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Plant Growth-Promoting Bacteria as a Natural Resource for Sustainable Rice Production under the Soil Salinity, Wastewater, and Heavy Metal Stress

Raghad S. Mouhamad and Michael Alabboud

Abstract

Rice is a cereal plant that is consumed in a grain form; however, its prolonged contact with irrigation wastewater might pose a threat to the consumers despite the following milling processes to eliminate the grain surface contamination which means that it needs further cooking to be suitable for human use. Additionally, excessive salt levels in wastewater can cause plant toxicity. Therefore, wastewater disposal can be handled by farm remediation. *Rhizobacteria* can also be used in this stressful environment to alleviate the problem by triggering a plant growth-promoting response (PGPR). The importance of promoting and biocontrol plant growth is based upon its long-term stability, as well as the numerous generated secondary metabolites, besides its ability to remove heavy metal. The current study revealed that PGPR allowed such toxic effects on sewage to encourage and define the characteristics of plant growth through urban environments.

**Keywords:** heavy metals, wastewater, PGPR

1. Introduction

1.1 Relationship between PGPB and rice production under nutrient and salinity

As a consequence of the continuous population growth worldwide along with the shortage of food sustainability [1], it is necessary to create an alternative agricultural productivity systems [2, 3]. One of the sustainable alternative strategies is the utilization of plant growth-promoting bacteria (PGPB) in agricultural practices [4]. Promoting plant growth (PGP) has numerous correlation capabilities either by endophyte in plant tissue [5], rhizosphere in seed surface as well as plant root [6], symbiosis in root nodules, and phyllosphere in stem and/or leaf surface (Turner). PGPB involve 1-aminocyclopropane-l-carboxylic acid (ACC) deaminase that is applied to seedling which could effectively stimulate plant growth by reducing plant ethylene rates [7] under drought, salinity [8, 9], flooding, and contaminant condition [10] and increasing phosphate solubility and availability in soil, along with the increase in plant biomass, root area, and total N and P contents in rice [11].

Rice production is reduced under saline agriculture system (**Figure 1**); therefore, it is becoming increasingly important to imply plant growth-promoting traits for mitigation of salt stress [12–14]. Promoting plant growth was shown to enhance growth effectively, and the growth-stimulating effect was also suggested to be beneficial in crop production under stressful conditions. Mechanisms for inducing plant growth-promoting response (PGPR) toward abiotic stress are usually interpreted as the result of certain phytohormone production, including ABA, GA, or IAA, or lower ethylene levels in roots of the ACC, which generates systemic bacterial resistance and enhances exopolysaccharides.

