We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

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-1-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 N₂-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 N₂-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-N₂ 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 (Ca²⁺), iron (Fe³⁺), and aluminum (Al³⁺) 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 tillers 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 cyanobacterial 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/hm² SiO₂) 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 ZnCO₃ 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 HgCl₂-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; <i>Novosphingobium</i>	Optimize rice cultivation	[31]
Bioindicator	Wastewater irrigation	[43, 44, 46, 47]
Indicators	Sustainable rice cultivation	[2]
Plant microbiome and <i>Herbaspirillum seropedicae</i> and <i>Bacillus amyloliquefaciens</i>	Plant growth	[1, 4, 5, 11, 18, 28, 48]
Seed endosphere; PGPR and ACC Deaminase and <i>Corynebacterium</i> and diazotrophic spp.	Plant growth	[7, 15, 21, 22, 25, 26, 49]
Soil <i>Rhizobacteria</i>	Heavy metals	[50–54]
<i>Azospirillum</i>	N ₂ fixing	[55]
Arbuscular mycorrhizal symbiosis and <i>Pseudomonas putida</i>	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]
<i>Ochrobactrum</i> sp. and <i>Bacillus</i> spp. and biofortification	Heavy metals	[40, 62]
	Ar-contaminated	[63]
Endophytic and PGPR and <i>Bacillus safensis</i>	Salt stress	[8, 9, 12, 64]
Genetically engineered	Hg	[65]
<i>Acinetobacter</i> 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.

IntechOpen

Author details

Raghad S. Mouhamad^{1*} and Michael Alabboud²

1 Department of Soil and Water Resources, Ministry of Science and Technology,
Baghdad, Iraq

2 Department of Horticultural Sciences, UTCAN, University of Tehran, Iran

*Address all correspondence to: raghad1974@yahoo.com

IntechOpen

© 2020 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Kakar K, Xuan TD, Haqani MI, Rayee R, Wafa IK, Abdiani S, et al. Current situation and sustainable development for rice cultivation and production in Afghanistan. *Agriculture*. 2019;**9**:49
- [2] SRP. Performance Indicators for Sustainable Rice Cultivation, Sustainable Rice Platform. Bangkok: SRP; 2015. Available from: <http://www.sustainablerice.org>
- [3] Kakar K, Xuan TD, Quan NV, Wafa IK, Tran H-D, Khanh TD, et al. Efficacy of *N*-methyl-*N*-nitrosourea mutation on physicochemical properties, phytochemicals, and momilactones A and B in Rice. *Sustainability*. 2019;**11**:6862
- [4] Prasad M, Srinivasan R, Chaudhary M, Choudhary M, Jat LK. Plant growth promoting rhizobacteria (PGPR) for sustainable agriculture: Perspectives and challenges. In: *PGPR Amelioration in Sustainable Agriculture*. Woodhead Publishing (Elsevier); 2019. pp. 129-157
- [5] Khare E, Mishra J, Arora NK. Multifaceted interactions between endophytes and plant: Developments and prospects. *Frontiers in Microbiology*. 2018;**9**:2732. DOI: 10.3389/fmicb.2018.02732
- [6] Souza R, de Ambrosini A, Passaglia LMP. Plant growth-promoting bacteria as inoculants in agricultural soils. *Genetics and Molecular Biology*. 2015;**38**:401-419
- [7] Glick BR. Bacteria with ACC deaminase can promote plant growth and help to feed the world. *Microbiological Research*. 2014;**169**:30-39
- [8] Shah G, Jan M, Afreen M, et al. Halophilic bacteria mediated phytoremediation of salt-affected soils cultivated with rice. *Journal of Geochemical Exploration*. 2017;**174**:59-65
- [9] Khan MHU, Khattak JZK, Jamil M, et al. *Bacillus safensis* with plant-derived smoke stimulates rice growth under saline conditions. *Environmental Science and Pollution Research*. 2017;**24**(30):23850-23863
- [10] Jan M, Shah G, Masood S, et al. *Bacillus cereus* enhanced phytoremediation ability of rice seedlings under cadmium toxicity. *BioMed Research International*. 2019;**2019**:12. Article ID 8134651. Available from: <https://doi.org/10.1155/2019/8134651>
- [11] Yasmin S, Rahman M, Hafeez FY. Isolation, characterization and beneficial effects of rice associated plant growth promoting bacteria from Zanzibar soils. *Journal of Basic Microbiology*. 2004;**44**:241-252
- [12] Sulastri, Wiyono S, Soepandie D, Santosa DA. IOP Conference Series: Earth and Environmental Science. The 4th International Seminar on Sciences, Vol. 187. 19-20 October 2017, Bogor, Indonesia: IOP Publishing Ltd; 2018
- [13] Mouhamad RS, Mutlag LA, Al-Khateeb MT, Iqbal M, Nazir A, Ibrahim KM, et al. Salinity tolerance at seedling stage for rice genotypes: In vitro analysis. *Netherlands Journal of Agricultural Science*. 2017;**5**:114-120
- [14] Mouhamad RS, Jaafar ZM, EAJ E-K, Iqbal M, Arif N. Evaluation of agronomic traits and inorganic nutritional composition of rice seed from IRSSTN genotypes in Iraq. *Journal of Rice Research*. 2018;**6**:189
- [15] Ashrafuzzaman M, Hossen FA, Ismail MR, Hoque A, Islam MZ, Shahidullah SM, et al. Efficiency of plant growth-promoting rhizobacteria

