not break down and accumulate in living beings, causing various diseases and disorders in the neurological, immunological, reproductive and digestive systems. Because these heavy metal ions (HMI) are not biodegradable, they can persist for decades or even centuries after being released into the environment. Pb, Hg, Cd, Cr and As are the most toxic heavy metals. Melanin can protect tissues by filtering or scavenging heavy metals from the surrounding neuronal retina and photoreceptor cells. The choroid plexus of the brain, like the retinal pigment epithelium, binds lead and acts as a protective barrier against harmful substances entering the brain. During pregnancy, potentially dangerous impurities in the blood of a pregnant woman can enter the fetus and cause a threat to the health of the child. Cd, Pb, Mn, and Hg have received much attention due to their ubiquity [47]. Exposure to heavy metals and other pollutants has caused a variety of problems for humans and wildlife, including carcinogenic, mutagenic, and teratogenic effects [48]. Structural abnormalities, nutritional imbalances, metabolic disorders and low levels have been observed in plants grown in polluted areas [49]. In addition, exposure to these hazardous metals has been linked to several serious diseases, including Alzheimer's disease. Because heavy metal exposure is difficult to completely avoid, chemoprevention is an important method to protect humans and animals from serious health problems caused by exposure to toxic metals.

The utility of several antioxidants, including the vitamin taurine, in reducing heavy metal-induced oxidative DNA damage has been investigated [50]. Liquid pollutants can harm human health and the environment. Landfill leachate and mine effluent, along with other sources of toxins, cause serious health and environmental damage. Pb, Cd, Hg and As are the most common heavy metals that can cause health problems with contaminated food. Heavy metals have been used in various situations in human culture for thousands of years. Although the serious health effects of heavy metals have been known for a long time, exposure to heavy metals continues and even increases in some countries. Unfortunately, food and foodstuffs are one of the most common causes of heavy metal contamination in the population [47]. These hazardous heavy metals need to be removed from the environment in order to protect both people and the ecosystem.

6 Plant response to heavy metal toxicity

Depending on the degree of oxidation of heavy metals, plant cells are harmed differently. The two ways in which they induce growth inhibition are either by decreasing the uptake of vital micro-and macro-elements into germinating seeds and interfering with various metabolic pathways, or by downregulating protein synthesis and influencing the activities of key enzymes mobilizing food reserves (protease and a-and b-amylases) from the endosperm of cotyledons. It changes several plant physiological processes at the molecular and cellular levels, including enzyme deactivation and protein and DNA denaturation. It substitutes important metal ions from functional and biomolecule units, causing conformational variations and damage to cell membranes, reducing plant metabolism, respiration, photosynthesis, and key enzymes [44, 51] (Fig. 2).

Furthermore, it disrupts redox homeostasis by producing reactive oxygen species (ROS) and free radicals [52]. As a result of interrelated physiological and molecular mechanisms, some plants have established tolerance mechanisms against heavy metals including minimizing on uptake of heavy metals within the cell [3, 53], immobilization in the wall of the cell, production of antioxidants [54], and phytochelation mechanisms and by sequestration in the cell.

The natural ecosystem contains a number of elements, but due to higher contamination or bioaccumulation than allowed limits, species-specific tolerance (plant, animal, and human) and their interactions with one another in the functioning of various species' living cells determine whether an element is toxic or nontoxic [55]. Both heavy metals and metalloids must be immobilized or physically removed from the soil since they cannot undergo chemical degradation in the soil [37]. Heavy metal-contaminated soils are traditionally excavated and disposed of in landfills. As a result of this method of remediation, heavy metals were removed from one place and disposed of in the adjacent environment. Additionally, soil washing was employed to remove the pollutants, although this method is quite expensive and requires further treatment to remove them. According to Gaur and Adholeya [56], the use of