A wide spectrum of endophyte bacteria is well adjusted to the rice niche under abiotic stress condition. The emergence of rice seedlings and growth and development parameters were previously reported to be significantly affected by many PGPR strains [15]. Beneduzi et al. [16] evaluated efficient bioinoculant for rice growth improvement by bacillus strain (SVPR30). Bisht and Mishra [17] reported that rice root length and shoot length increased by 9.7 and 13.9%, respectively, when inoculated with *B. thuringiensis* (VL4C); Nautiyal et al. [18] reported that rice inoculation with *B. amyloliquefaciens* (SN-13) under saline conditions in hydroponic/saline soils has improved stress sensitivity due to an altered transcription of 14 genes, including SERK1, ethylene-responding factor EREBP, NADP-malic enzyme (NADP-Me2), and SOS1. Additionally, downregulated expression of glucose-insensitive growth (IGG) and serine–threonine (Sapk4) protein kinase in
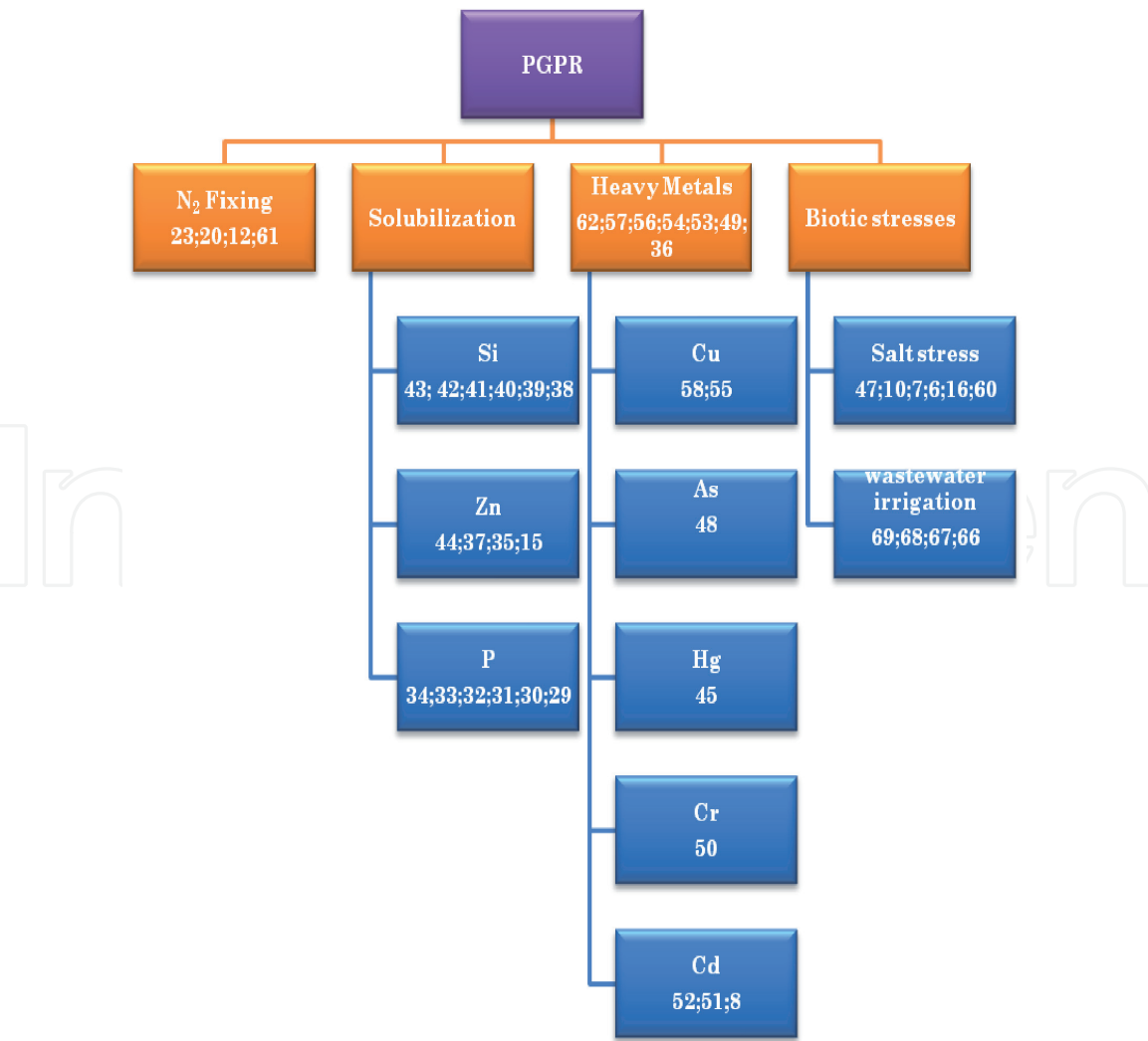
Figure 1.
Schematic description of the different plant promotion processes by PGPR.

the hydroponic setup and upregulated MAPK5 were observed in the greenhouse experiments [19]. The inoculation of SN13 improved the gene transcription involved in the sensitivity of ionic and salt stresses [20]. Endophytic bacteria can give N to rice without loss compared with other bacteria, because of their strong relationship with the plant [21]. Endophytic bacteria are a better N supplier to rice than other bacteria. Endophytic bacteria are the bacteria derived from the plants' inner tissues or extracted from plants with a sterilized layer, which have no infection symptoms [22]. The rice yield achieved by N_2-fixing *Pseudomonas* sp. was improved by 23% by Mäder et al. [23]. Several studies showed significantly greater K, N, and P levels with an increased rice output of 9.2% in co-inoculation with N_2-fixing microbes relative to the use of prescribed amounts of fertilizers as N, P, and K [24, 25]. There have been detailed documentations that rice is generally infected with a large variety of endophytic bacteria (*Azospirillum*, *Herbaspirillum*, *Rhizobium*, *Pantoea*, *Methylobacterium*, and *Burkholderia*, among others) [22]. Diazotrophs colonized effectively in the roots of rice may have a higher N fixation potential [26]. Endorhizosphere bacteria contribute far more than rhizospheric bacteria to N fixation since there is no competition with other rhizospheric microorganisms in the endorhizosphere and under low oxygen; carbon sources are provided [27, 28].

