CHAPTER

16 Exploring the genetic diversity and characterization of metal-resistant endophytic bacteria in contaminated sites

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1. Introduction

Most agricultural soils across the world have been contaminated with heavy metals such as cadmium (Cd), arsenic (As), mercury (Hg), lead (Pb), chromium (Cr), and others. Heavy metals in high concentrations are harmful to all living forms, from bacteria to humans (Goyal et al., 2020). When heavy metal concentrations exceed supraoptimal levels for plant normal functioning, they can inhibit plant growth and agricultural output (Tiwari & Lata, 2018). Heavy metal concentrations in soils have grown globally as a result of historical industrialization or from geogenic causes (Adriano, 2001). In plant cells, a high concentration of bioavailable heavy metals produces free radicals and reactive oxygen species (ROS). This is followed by uncontrolled oxidation and the start of a chain reaction involving cellular biomolecules such as nucleic acids, proteins, and lipids, resulting in oxidative stress and cellular damage. As a result, sensitive plants growing in heavy metal-contaminated areas exhibit altered metabolism, decreased nutritional value, decreased photosynthesis, decreased growth, decreased biomass production, and decreased yield (Kiran et al., 2022). To evade the consequences of heavy metal toxicity, tolerant plants have evolved a number of mechanisms that activate when exposed to heavy metals. Sequestration/buildup of toxic heavy metals in a cellular compartment such as vacuole or apoplast, and detoxification, that is, conversion into nontoxic forms, are the two primary strategies for heavy metal tolerance (Goyal et al., 2020). In this chapter, we summarized the negative impacts of heavy metals on plants' morphology, seed germination, and plant development, as well as the effects of heavy metals on people, which eventually affects human health.

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2. Effect of heavy metals on plant growth

Heavy metals that are accessible for plant absorption include those that are present in the soil solution as soluble components or that are easily solubilized by root exudates (Blaylock & Huang, 2000). Although some heavy metals are required for plant development and maintenance, excessive levels of these metals can be hazardous to plants. Plants' capacity to amass necessary metals also allows them to acquire nonessential metals (Djingova & Kuleff, 2000). Because metals cannot be broken down, when concentrations inside the plant surpass ideal levels, they have both direct and indirect effects on the plant (Chibuike & Obiora, 2014). Because of their existence in the soil environment, these heavy metals are also known as trace elements (10 mg/kg or mg/L in soil/aquatic medium) or ultra-trace elements (1 μg/kg or μg/L in soil/aquatic medium). In addition to these essential trace elements, another category of heavy metals, Class B metals, which are considered nonessential trace elements such as Hg, Ag, Pb, and Ni, etc., are extremely toxic in nature because they play no beneficial role in plant growth; adverse effects have been recorded at very low concentrations of these metals in the growth medium (Kumar et al., 2019). Other metals that are favorable to plants may benefit from "small" concentrations of these metals in the soil, which may boost plant growth and development. Plant growth has been shown to be reduced at greater concentrations of these metals (Chibuike & Obiora, 2014). Certain heavy metals are toxic to the growth, biochemistry, and physiology of various plants (Table 16.1).

Excessive heavy metal release into the environment causes plants to evolve various mechanisms to deal with their detrimental effects (Franco-Franklin et al., 2021). A study of plant responses and tolerance discovered that heavy metal stress induces the expression of many genes. Heavy metals stimulate a variety of signaling pathways in plants, including calcium-dependent signaling, mitogen-activated protein kinase (MAPK) signaling, ROS signaling, and phytohormonal response (Dutta et al., 2018).

3. Bacterial endophytes

Plants naturally communicate with a wide range of microorganisms in a variety of ways. Endophytic bacteria are bacteria that colonize the internal tissue of plants with no visible signs of illness or detrimental influence on the host (Pavithra et al., 2021; Schulz & Boyle, 2006). Endophytic bacteria can promote plant growth through a variety of mechanisms, including indole-3-acetic acid (IAA) synthesis, phosphate solubilization activity, siderophore production under Fe-limiting conditions, improved mineral nutrient uptake by plants, and nitrogen fixation activity (Ryan et al., 2008). Endophytic bacteria can stimulate plant host development even in the presence of abiotic stress (Das et al., 2021; Franco-Franklin et al., 2021).