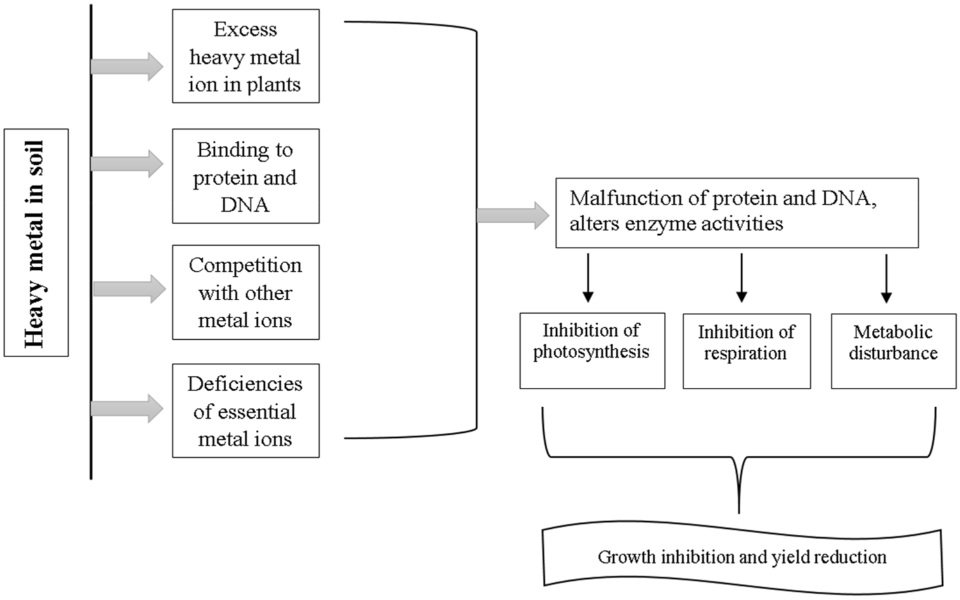

Fig. 2 Effects of heavy metals on plant growth

physiochemical methods in soil remediation alters biological activities of the soil, resulting in land becoming unsuitable for crop production.

During environmental stress, plant antioxidant systems are dramatically altered by the production of ROS molecules, including hydrogen peroxide, hydroxyl radicals, and superoxide radicals, which cause oxidative damage to biomolecules [57]. A variety of non-enzymatic and enzymatic antioxidants are produced by PGPR strains in this situation, thereby reducing ROS formation and protecting the host plant from ROS-induced oxidative effects [58]. For instance, under Ni and Zn stress, Plants inoculated with RP5 exhibit increased glutathione reductase activity [59]. Similarly, superoxide dismutase and catalase production were boosted after P. sp. infection. *Helianthus annuus* and *Solanum lycopersicum* were injected with CPSB21, which reduced ROS production [58, 60]. Plant growth can be enhanced by PGPR strains, which have non-specific mechanisms for promoting plant growth. For example, they make heavy metals less toxic by modulating their bioavailability, regulating phytopathogens, reducing their tolerance to metal stress, and increasing the antioxidant system of plants.

7 Phytoremediation

The term phytoremediation denotes the use of green plants to remove contaminants from polluted environments. Generally, phytoremediation has certain advantages, such as being an autotrophic system with large biomass that only requires a very small amount of fertilizer, being simple to manage, and being generally accepted by society due to its aesthetic appeal and environmental sustainability [61, 62]. The vegetative and reproductive parts of many plant species can accumulate various toxic metals. There are several characteristics of suitable phytoremediation plants, including fast growth with extensive root systems, great biomass production, adaptability, high tolerance, and the capacity to amass pollutants. Plants can be categorized into three classes according to their metal accumulating efficiency and metal tolerance: (1) accumulators (higher metal uptakers and accumulators), (2) indicators (poor metal uptake and transport), and (3) excluders (metal sensitive plants) [63]. Hyperaccumulator plants do accumulate high levels of heavy metals due to their capability to tolerate higher levels of heavy metal concentrations [64]. Nonetheless, the efficacy of a hyperaccumulator is affected by several edaphic factors that influence the rate at which the plant grows, produces biomass, and absorbs metals. In terms of edaphic factors, cation exchange capacity (CEC), metal bioavailability, pH, redox potential, temperature, aeration extent, water content, and organic matter are the most influential [65]. Other biotic factors influence soil nutrients, and reduce phytoremediation efficacy by reducing the growth and uptake of metals [21].