The bacterial IAA was shown in Etesami and Alikhani [29] to have significant roles in improving efficiency in the use of N and in increasing nitrogen-based substances in rice. Estrada et al. [30] also found that diazotrophic P-solubilizing bacteria improved the absorption of nutrients in rice, while Rangjaroen et al. [31] suggested that *Novosphingobium* diazotrophic is an important microbial tool of nitrogen providing for further production which renders it as a healthy biomonitor to improve organic rice cultivation.

De Souza et al. [32] demonstrated the decrease of in vitro phosphate solubility and minimization of acetylene (low reduction in acetylene) in rice shoots by bacteria, including *Herbaspirillum* sp., *Burkholderia* sp., *Pseudacidovorax*, and *Rhizobium* sp. Therefore, non-N_2 fixation growth promotion mechanisms include an IAA development and improved nutrient balanced absorption. Glick [7] shows that if a bacterium is used to produce nitrogen-solubilizing for plants, which have PGP traits (IAA, ACC deaminase, siderophore, and phosphate solubility), it should be used, and the genetic characteristics in plants should be transferred. The application of P fertilizers in rice production has continuously increased [33]. Sahrawat et al. [34] show that the use of rice P fertilizers has been continuously increased since it is one of the key restrictive factors in many regions of the world for the production of upland rice. Othman and Panhwar [35] detected that the sum of nutrition provided by aerobic rice is the same as the flooded rice, but the abundance of P is a challenge due to its immediate immobilizing and fixing with calcium (Ca^{2+}), iron (Fe^{3+}), and aluminum (Al^{3+}) elements. P deficiency in aerobic crops is also widely seen as a phenomenon [36]. The secretion of organic acids and the interaction of mycorrhizal fungi are among these methods that are very weak in rice under flooding conditions. Islam and Hossain [37] have stated that P deficiency is quite normal which increases the demand for mycorrhizal fungal interactions under flood conditions. Panhwar et al. [38] detected that the rice plants need an ancillary structure that quickly goes beyond such degraded regions and receives P for exorbitant neighboring soil composition through the development of a vast network of phosphate-solubilizing bacteria (PSB) which might satisfy some of the nutrient needs.

The growth of many plants including staple rice is hindered by micronutrient-deficient soils [39]. The toxicity of Fe is also important as Fe is one of the major constraints on the production of lowland rice. Furthermore, the scarcity of Mn in upland rice is also commonly seen [40].

A significant increase in the number of tilers provided by plan (15.1%), crop panicles (13.3%), overall grain intake Zn (52.5%), and a modest yield of the dry product by pot (12.9%) has been shown by Vaid et al. [41]. This rise was detected through soil solubilization of insoluble Zn, all of which as a result of the production of bacterial gluconic acid.

Fe, Zn, Cu, and Mn concentrations were increased by 13–16% (*Brevundimonas diminuta* PR7) and in rice co-inoculation (*Providencia* sp. PR3) (*Ochrobactrum anthropi* PR10); Adak et al. [42] detected that Fe absorbance was enhanced by 13–46% using cyanobacterial inoculants and 15–41% in Zn with the use of cyano-bacterial inoculums, in rice cultivation for various modes.

1.2 Relationship between PGPB and rice production under wastewater and heavy metals

Metals as zinc (Zn), molybdenum (Mo), cobalt (Co), chromium (Cr), selenium (Se), copper (Cu), iron (Fe), manganese (Mn), magnesium (Mg), and nickel (Ni) have essential nutrients necessary for a diversity of biological and physiological functions [43]. Biological functions that are not identified are identified as nonessentials: bismuth (Bi), antimony (Sb), platinum (Pt), indium (In), arsenic (As), beryllium (Be), mercury (Hg), barium (Ba), gallium (Ge), gallium (G), gold (Au), lead (Pb), barium (Be), nickel (Ni), silver (Ag), aluminum (Al), as well as uranium (U) [44].