Bacteria in serpentine soil and their interactions with hyperaccumulating plants have piqued the interest of several researchers due to biotechnological applications for bioremediation and studying the composition of bacterial communities living in a naturally contaminated environment (Pavithra et al., 2020). Bacterial endophytes have been identified from a variety of plant species, and in certain situations, they may boost plant development or give increased tolerance to biotic and abiotic stressors such as heavy metals. Furthermore, endophytic bacteria can be genetically engineered to provide the host plant with additional capacities for phytoremediation. Endophytes describe an appealing and

Table 16.1 Toxicity of certain heavy metals to the growth, biochemistry, and physiology of various plants.

Heavy metal	Plant	The toxic effect on plant	References
Al	Mouse-ear cress, *Arabidopsis thaliana*	Growth inhibition; ROS increase; lipid peroxidation	Kochian et al. (2015), Reyna-Llorens et al. (2015)
As	Canola (*Brassica napus*)	Stunted growth; chlorosis; wilting	Cox et al. (1996)
	Mung bean (*Vigna radiata*)	Inhibition of germination, root growth, and cell division	Mumthas et al. (2010)
	Rice (*Oryza sativa*)	Reduction in seed germination; decrease in seedling height; reduced leaf area and dry matter production	Marin et al. (1993), Abedin et al. (2002)
	Tomato (*Lycopersicon esculentum*)	Reduced fruit yield; decrease in leaf fresh weight	Barrachina et al. (1995)
Co	Tomato (*Lycopersicon esculentum*)	Reduction in plant nutrient content	Jayakumar et al. (2013)
	Mung bean (*Vigna radiata*)	Reduction in antioxidant enzyme activities; decrease in plant sugar, starch, amino acids, and protein content	Jayakumar et al. (2008)
	Radish (*Raphanus sativus*)	Reduction in shoot length, root length, and total leaf area; decrease in chlorophyll content; reduction in plant nutrient content and antioxidant enzyme activity; decrease in plant sugar, amino acid, and protein content	Jayakumar et al. (2007)
Cd	Wheat (*Triticum* sp.)	Reduction in seed germination; decrease in plant nutrient content; reduced shoot and root length	Ahmad et al. (2012), Yourtchi and Bayat (2013)
	Garlic (*Allium sativum*)	Reduced shoot growth; Cd accumulation	Jiang et al. (2001)
	Maize (*Zea mays*)	Reduced shoot growth; inhibition of root growth	Wang et al. (2007)
Cr	Wheat (*Triticum* sp.)		

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Table 16.1 Toxicity of certain heavy metals to the growth, biochemistry, and physiology of various plants.—cont'd

Heavy metal	Plant	The toxic effect on plant	References
		Reduced shoot and root growth	Sharma and Sharma (1993), Panda and Patra (2000)
	Tomato (*Lycopersicon esculentum*)	Decrease in plant nutrient acquisition	Moral et al. (1995), Moral et al. (1996)
	Onion (*Allium cepa*)	Inhibition of germination process; reduction of plant	Nematshahi et al. (2012)
Cu	Bean (*Phaseolus vulgaris*)	Accumulation of Cu in plant roots; root malformation and reduction	Cook et al. (1998)
	Black bindweed (*Polygonum convolvulus*)	Plant mortality; reduced biomass and seed production	Kjær and Elmegaard (1996)
	Rhodes grass (*Chloris gayana*)	Root growth reduction	Sheldon and Menzies (2005)
Hg	Rice (*Oryza sativa*)	Decrease in plant height; reduced tiller and panicle formation; yield reduction; bioaccumulation in shoot and root of seedlings	Du (2005), Kibra (2008)
	Tomato (*Lycopersicon esculentum*)	Reduction in germination percentage; reduced plant height; reduction in flowering and fruit weight; chlorosis	Shekar et al. (2011)
Mn	Broad bean (*Vicia faba*)	Mn accumulation shoot and root; reduction in shoot and root length; chlorosis	Arya and Roy (2011)
	Cucumber (*Cucumis sativus*)	Chlorosis, necrosis, inhibition of growth	Dragišić Maksimović et al. (2012)
	Mung bean (*Vigna radiata*)	Reduction in germination, growth, and chromosome length	Mumthas et al. (2010)
	Pea (*Pisum sativum*)	Reduction in chlorophylls *a* and *b* content; reduction in relative growth rate;	Doncheva et al. (2005)