Several processes are involved in the plant's uptake of metals, based on the type of plant and the amount of heavy metals [10]. These processes include uptake, exclusion, translocation, distribution, accumulation, and osmoregulation [66]. Generally, concentration, accumulation, and translocation occur in the aerial parts of plants. The process of metal uptake is initiated by the extraction of metal from soil solutions and their mobilization towards the roots. Additionally, roots can absorb metals by adjoining metal ions to their cell walls and transporting them to the aerial part of the plant [10, 62, 67]. Transporter proteins and the plant vascular system are involved in the transport process. Under aquatic conditions, phytoremediation occurs through direct absorption of wastewater, which is largely determined by the type of hyperaccumulator plants and wastewater level. Aquatic plants absorb metal from contaminated wastewater through passive metal transport, involving adsorption, resulting in the accumulation of metals in aerial parts [10, 68]. Phytoremediation processes are categorized into phytostabilization (reducing metal mobilization by plant activities), phytoextraction (metal assimilation into plant biomass), phytofiltration (absorption and/or adsorption from the aqueous environment of metal pollutants by plant parts) and phytovolatilization (converting some heavy metals into gaseous state that vaporize through the leaves into the atmosphere) [56, 68]. Some plant species demonstrated maximum remediation effectiveness when exposed to slight metal contamination. Heavy metal exposure will result in slow growth and a reduction in biomass production in plants. To minimize these disadvantages, different biological resources could be utilized [69].

In addition to recycling nutrients, controlling disease, maintaining soil structure, and reducing metal toxicity levels, the rhizosphere microbes are among the potential biological resources that can help plants endure elevated metal toxicity and increase the effectiveness of phytoremediation. Additionally, rhizospheric microorganisms possess a unique ability to uptake/reduce/transform heavy metals through the use of various strategies, including biotransformation, biomineralization, biodegradation biovolatilization, bioaccumulation, biosorption, and bioleaching, thereby reducing the toxicity of heavy metals in plants [70].

8 Role of PGPR in phytoremediation

The use of eco-friendly farming techniques can replace the application of chemicals. Using non-environmentally harmful sources of synthetic pesticides and fertilizers allows for the use of reasonable farming techniques [71]. A viable alternative strategy to increase plant growth and yield in a controlled fashion is the introduction of associative bacteria with the capacity to boost plant development [72]. Rhizobacteria that promote plant growth comprise free-living, associative symbioses that coexist with plants in symbiotic relationships (*Frankia* spp. and *Rhizobium* spp.). In the symbiotic relationship between microflora and plants, bacteria consume carbon from the host plant as food and then break down or saturate the pollutant to make it easier for the plant to absorb the released elements by the plants [73, 74]. A surprising fact about symbiosis is that the majority of its energy comes from photosynthesis, which is discharged as exudates from plant roots [75, 76].

Due to the diversity of PGPR, their population may alter as physicochemical conditions in the soil change. According to Zafar-ul-hye et al. [77] and Lynch et al. [76] these bacteria help to lessen the impact of pollution on plants that have fertilizer given to them. The PGPR biofertilizers upsurge the accessibility of nutrients that directly enhance plant development and remediate soils contaminated with trace metals, or they indirectly lessen the inhibitory effects of certain diseases on plants by functioning as tiny biological control entities [78]. Some specific metal peptides that bind to metals are involved in metal chelation or buildup. Nitrogen fixation, phytohormone production (e.g., auxin and cytokinin), and phosphorus solubilization are examples of direct mechanisms used by microorganisms to promote plant growth. Indirect mechanisms comprise the reduction of diseases and the prevention of harmful effects of plant pathogens, besides the removal of toxic metals from soils [79–82].

The ability of PGPR to reproduce and survive in the soil depends on a variety of soil parameters including temperature, pH, texture, nutritional condition, and trace metal concentration. All these factors cause changes in plant development. The inoculation of PGPR is, however, countered by several other factors, such as limited application effectiveness, cell suitability, and the detrimental effects of numerous soil conditions [83]. Besides enhancing plant development, PGPR also affect soil parameters through a variety of methods to reduce soil metal contamination [84]. According to Ma et al. [64] and Sharma and Archana [85], PGPR decreases metal pollution by lowering metal bioaccumulation, precipitation, biosorption, oxidation, complexation, and reduction as well as the change of enzymatic metals. This decreases the metal ions toxicity to not only plants but also to animals. Effects of some PGPR on plants not only in the case of phytoremediation of metals but also in the case of growth and development are summed up in Table 2.