Ma and Takahashi [45] demonstrate that the rice PGPB ability can be used to resolve deficits in micronutrients and to biofertilize (**Table 1** and **Figure 1**). Rice is a plant that accumulates Si and considered an Si accumulator as silicon content in dry weight of the shoots may reach up to 10%, and therefore, the plants require high Si content. Rice is associated with Si depletion in its unit area; due to the removal from the earth of 100 kg of Si for brown rice (about 20 kg/hm^2 SiO$_2$) and exports to the farm by the extraction of straw residues during harvest and the conniving for exogenous use of Si in rice growing, Si in paddy field is available [66].

Bocharnikova et al. [67] and Ning et al. [68] previously reported that Si-deficient paddy soils may be needed to generate an economically sustainable rice crop capable of producing high yield and disease resistance. Si fertilizers are being used for growing rice production in many countries and have positive effects. Vasanthi et al. [69] detected that the *Bacillus globisporus*, *B. crustacea*, *B. flexus*, *B. megaterium*, *Pseudomonas fluorescens*, and *Burkholderia eburnean* can activate K and Si in feldspar, muscovite, and biotite silicate mineral resources. Specific pathways are used to generate disproportionate protons, organic ligand, organic acid, anion, hydroxyl, EPS, and enzymes. However, the solubilizing Si, K, and P in soil might be accompanied by an increased supply of Fe and Mn metals in plants by interacting with P-fixing sites.

Gandhi and Muralidharan [19] show that the rice growth, development, yield, and Zn solubility from ZnO and ZnCO$_3$ to *Acinetobacter* sp. have been greatly increased.

This gene recombination processing was also extended to rice, which produces rice transgenics generated via a partial weapon bombardment containing a 250 lM HgCl$_2$-resistant merA gene [65]. Recently, mercury toxicity has been identified as a triggering factor in aromatic amino acid biosynthesis (tryptophan and phenylalanine), aggregation of calcium, and activation of MAPK in rice [70]. The synthesis and accumulation of the Glybet were stimulated by *Pseudomonas* alkaline inoculation in rice plants [64]. Chakrabarty et al. [63] detected that the As (III)-treated rice seedlings proposed signal transduction regulation and hormonal and crop defense signaling mechanisms (ABA metabolism). Comparative rice-treated transcriptomic study showed explicitly the shifts in plant reaction to metal pressure

Results of bacteria added to plants		References
Mutation	Physicochemical	[3]
PGPR; *Novosphingobium*	Optimize rice cultivation	[31]
Bioindicator	Wastewater irrigation	[43, 44, 46, 47]
Indicators	Sustainable rice cultivation	[2]
Plant microbiome and *Herbaspirillum seropedicae* and *Bacillus amyloliquefaciens*	Plant growth	[1, 4, 5, 11, 18, 28, 48]
Seed endosphere; PGPR and ACC Deaminase and *Corynebacterium* and diazotrophic spp.	Plant growth	[7, 15, 21, 22, 25, 26, 49]
Soil *Rhizobacteria*	Heavy metals	[50–54]
Azospirillum	N_2 fixing	[55]
Arbuscular mycorrhizal symbiosis and *Pseudomonas putida*	Salinity stress; biological control; drought stress	[20, 29, 56, 57]
PGPR	Cu-contaminated	[43, 58]
Exogenous application	Cd-contaminated	[10, 59, 60]
Genomic rice	Cr-contaminated	[61]
Ochrobactrum sp. and *Bacillus* spp. and biofortification	Heavy metals	[40, 62]
	Ar-contaminated	[63]
Endophytic and PGPR and *Bacillus safensis*	Salt stress	[8, 9, 12, 64]
Genetically engineered	Hg	[65]
Acinetobacter sp. and PGPR	Zinc solubilizing	[19, 39, 41]
Bacterial species	Si solubilization	[42, 45, 66–69]
Phosphate-solubilizing bacteria	Phosphate solubilization	[33–38]