Table 16.1 Toxicity of certain heavy metals to the growth, biochemistry, and physiology of various plants.—cont'd

Heavy metal	Plant	The toxic effect on plant	References
		reduced photosynthetic O_2 evolution activity and photosystem II activity	
	Spearmint (*Mentha spicata*)	Decrease in chlorophyll-a and carotenoid content; accumulation of Mn in plant roots	Asrar et al. (2005)
	Tomato (*Lycopersicon esculentum*)	Slower plant growth; decrease in chlorophyll concentration	Shenker et al. (2004)
Ni	Pigeon pea (*Cajanus cajan*)	Decrease in chlorophyll content and stomatal conductance; decreased enzyme activity which affected Calvin cycle and CO_2 fixation	Sheoran et al. (1990)
	Rye grass (*Lolium perenne*)	Reduction in plant nutrient acquisition; decrease in shoot yield; chlorosis	Khalid and Tinsley (1980)
	Wheat (*Triticum* sp.)	Reduction in plant nutrient acquisition	Pandolfini et al. (1992), Barsukova and Gamzatova (1999)
	Rice (*Oryza sativa*)	Inhibition of root growth	Lin and Kao (2006)
Pb	Maize (*Zea mays*)	Reduction in germination percentage; suppressed growth; reduced plant biomass; decrease in plant protein content	Hussain et al. (2013)
	Portia tree (*Thespesia populnea*)	Reduction in the number of leaves and leaf area; reduced plant height; decrease in plant biomass	Kabir et al. (2010)
	Oat (*Avena sativa*)	Inhibition of enzyme activity which affected CO_2 fixation	Moustakas et al., 1994
Zn	Cluster bean (*Cyamopsis tetragonoloba*)	Reduction in germination percentage; reduced plant height and biomass; decrease in	Manivasagaperumal et al. (2011)

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Table 16.1 Toxicity of certain heavy metals to the growth, biochemistry, and physiology of various plants.—cont'd

Heavy metal	Plant	The toxic effect on plant	References
		chlorophyll, carotenoid, sugar, starch, and amino acid content	
	Pea (*Pisum sativum*)	Reduction in chlorophyll content; alteration in structure of chloroplast; reduction in photosystem II activity; reduced plant growth	Doncheva et al. (2001)
	Ryegrass (*Lolium perenne*)	Accumulation of Zn in plant leaves; growth reduction; decrease in plant nutrient content; reduced efficiency of photosynthetic energy	Bonnet et al. (2000)

long-term bio-based method for increasing agricultural yield and tolerance to environmental challenges (Tiwari, 2022). As highlighted in major research (Nguyen & Phan, 2023; Tiwari et al., 2023), bacterial and fungal endophytes have exhibited favorable effects in addressing HM contamination and enhancing plant tolerance for greater adaptation and survival.