9 Mechanism of phytoremediation by PGPR

The efficiency of PGPR-assisted phytoremediation depends greatly on several factors, which include plant development, rhizospheric activity, heavy metal bioavailability, and metal tolerance. Among these, metal bioavailability and rhizospheric activity have a significant impact on how effectively plants do phytoremediation. Typically, heavy metals found in contaminated environments are bound to various inorganic and organic components, and their bioavailability is directly associated with their chemical speciation [10]. A variety of metabolic compounds are produced by PGPR strains to modify the nature of metals i.e. oxidation–reduction and acidification reactions) and their mobility i.e. chelation, immobilization, and precipitation) at the rhizospheric environment. This increased the effectiveness of phytoextraction, phytostabilization, and phytovolatilization of the plant (Fig. 3).

9.1 PGPR-assisted phytoextraction

Phytoextraction, or the capability of plants to take contaminants up into their roots and transport them to the surface, can be upgraded by changing heavy metal solubility, mobility, bioavailability, and transport by lowering soil pH, demineralization, producing chelators, redox state, and so on [94]. The above parameters are significantly affected by PGPR inoculations due to the production of many metabolic compounds that promote heavy metal buildup. The principal metal chelating agents, known as microbial siderophores, are critical for heavy metal solubilization and conversion into plant-available forms [94]. Mousavi et al. [95] investigated the effect of inoculating *H. annuus* with the *P. fluorescens* and siderophore-producing bacterial strains *B. safensis* FO-036b (T) on growth and metal accumulation. In this case,

Table 2 Recent examples of PGPR-assisted phytoremediation of metal-contaminated soil

Host	PGPR strain	Source	Beneficial features	Effects on plants	Reference
Oryza sativa	*Bacillus* sp. (ZC3-2-1)	The root surface of tall fescue obtained from Tianjin University	Promoting the phytoextraction and immobilization of the metal, maintaining ion homeostasis and regulating endogenous plant hormone concentrations, such as indole acetic acid (IAA)	Enhancement of rice growth and bioremediation efficiency	Liu et al. [86]
	Massilia sp.	The roots of tall fescue grown in plastic-contaminated soil in Nankai District, Tianjin	Regulation of photosynthesis, ion homeostasis and endogenous plant hormone concentrations, such as indole acetic acid (IAA)	Enhancement of the shoot height, biomass of the plant and bioremediation efficiency	Liu et al. [87]
Acacia sp.	*Bacillus amyloliquefaciens*	E-waste site, Bangkok, Thailand	IAA, Siderophore	Promote plant growth and improve the uptake of Ni	Joradon et al. [88]
Brassica juncea	*Bacillus* sp. Kz5 and *Enterobacter* sp. Kz15	Rizosphere of plants grown in copper-mine soils, China	IAA, Siderophore, phytoextraction	Enhancement of the biomass, root morphology, photosynthetic activity, and rhizosphere soil properties	Zhang et al. [89]
	Klebsiella variicola and *Pseudomonas otitidis*	The root surface of *B. juncea* seedlings, Gujrat, India	Siderophore, IAA, phytoextraction	Enhancement of vegetative growth and metal accumulation	Sharma et al. [90]
Calendula officinalis	*Burkholderia cepacia* CS8	Rhizospheric soil, Pakistan	IAA, siderophore	Enhancement of Plant biomass, chlorophyll content, antioxidant enzyme activities and phytoextraction	Khan et al. [91]
Phoenix dactylifera L	*Exiguobacterium* TNDT2	Indian date palm rhizosphere	Siderophore, IAA	influence date palm's growth traits, notably the root length, root fresh weight, shoot height, as well as shoot fresh weight, translocation and uptake (Phytoextraction)	Akensous et al. [35]
Sorghum bicolor	*Brachybacterium muris* and *Micrococcus yunnanensis*	petroleum-polluted soil, Iran	Siderophore, IAA	Growth increment (height, fresh and dry weight) and bioaugmented bioremediation	Koohkan et al. [92]
Triticum aestivum	*Paraclostridium* sp. DLY7	oil contaminated soil	Siderophore, IAA	Growth increment (height, fresh and dry weight), reduce the stress of pollutants on plants	Chen et al. [93]
Zea mays	*Paraclostridium* sp. DLY7	oil contaminated soil	Siderophore, IAA	Growth increment (height, fresh and dry weight), reduce the stress of pollutants on plants	Chen et al. [93]