- (PGPR) for the enhancement of rice growth. African Journal of Biotechnology. 2009;8(7):1247-1252
- [16] Beneduzi A, Peres D, Vargas LK, Bodanese-Zanettini MH, Passaglia LM. Evaluation of genetic diversity and plant growth promoting activities of nitrogen-fixing bacilli isolated from rice fields in South Brazil. Applied Soil Ecology. 2008;39(3):311-320
- [17] Bisht SC, Mishra PK. Ascending migration of endophytic *Bacillus thuringiensis* and assessment of benefits to different legumes of NW Himalayas. European Journal of Soil Biology. 2013;56:56-64
- [18] Nautiyal CS, Srivastava S, Chauhan PS, Seem K, Mishra A, Sopory SK. Plant growth-promoting bacteria *Bacillus amyloliquefaciens* NBRISN13 modulates gene expression profile of leaf and rhizosphere community in rice during salt stress. Plant Physiology and Biochemistry. 2013;66:1-9
- [19] Gandhi A, Muralidharan G. Assessment of zinc solubilizing potentiality of *Acinetobacter* sp. isolated from rice rhizosphere. European Journal of Soil Biology. 2016;76:1-8
- [20] Tiwari S, Lata C, Chauhan PS, Nautiyal CS. *Pseudomonas putida* attunes morphophysiological, biochemical and molecular responses in *Cicer arietinum* L. during drought stress and recovery. Plant Physiology and Biochemistry. 2016;99:108-117
- [21] Kandel SL, Herschberger N, Kim SH, Doty SL. Diazotrophic endophytes of poplar and willow for growth promotion of rice plants in nitrogen-limited conditions. Crop Science. 2015;55:1765-1772
- [22] Mano H, Morisaki H. Endophytic bacteria in the rice plant. Microbes and Environments. 2008;23:109-117
- [23] Mäder P, Kaiser F, Adholeya A, Singh R, Uppal HS, Anil K, et al. Inoculation of root microorganisms for sustainable wheat-rice and wheat-black gram rotations in India. Soil Biology and Biochemistry. 2011;43:609-619
- [24] Ladha JK, Reddy PM. Nitrogen fixation in rice systems: State of knowledge and future prospects. Plant and Soil. 2003;252:151-167
- [25] Yasmin S, Bakar MAR, Malik KA, Hafeez FY. Isolation, characterization and beneficial effects of rice associated plant growth promoting bacteria from Zanzibar soils. Journal of Basic Microbiology. 2004;3:241-252
- [26] Naher UA, Othman R, Shamsuddin ZHJ, Saud HM, Ismail MR. Growth enhancement and root colonization of rice seedlings by rhizobium and *Corynebacterium* spp. International Journal of Agriculture and Biology. 2009;11:586-590
- [27] Rosenblueth M, Ormeño-Orrillo E, López-López A, Rogel MA, Jazmín Reyes-Hernández B, Martínez-Romero JC, et al. Nitrogen fixation in cereals. Frontiers in Microbiology. 2018;9:1794
- [28] James EK, Gyaneshwar P, Mathan N, Barraquio WL, Reddy PM, Iannetta PP, et al. Infection and colonization of rice seedlings by the plant growth-promoting bacterium *Herbaspirillum seropedicae* Z67. Molecular Plant-Microbe Interactions. 2002;15:894-906
- [29] Etesami H, Alikhani HA. Evaluation of gram-positive rhizosphere and endophytic bacteria for biological control of fungal rice (*Oryza sativa* L.) pathogens. European Journal of Plant Pathology. 2017;147(1):7-14
- [30] Estrada-de los Santos P, Vinuesa P, Martínez-Aguilar L, Hirsch AM, Caballero-Mellado J. Phylogenetics analysis of *Burkholderia* species by

multilocus sequence analysis. *Current Microbiology*. 2013;**67**:51-60

[31] Rangjaroen C, Sungthong R, Rerkasem B, Teaumroong N, Noisangiam R, Lumyong S. Untapped endophytic colonization and plant growth-promoting potential of the genus *Novosphingobium* to optimize rice cultivation. *Microbes and Environments*. 2017;**32**(1):84-87