4. Arsenic contamination

From the 1890s until the 1970s, agricultural applications of arsenate-based pesticides left substantial acreage of As residues, notably on land utilized for apple, potato, and blueberry crops. Arsenate was used at rates of up to 80 kg per ha in most fruit orchards until pesticides like DDT (dichlorodiphenyl-trichloroethane) were introduced in the late 1940s, resulting in widespread pollution. As-polluted soils in large regions and tiny localized areas are difficult and expensive to treat using traditional methods. Endophytic bacteria and fungi that colonize certain plants have been demonstrated to improve plant nutrient utilization, boost disease resistance, and promote the degradation of soil and water pollutants such as trichloroethylene (TCE) and polycyclic aromatic hydrocarbons (PAHs). Plant growth was hampered by high As concentrations in the soil. A high concentration of As in the soil typically interferes with the normal absorption of nutrients such as P and Fe, hindering plant development. When compared to nontreated plants, inoculation with endophytic bacteria had a greater favorable effect on the number of nodules, shoot, and root biomass. This phenomenon may occur as a result of their capacity to solubilize phosphate, produce siderophores, and/or fix nitrogen to create an appropriate form of P, Fe, and N, so encouraging plant development. Many nonrhizobial bacteria have been shown to fix nitrogen and generate nitrogen-fixing nodules on legume roots (Martinez-Hidalgo & Hirsch, 2017).

Proteobacteria, *Actinobacteria*, *Acinetobacter*, *Burkholderiales*, *Flavobacterium*, *Pseudomonas*, *Rahnella*, and *Firmicutes* were identified based on 16S rRNA gene sequence analysis of typical endophytic bacterial isolates utilized against As (Tashan et al., 2021). *Agrobacterium*, *Stenotrophomonas*, *Pseudomonas*, *Rhodococcus*, and *Bacillus* were the most common genera discovered. The bacteria with the highest arsenite resistance (minimum inhibitory concentration >45 mM) belonged to the genera *Agrobacterium* and *Bacillus*. The strains with high As tolerance also produced a lot of IAA (Gu et al., 2018).

5. Lead and cadmium contamination

Pb and Cd are two heavy metals that are widely employed in industrial processes; therefore, their ambient levels have risen significantly (Kumar, Subrahmanyam, et al., 2021; Kumar, Tripti, et al., 2021). They have no useful role in biological systems and, even at low concentrations, are highly harmful to living organisms. Pollution from Pb and Cd is a big problem across the world since they are stable, persistent, and cannot be biodegraded. As a result, they accumulate in many crops and enter the food chain, producing chronic and acute diseases in people (Tchounwou et al., 2012). To lower Pb and Cd concentrations in the environment and thereby avoid adverse impacts on human health and ecosystems, physicochemical approaches have been developed. Despite their efficiency, most are costly, inefficient, and environmentally unfriendly. Phytoremediation is an environmentally beneficial approach that removes Pb and Cd from soil and water using plant species and other endophytic bacteria (Fan et al., 2020; Rubio-Santiago et al., 2023).