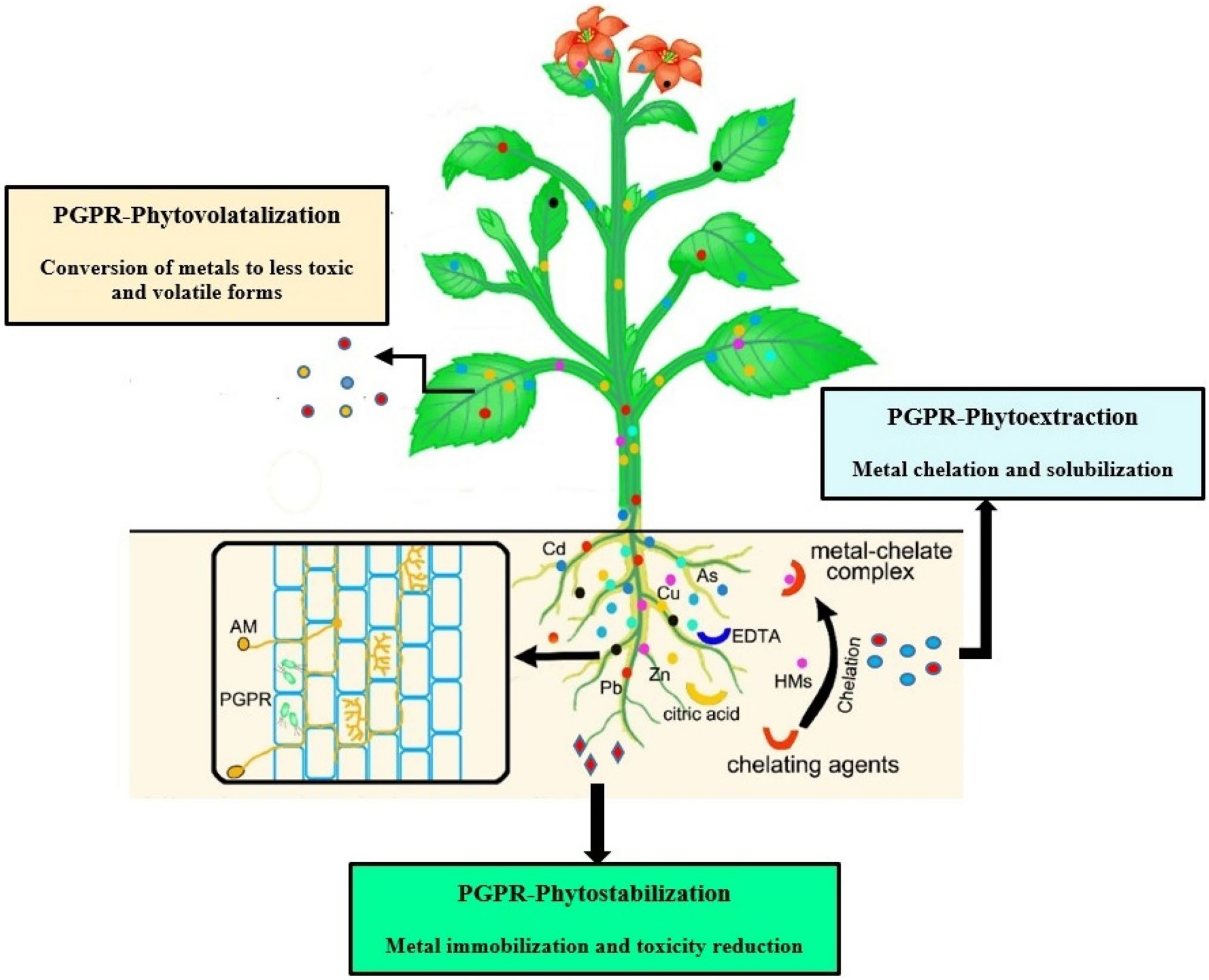

Fig. 3 PGPR assisted phytoremediation of heavy metal contaminated soil

inoculation with microbes solubilizes and upsurges Pb and Zn accumulation. Mishra et al. [96] and Ali et al. [97] discovered that inoculating PGPR strains that generate siderophores dramatically boosted the buildup of Fe, Pb, and Zn in the corresponding host plants. In addition, PGPR strains generated a variety of organic acids of low molecular weight including oxalic, 2-ketoglutaric, succinic, gluconic, citric, and malic. Among these, oxalic and citric acids stand out for their significant contributions to the complexation reduction process, which leads to metal solubilization and mobility [98]. Microbial biosurfactants have an important role in controlling the bioavailability and mobility of heavy metals to plant roots. *Acinetobacter* strains (apoemulson, alasan, emulsan, and biodispersan), *Serratia* (a cyclic lipopeptide biosurfactant serrawettin), *Bacillus* (surfactin), and *Pseudomonas* (glycolipid biosurfactant) are the most important PGPR species for biosurfactant production. The interaction and complex formation of secreted biosurfactants with insoluble metals at the interface of rhizosphere soil particles causes a change in the mobility of metals in soil solution [84, 98]. In addition to biosurfactants, bioleaching is an essential feature of PGPR strains because it aids in the mobilization of heavy metals from mineral resources. As a result, rhizobacterial inoculations increase metal bioavailability in contaminated soils for plant uptake. Table 3 shows the effects of PGPR inoculation on plant heavy metal phytoextraction efficacy.