[32] De Souza V, Piro VC, Faoro H, Tadra-Sfeir MZ, Chicora VK, Guizelini D, et al. Draft genome sequence of *Herbaspirillum huttiense* subsp. *putei* IAM 15032, a strain isolated from well water. *Genome Announcements*. 2013;**1**:e00252-e00212

[33] Syers JK, Johnston AE, Curtin D. Efficiency of soil and fertilizer phosphorus use. Rome, Italy: FAO Fertilizer and Plant Nutrition Bulletin 18; 2008

[34] Sahrawat KL, Abekoe MK, Diatta S. Application of inorganic phosphorus fertilizer. In: Tian G, Ishida F, Keatinge D, editors. *Sustaining Soil Fertility in West Africa*. Madison, Wisconsin, USA: Soil Science Society of America Special Publication Number 58. Soil Science Society of America and American Society of Agronomy; 2001. pp. 225-246

[35] Othman R, Panhwar QA. Phosphate-solubilizing bacteria improves nutrient uptake in aerobic rice. In: Khan MS, editor. *Phosphate Solubilizing Microorganisms*. Cham: Springer; 2014. pp. 207-224

[36] Fageria NK. Nutrient management for improving upland rice productivity and sustainability. *Communications in Soil Science and Plant Analysis*. 2001;**32**:2603-2629

[37] Islam MT, Hossain MM. Plant probiotics in phosphorus nutrition in crops, with special reference to rice. In: Maheshwari DK, editor. *Bacteria in*

Agrobiology: Plant Probiotics. Berlin: Springer; 2012. pp. 325-363

[38] Panhwar QA, Jusop S, Naher UA, Othman R, Razi MI. Application of potential phosphate-solubilizing bacteria and organic acids on phosphate solubilization from phosphate rock in aerobic rice. *Scientific World Journal*. 2013;**2013**:10. Article ID: 272409. Available from: <https://doi.org/10.1155/2013/272409>

[39] Kamran S, Shahid I, Baig DN, Rizwan M, Malik KA, Mehnaz S. Contribution of zinc solubilizing bacteria in growth promotion and zinc content of wheat. *Frontiers in Microbiology*. 2017;**8**:2593

[40] Bouis HE, Welch RM. Biofortification—A sustainable agricultural strategy for reducing micronutrient malnutrition in the global south. *Crop Science*. 2010;**50**:S-20

[41] Vaid SK, Kumar B, Sharma A, Shukla AK, Srivastava PC. Effect of Zn solubilizing bacteria on growth promotion and Zn nutrition of rice. *Journal of Soil Science and Plant Nutrition*. 2014;**14**:889-910

[42] Adak A et al. Micronutrient enrichment mediated by plant-microbe interactions and rice cultivation practices. *Journal of Plant Nutrition*. 2016;**39**:1216-1232

[43] Tchounwou P, Newsome C, Williams J, Glass K. Copper-induced cytotoxicity and transcriptional activation of stress genes in human liver carcinoma cells. *Metal Ions in Biology and Medicine*. 2008;**10**:285-290

[44] Chang LW, Magos L, Suzuki T, editors. *Toxicology of Metals*. Boca Raton, FL, USA: CRC Press; 1996

[45] Ma JF, Takahashi E. *Soil, Fertilizer, and Plant Silicon Research in Japan*.

Amsterdam, the Netherlands: Elsevier; 2002. pp. 1-294

[46] Chung BY, Song CH, Park BJ, Cho JY. Heavy metals in brown rice (*Oryza sativa* L.) and soil after long-term irrigation of wastewater discharged from domestic sewage treatment plants. *Pedosphere*. 2011;**21**(5):621-627

[47] Jang T, Jung M, Lee E, Park S, Lee J, Jeong H. Assessing environmental impacts of reclaimed wastewater irrigation in paddy fields using bioindicator. *Irrigation Science*. 2013;**31**(5):1225-1236

[48] Turner TR, James EK, Poole PS. The plant microbiome. *Genome Biology*. 2013;**14**(6):209

[49] Walitang DI, Kim K, Madhaiyan M, Kim YK, Kang Y, Sa T. Characterizing endophytic competence and plant growth promotion of bacterial endophytes inhabiting the seed endosphere of rice. *BMC Microbiology*. 2017;**17**(1):209

[50] Suman J, Uhlik O, Viktorova J, Macek T. Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment? *Frontiers in Plant Science*. 2018;**9**:1476

[51] Morkunas I, Woźniak A, Mai V, Rucińska-Sobkowiak R, Jeandet P. The role of heavy metals in plant response to biotic stress. *Molecules*. 2018;**3**:2320