Table 1.
Plant growth-promoting Rhizobacteria *used in rice production.*

in the rates of phytohormones: As and Pb resistant by *Bacillus* spp. There are various PGPR features that contribute to the bioremediation and rice cultivar growth promotion; Cd-resistant *Ochrobactrum* sp. was first reported by Pandey et al. [62]. The presence of CDPKs was demonstrated by Cr pressure as their activity increased with increasing Cr (VI) concentration. Huang et al. [61] showed that rice roots have long- and short-term stress transcription profiling. Yeh et al. [59] have demonstrated Cd-induced gene transcription of OsMAPK2 and MBP kinase in rice plant. The activation of heavy metal mediated MAPK by ROS production, build-up, and alteration of the antioxidant system in the rice; ROS is well-rated for its disruption specific pathways such as auxin, ethylene, and jasmonate (JA) phytohormone. However, exposure to JAs has shown that antioxidant reaction has been enhanced due to rice stress sensitivity of Cd [60]. However, an extensive study on heavy metal in plants has shown great interest in the extensive study of the plant microbial-metal relationship due to its direct impact on enhanced production of biomass and improved metal tolerances [50].

Plants have developed a number of defense mechanisms to resist heavy metal stresses and toxicities such as reducing heavy metal consumption, sequestering metal into vacuoles, binding phytochelatins or metallothionein, and antioxidant activation [51]. The toxic substances As, Pb, Cd, and Hg are considered by Disease Registry Agency as the most toxic metals (**Figure 1**) for their toxicity frequency and above all their flora and fauna exposure potential. Pb toxicity leads to ATP

inhibition, lipid peroxidation, and damage to DNA through the production of ROS [43].

In recent decades there has been rapid progress in the area of plant reactions and the tolerance of stress of metal when related bacteria are present with plants. The activation of these genes, which are crucial to heavy metal stress signaling, also suggests dynamic crosspieces of stress and resistance between plant, microbes, and heavy metals [52]. Heavy metal remediation is necessary to protect and preserve the environment. There are only a small number of evidence that heavy metals are remediated by extracellular capsules, heavy metal precipitation, and oxidation reduction [53].

It will be used in the immediate future for remediation of contaminated soils, as shown by the beneficial effects of microbe causes and the planned interconnection between heavy metal resistance and plant growth abilities [58]. Additionally, arbuscular mycorrhizal fungi (AMF) ecological species and ecotypes, metal and edaphic conditions of its availability, and soil and water, including soil fertilizer and requirements of plants for growing under light or root conditions, depend on various factors of exposure to heavy metals in the environment [56].

AMF changes salt stress toxicity. AMF exists due to enhanced mineral nutrition and as a result of various physiological processes such as photosynthesis, water usage efficiency, osmoregulator production, higher K+/Na + ratio, and molecular changes caused by the expression of genes [57].

The synergistic effects on plant growth, particularly in growth restrictions, of the co-inoculation with PGPR and AMF, have shown that the growth responses are significant when rice plants are inoculated with AMF and *Azospirillum*. All of these findings thus show that rice mycorrhization is important [55].

The methods employed by PGPB to promote plant remediation cycle include enhancing plant metal resistance and increasing plant growth as well as altering plant metal accumulation; however, the recent PGPB studies in metal phytoremediation showed that plant inoculation with plant-building bacteria-induced metal phytotoxicity can be alleviated and the production of plant biomass produced in metal-contaminated soils can be strengthened [48, 49, 54]. The reuse of wastewater as a strategy to adjust to climate change is shown in Vietnam. Chung et al. [46] illustrated that rice wastewater effluents can be irrigated for at least 22,719 ha (16% of the urban rice area) in plants annually. Additionally, Jang et al. [47] found that there is no significant environmental risk to rice paddy agroecosystems that were associated with wastewater irrigation (**Table 1** and **Figure 1**).

2. Conclusion

The main limiting factors for cultivation worldwide are water stress conditions [71]. Wastewater water has a negative effect on the production and yield of rice. Selected PGPR might be the perfect candidate for heavy metal pollution and related surface constraints for growth and yields of rice plants irrigated with wastewater as PGPR extracted wastewater strains of bioremediation products show positive results in the literature.

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