Bacillus megaterium is a gram-positive soil bacterium with considerable potential for phytoremediation of metal-polluted areas (Esringüa et al., 2014). Li et al. (2017) revealed that a hybrid *Pennisetum* with endophytic *B. megaterium* H3 may be used for biomass production and Cd phytostabilization at various degrees of Cd contamination in aquatic settings (Saleem et al., 2007). And it was discovered that *B. megaterium* might promote Cd accumulation in plants by minimizing the detrimental impacts of heavy metals (Esringüa et al., 2014). *Pseudomonas aeruginosa* biosorption of Pb and Cd in aqueous solution was previously reported (Chang et al., 1997). *P. aeruginosa* strain ASU6a was discovered to immobilize lead [Pb^{2+}] via cell surface carbonyl, phosphate, hydroxyl, and amino groups (Gabr et al., 2008). Another study discovered that amide and sulfonamide groups, as well as carboxyl and hydroxyl groups on the cell surface of "*Bacillus* sp. ATS-2" may bind Pb2+ (Abuk et al., 2006). Similar results were obtained when *Saccharomyces cerevisiae* was used to immobilize Pb2+ (Abuk et al., 2007). The primary Pb concentration and pH have a considerable influence on the adsorption capacity of Pb2+ on the cell surface. Metal biosorption is enhanced with increasing pH from 2 to 6 in research with *Pseudomonas pseudoalcaligenes* and *Micrococcus luteus* (Leung et al., 2000). The maximum absorption capacity was observed at pH 5 with an initial metal content of 100 mg L^{-1}. Pb-resistant *P. aeruginosa* strain 4 EA isolated from vehicle battery waste has been shown to survive 0.8 mM Pb nitrate by considerable Pb biosorption (11% by weight) on cell (Naik & Dubey, 2011). Muñoz et al. (2015) discovered that the bacterial isolate *Klebsiella* sp. 3S1 is very efficient in Pb absorption via biosorption and might be employed as an inexpensive biosorbent for Pb-contaminated soil reclamation. Rahman et al. (2019) discovered that a Pb-resistant bacterium, *Staphylococcus hominis* strain AMB-2, isolated from an industrial environment, demonstrated considerable Pb and Cd biosorption from an aqueous medium. Chen et al. (2019) identified a Pb-binding flagellin protein (a protein rich in carbonyl-containing amino acids) produced by *Enterobacteriaceae Serratia* Se1998. The protein has a very high Pb-binding capability and contributes significantly to the microbial molecular process of Pb tolerance and biosorption. These properties of Pb-tolerant bacterial strains imply that they are appropriate instruments for the bioremediation of Pb-contaminated soil or water (Mitra et al., 2021).

6. Copper contamination

Copper is widely utilized, particularly in the metal and metal-related sectors. As a result, it is commonly found in wastewater effluents and receiving bodies of these effluents. It is extremely harmful to soil and water resources. As a result, copper-containing wastewater effluents should be treated properly before being discharged into receiving bodies. The USEPA established a copper discharge limit of 1.3 mg L^{-1} and the WHO established a limit of 2 mg L^{-1} (Al-Saydeh et al., 2017). Despite being an important nutrient, large amounts of copper can be harmful to plants (Fathollahi et al., 2021). In one study, *Leifsonia xyli*, a rhizospheric bacterium, was found to reduce copper metal stress in tomatoes by generating two distinct PGRs, gibberellins and IAA (Kang et al., 2017). *Pantoea* sp. was found in the rhizosphere of *Ziziphus nummularia* synthesizing the ACC deaminase enzyme and relieving copper stress in wheat crops (Singh & Jha, 2018). In another study, the copper-accumulating bacteria *Pseudomonas* sp. were shown to produce ACCD (1-aminocyclopropane-1-carboxylate deaminase) and improve plant development in *Helianthus annuus* L. (Kumar, Subrahmanyam, et al., 2021; Kumar, Tripti, et al., 2021). Similarly, *Acinetobacter* sp. and *Pseudomonas putida*, which produce siderophores, IAA, and phosphorus solubilization, have been found to alleviate copper stress in maize and improve growth by increasing biomass and chlorophyll content (Rojas-Tapias et al., 2014). *Bacillus* sp. and *Streptomyces griseus* showed good biosorption yields, indicating that they might be employed reliably for bioremediation of copper-contaminated wastewaters, according to Özkoç et al. (2022, pp. 1−17). Huo et al. (2012) discovered that inoculating guinea grass with the Cu-resistant endophytic bacteria *Pantoea* sp. Jp3-3 greatly reduced Cu uptake and accumulation during extreme Cu stress. The absorption and accumulation of metals, whether it rises or decreases in the presence of endophytes, is mostly determined by the concentration of metals in the soil (Li et al., 2012).