[52] Tiwari S, Lata C. Heavy metal stress, signaling, and tolerance due to plant-associated microbes: An overview. *Frontiers in Plant Science*. 2018;**9**:452. Published 6 April 2018. DOI: 10.3389/fpls.2018.00452

[53] Babalola A. A new strategy for heavy metal polluted environments: A review of microbial biosorbents. *International Journal of Environmental Research and Public Health*. 2017;**14**:94

[54] Jing YD, He ZL, Yang XE. Role of soil rhizobacteria in phytoremediation of heavy metal contaminated soils. *Journal of Zhejiang University. Science*. 2007;**8**(3):192-207

[55] Fukami J, Cerezini P, Hungria M. *Azospirillum*: Benefits that go far beyond biological nitrogen fixation. *AMB Express*. 2018;**8**:1-1

[56] Gai JP, Cai XB, Feng G, Christie P, Li XL. Arbuscular mycorrhizal fungi associated with sedges on the Tibetan plateau. *Mycorrhiza*. 2006;**16**(3):151-157

[57] Evelin H, Devi TS, Gupta S, Kapoor R. Mitigation of salinity stress in plants by arbuscular mycorrhizal symbiosis: Current understanding and new challenges. *Frontiers in Plant Science*. 2019;**10**:470

[58] Ren XM, Guo SJ, Tian W, et al. Effects of plant growth-promoting bacteria (PGPB) inoculation on the growth, antioxidant activity, Cu uptake, and bacterial community structure of rape (*Brassica napus* L.) grown in Cu-contaminated agricultural soil. *Frontiers in Microbiology*. 2019;**10**:1455

[59] Yeh CM, Hsiao LJ, Huang HJ. Cadmium activates a mitogen-activated protein kinase gene and MBP kinases in rice. *Plant & Cell Physiology*. 2004;**45**:1306-1312

[60] Singh I, Shah K. Exogenous application of methyl jasmonate lowers the effect of cadmium-induced oxidative injury in rice seedlings. *Phytochemistry*. 2014;**108**:57-66

[61] Huang T-L, Huang L-Y, Fu S-F, Trinh NN, Huang H-J. Genomic profiling of rice roots with short- and long-term chromium stress. *Plant Molecular Biology*. 2014;**86**:157-170

[62] Pandey S, Ghosh PK, Ghosh S, De TK, Maiti TK. Role of heavy metal resistant *Ochrobactrum* sp. and *Bacillus*

spp. strains in bioremediation of a rice cultivar and their PGPR like activities. *Journal of Microbiology*. 2013;**51**:11-17

[63] Chakrabarty D, Trivedi PK, Misra P, Tiwari M, Shri M, Shukla D, et al. Comparative transcriptome analysis of arsenate and arsenite stresses in rice seedlings. *Chemosphere*. 2009;**74**:688-702

[64] Jha Y, Subramanian RB, Patel S. Combination of endophytic and rhizospheric plant growth promoting rhizobacteria in *Oryza sativa* shows higher accumulation of osmoprotectant against saline stress. *Acta Physiologiae Plantarum*. 2011;**33**:797-802

[65] Heaton ACP, Rugh CL, Kim T, Wang NJ, Meagher RB. Toward detoxifying mercury-polluted aquatic sediments with rice genetically engineered for mercury resistance. *Environmental Toxicology and Chemistry*. 2003;**22**:2940-2947

[66] Savant NK, Datnoff LE, Snyder GH. Depletion of plant-available silicon in soils: A possible cause of declining rice yields. *Communications in Soil Science and Plant Analysis*. 1997;**28**:1245-1252

[67] Bocharnikova EA, Loginov SV, Matychenkov VV, Storozhenko PA. Silicon fertilizer efficiency. *Russian Agricultural Sciences*. 2010;**36**:446-448

[68] Ning D, Song A, Fan F, Li Z, Liang Y. Effects of slag-based silicon fertilizer on rice growth and brown-spot resistance. *PLOS One*. 2014;**9**:e102681

[69] Vasanthi N, Saleena LM, Raj SA. Silica solubilization potential of certain bacterial species in the presence of different silicate minerals. *Silicon*. 2018;**10**:267-275

[70] Chen X, Zuo S, Schwessinger B, Chern M, Canlas PE, Ruan D, et al. An XA21-associated kinase (OsSERK2) regulates immunity mediated by the

XA21 and XA3 immune receptors *Mol. Planta*. 2014;**7**(2014):874-892

[71] Mouhamad RS. Morphological study of different varieties of rice traits influencing nitrogen and water uptake efficiency. *Revista Bionatura*. 2020;**5**(1):1039-1043. DOI: 10.21931/RB/2020.05.01.5