9.2 PGPR-assisted phytostabilization

Some PGPR strains can inhibit the accumulation and mobilization of heavy metals by developing several distinct processes, including bioaccumulation, biotransformation, adsorption, biosorption, complexation, precipitation, and

Table 3 PGPR assisted phytoextraction of heavy metals

PGPR strains	PGP activities of the strains	Hyperaccumulator plants	Phytoaccumulation of heavy metals	Reference
Pseudomonas aeruginosa	IAA, Siderophores	*Lolium multiflorum*	Cd	Shi et al. [99]
Bacillus sp. (ZC3-2-1)	IAA, Siderophores	*Oryza sativa*	Cd, Zn	Liu et al. [86]
Azotobacter chroococcum, Bacillus subtilis	IAA, Siderophores	*H. annuus*	Cd	Abeed et al.[100]
Brucella intermedium (E1) and *Bacillus velezensis* (EW8)	IAA, Siderophores	*H. annuus*	Ni, Cd	Kriti et al.[101]
Agrococus terreus	IAA, siderophores	*Zea mays*	Zn, Ni	Shahzad et al.[102]
Pantoea conspicua	IAA, siderophores, EPS	*H. annuus*	As	Quadir et al. [103]
Bacillus thuringiensis SE1C2	Siderophore, IAA	*S. bicolor*	Cd, Zn	Anbuganesan et al. [104]
Bacillus pumilus MB246, *Serratia nematodiphila* MB307 *and Delftia Lacustris* MB322	IAA, siderophore	*Vigna radiata*	Pb, Ni, Cr	Zulfiqar et al. [105]
Pseudomonas sp. W112	IAA, siderophore	*Triticum aestivum*	Cd	Guo et al. [106]
Bacillus cereus	IAA, siderophore	*Triticum aestivum*	Cd	Direk et al. [107]

alkalization. According to Sessitsch et al. [108], extracellular capsules (EPS), carboxyl, sulfhydryl, hydroxyl, amide, sulfonate, and amine groups on the surface of bacterial cells have a momentous role in the adsorption and immobilization of heavy metals. Heavy metals with cationic charges could be easily captured by anionic-charged bacterial EPS molecules. The microbial EPS has a general negative charge thanks to functional groups like phosphate, amine, carboxyl, sulfhydryl, and hydroxyl [109]. As pointed out by Wang et al. [110], these functional groups have a significant part in the adsorption of cationic-charged heavy metals, reducing heavy metal availability and mobility in the rhizosphere. As observed by Mukherjee and Sinha [111], adsorption of heavy metals by bacterial cell wall components in *Hordeum vulgare* was associated with reduced Cd accumulation.

PGPR might decrease metal mobility by employing bioaccumulation and biosorption approaches [22, 109]. Microorganisms can absorb heavy metals via metabolism-independent passive transport or metabolism-dependent active transport [109, 112]. Metals are immobilized by several microbial mechanisms following biosorption, including transformation, accumulation, precipitation, sequestration, and accumulation [64]. Furthermore, microbial reduction and/or oxidation processes change the ionic state of heavy metals (Mn, Cr, Fe, Hg, and Se), transforming the hazardous mobile form to a less hazardous immobile form [22, 64, 113]. Karthik et al. [109] reported the biotransformation and immobilization of Cr(VI) by rhizobacterial strain. The four primary processes in this immobilization and biotransformation are Cr (VI) biosorption and interaction by cell surface functional groups, Cr(VI) transport to cytosolic solution by phosphate/sulfate transporters, Cr(III) immobilization, and Cr(VI) reduction in cytosolic solution. *Serratia* sp uses a variety of processes to decrease Cr(VI) and immobilize reduced organo-Cr(III), according to Srivastava and Thakur [54]. These mechanisms include precipitation, ion exchange, complexation, and immobilization. *Stenotrophomonas maltophilia* strain has been revealed to have the ability to reduce and immobilize Se [114]. These microbial activities have a significant influence on metal and semi-metal toxicity and mobilization, transforming dangerous metals into lesser toxic forms and rendering them inaccessible to the plant root. According to Chatterjee et al. [115], inoculating the chili plant with the *Cellulosimicrobium cellulans* KUCr$_3$ strain decreased Cr buildup by 57 and 37% in the root and shoot tissues, respectively. Table 4 summarizes the influence of heavy metal-resistant PGPR strains on heavy metal buildup in plants.