7. Nickel contamination

Because of its role in plant development and environmental feedback, the bioavailable proportion of nickel (Ni) in the soil is critical. High Ni concentrations in the soil environment, particularly in the root zone, may slow plant development, resulting in lower plant biomass and production. Endophytic microbes, on the other hand, show high potential for reducing Ni toxicity, especially when combined with zeolite (Naveed et al., 2020). However, other researchers believe that the existence of metal-resistant endophytes reduces plant metal absorption and accumulation. Lode-wyckx et al. (2001) discovered that inoculating Ni-resistant *Herbaspirillum seropedicae* into *Lolium perenne* led in a considerable drop in Ni content in the roots (11%) and shoots (14%). Similarly, Madhaiyan et al. (2007) discovered that inoculating tomato plants with the endophytic bacteria *Methylobacterium oryzae* and *Burkholderia* sp. decreased Ni and Cd absorption and accumulation. *Caulobacter* sp. MN13, an endophytic plant growth-promoting endophytic bacteria isolated from surface-disinfected roots of maize plants (Naveed et al., 2014; Prischl et al., 2012), was employed to improve growth, production, and Ni immobilization (Naveed et al., 2020). *Stenotrophomonas* sp., *Pseudomonas* sp., and *Sphingobium* sp., three novel endophytic bacterial species of *Tamarix chinensis*, display numerous plant growth-promoting properties indole acetic acid (IAC), siderophores, and 1-aminocyclopropane (Chen et al., 2020).

8. Chromium contamination

Cr is an essential element for all living things. In recent years, several human activities have been responsible for Cr(VI) pollution of the environment (Murthy et al., 2022). Cr enters the ecosystem as a result of anthropogenic activities such as urbanization, industrialization, and mining (Samuel et al., 2018), all of which contribute to global Cr pollution. It is one of the most dangerous and carcinogenic heavy metals present in the earth's crust (Bhalerao & Sharma, 2015), even at concentrations as low as 0.2 g m^3 (Darakas et al., 2013; Pratush et al., 2018). Although Cr is required in trace levels by all living forms, it is a very deadly contaminant when excessive concentrations enter the food chain (McNeill et al., 2012, p. 36; Shrivastava et al., 2002).

Several remediation solutions for Cr-contaminated sites have been established; they mostly focus on promoting green technologies via different chemical transformations, adsorption, oxidation-precipitation, and oxidation-reduction processes (Jiang et al., 2020). Bacteria operate as phytoremediation promoters by producing IAA, solubilizing phosphate, and producing EPS. The chromate reductase (ChR) gene is found in endophytic bacteria and catalyzes the reduction of Cr(VI) to Cr(III) (Patra et al., 2010). *Agrobacterium rhizogenes* have the ability to collect and decrease heavy metal Cr(VI) while also promoting plant development (Rosariastuti et al., 2013). *Bacillus*, *Pseudomonas*, *Enterobacter*, *Staphylococcus*, *Microbacterium*, and *Arthrobacter* isolated from *Prosopis juliflora* generate supportive chemicals for Cr(VI) phytoremediation, according to Khan et al. (2015). According to Chitraprabha and Sathyavathi (2018), *Enterobacter cloacae* coupled with *Tagetes erecta* can accumulate and decrease Cr(VI). Kumar et al. (2014) isolated *Enterobacter aerogenes* that were resistant to Cr(VI) at concentrations up to 600 mg/L and could generate IAA and solubilize phosphate. Khan et al. (2015) discovered an *Enterobacter* sp. that is resistant to Cr(VI) and can produce phytoremediation-supporting chemicals. Endophytic bacteria that tolerate Cr(VI) have the ChR gene. Wani and Adeosun (2017) discovered that the ChR gene encodes an enzyme that catalyzes the reduction conversion of Cr(VI) to Cr(III). According to Patra et al. (2010), the ChR gene is found in *Arthrobacter aurescens*, *Bacillus atrophaeus*, and *Rhodococcus erythropolis*. *Klebsiella pneumoniae* and *Mangrovibacter yixingensis* both carried a ChR gene, according to Sanjay et al. (2018). Wang et al. (1990) discovered the ChR gene in *Escherichia coli* ATCC 33456, *Ochrobactrum anthtopi*, and *E. cloacae* HO1. By using NAD(P)H extracellular reductase, these bacteria may decrease Cr(VI) aerobically. Endophytic bacteria *Kocuria rhizophila* of *Oxalis corniculata* (hyperaccumulator plant) may accumulate metal ions and have higher resistance to Cr (Haq et al., 2016).

9. Zinc contamination

Zinc (Zn) is involved in several biological activities. It is necessary for macromolecule structural stability and functions as a cofactor for over 300 enzymes (McCall et al., 2000). In excess, however, it may impede the aerobic respiratory chain, be poisonous, and operate as a powerful disruptor of biological systems (Blanco, 2000). Zn concentrations on agricultural land that have reached harmful levels as a result of numerous human activities, such as the application of metal-contaminated sewage sludge or mining operations, may endanger sustainable and high-quality food production (Li & Christie, 2001). *Cupriavidus*, *Klebsiella*, *Serratia*, *Micrococcus*, *Pseudomonas*, *Streptomyces*, *Proteus*, and other Zn-tolerant PGPR strains have been identified (Afzal et al., 2017; Bhojiya and Joshi et al., 2016; Ortiz-Ojeda et al., 2017). *Paenibacillus* sp. RM (Host-*Tridax procumbens*) is a suitable option for Zn bioremediation because of its possible role in encouraging plant growth, secondary metabolite synthesis, and heavy metal bioremediation (Govarthanan et al., 2016). Two symbiotic isolates, *Mesorhizobium loti* and *Agrobacterium radiobacter*, show the best potential for HM resistance and PGP features (Hubber et al., 2007). *Sedum alfredii*'s bacterial endophytes VI8L2, II8L4, and VI8R2 may be one of the finest possibilities for boosting phytoremediation of Zn-contaminated soil due to their innate capacity to enhance plant development (Long et al., 2013).

10. Mercury contamination

Hg is a nonessential metal that is toxic and persistent (Selin, 2014). Few anthropogenic sources of Hg include the production of paints, disinfectants, medicines, pulp and paper, fungicides, and bactericidal agents. Hg is also discharged into the environment as a by-product of Hg mining, gold refining, fuel combustion, and instrument fabrication (Moreno et al., 2008). Hg bioaccumulation and biomagnification in the trophic chain have consequences for society, the environment, and human and animal health (Matulik et al., 2017). Endophytic bacteria *Bacillus amyloliquefaciens* of *Eleusine indica* and *Jeotgalicoccus huakuii* of *Cynodon dactylon* are employed for phytoremediation of Hg-contaminated soil due to their high siderophore synthesis and absence of hemolysis (Ustiatik et al., 2021). To improve growth on Hg-contaminated substances and minimize Hg phytotoxicity, *Acinetobacter baumannii*, *Serratia marcescens*, *Pseudomonas* sp., *K. pneumoniae*, and other Hg-resistant endophytic bacteria were introduced into maize plants (Mello et al., 2020). *Bacillus* sp., *Burkholderia* sp., *Enterobacter* sp., *K. pneumoniae*, *Lysobacter soli*, and *Pantoea* sp. aided maize (*Zea mays*) growth on Hg-supplemented substrates (Mello et al., 2019).

11. Conclusion

In conclusion, utilizing endophytic bacteria to mitigate abiotic stresses caused by environmental variations, physiological changes within plants, and a harmful effect of synthetic fertilizers, pesticides, and heavy metal contamination is essential. The emerging field of bioremediation, which involves using endophytic bacteria to detoxify recalcitrant residues of herbicides, insecticides, synthetic chemicals, and heavy metals, holds great promise. Further research on endophytic bacteria can enhance our understanding of their relationship with host plants and provide new insights into this area of research. To identify the most effective bacterial strains for bioremediation and better comprehend the plant–bacteria relationship, additional studies on the inoculation of effective bacterial strains on various plants are necessary. It is also crucial to investigate the efficiency of individual strains in detoxification and the plant–bacteria relationship of plants growing in metalliferous soils. While genetically engineered microbes may have the potential for bioremediation, their impact on the ecosystem must be evaluated before commercialization.

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