9.3 PGPR-assisted phytovolatilization

The phytovolatilization of heavy metals is greatly affected by PGPR inoculation, much like phytoextraction and phytostabilization. For example, a PGPR strain that was resistant to mercury produced the organomercurial lyase enzymes that are encoded by the MerB gene and cleave organomercurials into mercury-based (HgII) ions [127, 128]. Silver and Hobman [129] discovered in a separate investigation that the MerA gene in microorganisms encodes mercuric reductase, an intracellular flavoenzyme that is responsible for converting harmful ionic mercury dioxide (Hg) into less dangerous volatile mercury (0). These microbial mechanisms considerably reduce the toxicity of Hg and boost the efficacy of phytovolatilization. Various studies put such microbial genes into the plant system and then analyzed the improved phytovolatilization efficacy of Hg [105].

10 Disadvantages of PGPR-assisted phytoremediation

There are some disadvantages associated with using PGPR for heavy metal decontamination:

a. Where the concentration of metals is significantly elevated, the effectiveness of bioremediation from heavy metal-contaminated soil is limited.
b. Because it is impossible to destroy every metal completely and quickly, this procedure is susceptible. Only biodegradable metals can be treated using the bioremediation technique.
c. Compared to other physical and chemical methods, bioremediation procedures require a lot more time.
d. Not all contaminants are eliminated from the contaminated sites.
e. Bioremediation procedures are often accurate; they require the right amount of pollutants and nutrients, the right kind of habitat, and a capable microbial population.
f. The byproduct of heavy metal biodegradation may be more dangerous than the original contaminants.
g. Nevertheless, because microorganisms need energy to survive in the soil, the breakdown of contaminants by them can also result in complex processes. Simultaneously, the chemicals are required for microbial activity, which promotes the growth of some germs but may disturb other native microorganisms that are already present.

Table 4 PGPR assisted phytostabilization of heavy metals

PGPR strains	PGP activities of the strains	Test crops	Phytostabilization of heavy metals	Reference
Bacillus subtilis	IAA, Siderophore	*Lolium perenne*	Cd	Li et al. [116]
Pseudomonas sp.	IAA, Siderophore, HCN	*Brassica napus*	Cd	Saha and Pal [117]
Pseudomonas sp.	N fixation P solubilization IAA production Siderophores	*Medicago sativa*	Cr(Pyrene)	Tirry et al. [118]
Bacillus sp. EhS7, *Acinetobacter* RA1, *Bacillus* RA2	IAA production P solubilization	Perennial ryegrass, Tall fescue	Cu, Cd	Ke et al. [119]
Serratia sp. AI001, *Klebsiella* sp. AI002	IAA	*Solanum nigrum*	Cd	Ullah et al. [98]
Bacillus pumilus	IAA, siderophore, ACCD	*Z. mays* L	Cd	Hayat et al. [120]
Jeotgalicoccus huakuii, *Bacillus amyloliquefaciens*	IAA	*Cynodon dactylon*, *Eleusine indica*	Hg	Ustiatik et al. [121]
PGPE consortium	IAA	Intercropped: *Sedum alfredii*, *Vicia fava*	Cd, Pb	Tang et al. [122]
Pseudomonas aeruginosa	IAA, siderophore, HCN	*Jatropha gossypifolia*	Cd, Pb, Zn, Al	Chi et al. [123]
Bacillus thuringiensis (MW887525), *Bacillus cereus* (MW887524), *Achromobacter denitrificans* (MW886333), *Bacillus subtilis* (MW886231)	IAA, Siderophore	*Cannabis sativa* L	Fe, Cu, Zn, Mn, Pb, Ni, Cd, Cr	Singh et al. [124]
Bacillus sp. ZV6	IAA, Siderophore production	*Salix alba*	Ni	Virk et al. [125]
Pseudomonas sp.	IAA, Siderophore production	*Helianthus annuus*	Pb	Ayub et al. [126]

11 Key issues and challenges of phytoremediation

Phytoremediation is an attractive option for soil heavy metals removal but it also has some issues and challenges, like:

I. A long time (several years) is required for soil remediation.
II. The majority of metal hyperaccumulator plant's low biomass and sluggish development rate typically limit their ability to collect metals by phytoextraction.
III. After phytoextraction, the contaminated biomass must be properly disposed of (as hazardous waste).
IV. In tropical and sub-tropical places where the climate is influenced, pests and disease attacks may weaken and render some plants' ability for accumulation useless.
V. Limited bioavailability of the pollutants in the soil, or difficulty mobilizing a more firmly bound percentage of metal ions from the soil.
VI. As a hyperaccumulator, invasive plant species introduction must be avoided as it may reduce native floral variety.
VII. Soil amendments and agronomic techniques may have a detrimental effect on the mobility of pollutants.
VIII. The weather and climate have a major influence on the sustainability of bioremediation.
IX. When plants grow sustainably in heavily contaminated soil, bioremediation is a viable strategy for areas with low to moderate metal pollution levels.
X. Mishandling of biomass can result in the transmission of accumulated metals into the food chain.

12 Future prospects

According to the explanation above, microbial-aided phytoremediation is a reliable procedure. In addition, numerous topics need greater inquiry because of a lack of knowledge or a lack of clarity. These are as follows:

i. In metal-polluted soils, interactions between microbes and plants have been the subject of a very small number of published investigations. The functional properties of bacterial isolates (i.e., production of several metabolites, biosorption, adapting strategies, metal-resistant, and immobilization/mobilization mechanisms, etc.) can be used to identify the factors influencing bacteria's ability to colonize the interior tissues of the plant and/or rhizosphere, promote plant growth, and facilitate metal uptake. For this strategy to work, the inoculums must colonize effectively and endure harsh conditions.
ii. It is difficult to say if changes in heavy metal speciation mediated by bacteria influenced plant development and metal accumulation/distribution both inside plants and in the rhizosphere.
iii. Additional research is necessary to investigate the mechanisms that are primarily in charge of bacteria-assisted phytoremediation, including the plant root-mediated processes and interactive effects of the PGPR on the mobilization and solubilization of metal ions in soils, because plant-mediated processes, such as phytosiderophores or the exudation of organic acids, may also aid in the sequestration and solubilization of metal ions from soil.
iv. Future studies must focus on understanding the ecology and diversity of plant-associated PGPR in various metal-polluted soils to put these PGPB-assisted phytoremediation into practice. Certainly, a deeper comprehension of the impact of naturally adapted native microorganisms that have been grown and enhanced in the lab on the phytoremediation capacity of different plants in diverse metal-polluted soils will yield better results for developing this technique.

It is still regarded as a relatively new alternative with few long-term field trials, despite having been extensively researched over the past few decades. To fully understand the interactions between microbes and host plants in environments contaminated by metals, more research is necessary.

13 Conclusions

The harmful effects of heavy metals on the biosphere have drawn attention from all around the world to the need to create appropriate methods for eliminating these contaminants from the environment. Despite the development of numerous physiochemical and biological techniques, phytoremediation remains a remarkably dependable and effective method for the removal of metals. The best option for raising the plant's metal removal efficiency is PGPR. Reclamation of metal-contaminated soils using plants and potential PGPR is a practical, low-cost, and developing method that has made significant advancements in in-situ remediation. Through a variety of metabolism-dependent and/or independent actions, PGPR modify the nature of heavy metals, promoting the plant's development and phytoremediation efficacy. Moreover, more research is required to determine how well phytoremediation works in response to abiotic climate change-related challenges like salinity and drought. Delivering "real" results and giving a deeper understanding of the processes involved without moderated factors are two reasons why field trials are so important. Analysis of factors including the host plant species' and inoculant's compatibility as well as the microorganisms' capacity to function and multiply in contaminated soils over extended periods of time must be done in natural field condition. However, inoculation with PGPR and metal-solubilizing microorganisms portends enormous promise for improving the health, biomass yield, and metal accumulation capability of hyperaccumulators as well as raising the availability of target elements.

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