

Editorial

Developing Plant-Growth-Promoting Rhizobacteria: A Crucial Approach for Achieving Sustainable Agriculture

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1. Introduction

The rhizosphere is the zone surrounding plant roots where microbial activity attains its maximum potential, playing pivotal roles in maintaining plant health. Hence, the rhizosphere microbiome has been recognized as the second most important genome in plants. Among plant genomes, plant-growth-promoting rhizobacteria (PGPR) has various beneficial functions, and thus has been extensively studied and used to increase plant productivity [1,2]. PGPRs can promote plant growth via multiple pathways, including the activation of nutrients and decreased reliance on chemical fertilizer [3]; the suppression of soil-borne disease via the production of antibiotics [4]; the priming of plant defenses by inducing systemic resistance (ISR) [5]; and maintaining the balance of soil microbiota [6]. PGPRs serve as the most major source of biofertilizer strains, enhancing soil quality and promoting sustainable agriculture with reduced reliance on fertilizers or pesticides. Based on previously published articles and prospective manuscripts, this Editorial provides a rational basis for achieving sustainable agriculture through the use of PGPRs.

2. Overview of the Special Issue

This Special Issue collates research articles that present new developments and methodologies related to PGPRs. These include the promotion of germination and shoot development [7], the enhancement of root colonization ability and nodule formation [8], and the responses of rhizosphere microbes under salt and drought stress [9–11].

2.1. Growth Promotion

The application of PGPRs enhanced seed germination rates and the vigorous growth of cucumber seedlings. Pérez-García et al. [7] found that *Bacillus cereus* (KBEndo4P6), *Acinetobacter radioresistens* (KBEndo3P1), *Pseudomonas paralactis* (KBEndo6P7), and *Sinorhizobium meliloti* (KBekto9P6) significantly improved the germination index, vigor, radicle length and phytochemical compounds in plants, demonstrating promising applications.

2.2. Abiotic Stresses

Abiotic stresses are major constraints on crop yield, food quality, and food security. *Bacillus cereus* L90 can improve the photosynthetic characteristic of walnut (*Juglans regia*) by increasing the production of IAA, gibberellins, and zeatin [10]. Similarly, *Bacillus subtilis* GE1 and *Pseudomonas brassicacearum* X123 can enhance the drought adaptability of walnut seedlings [11].



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2.3. Soil Microbial Community

Salt stress can change the microbial community structure of rhizosphere. Xia et al. [9] found that the core rhizosphere phyla of chamomile (*Matricaria chamomilla* L.) may be the key to salt stress adaptability, including *Proteobacteria*, *Acidobacteriota*, and *Ascomycota*.

2.4. Chemotaxis

Chemotaxis and motility are the two factors that determine the ability to colonize roots. *Ensifer alkanisoli* YIC4027T established a nitrogen-fixing symbiosis on the roots of *Sesbania cannabina*. Guo et al. [8] found that motile rhizobia utilize a novel strategy in two pathways, *che1* and *che2*, to enhance the efficiency of nodule formation in *S. cannabina*.

3. Role of PGPRs in Biocontrol

PGPRs can provide benefits to plants, and many studies have demonstrated the potential roles of PGPRs as biological control agents, replacing synthetic fungicides [12]. The investigation of the biocontrol potential of PGPRs in the rhizosphere, which includes the associated mechanisms of biocontrol and the ability to increase crop productivity under biotic stress conditions, is also an important research topic of this Special Issue.

3.1. Production of Bioactive Substance

PGPRs can produce a variety of bioactive substances that have the potential to inhibit the growth or activity of other microorganisms. One of the most important of these bioactive substances is metabolites. PGPRs produce antimicrobial substances via both ribosomal and non-ribosomal synthesis pathways [13]. Bacteriocins are a common type of antibiotic synthesized by ribosomal pathways, while lipopeptides (LPs) and polyketides (PKs) are produced via non-ribosomal synthesis pathways [14,15]. PGPRs such as *Bacillus* sp. strains allocate a relatively substantial proportion of their genomes to synthesizing diverse antibiotics. *Bacillus velezensis* FZB42 dedicates over 10% of its genome to biosynthetic gene clusters (BGCs) that encode antibiotics for antagonizing plant pathogen [16,17], as well as *Bacillus velezensis* SQR9 [18,19].

Aside from antibiosis, PGPRs are capable of secreting extracellular hydrolytic enzymes [20], the presence of the chitinase of *Rhizobacteria* impedes the germination and germ tube elongation of the pathogenic fungus [21]. *Bacillus subtilis* secretes chitinase, protease and cellulase, which can lyse *Rhizoctonia solani*, among other enzymes [22]. Other enzymes, such as glucanase, xylanase and pectinase, were also found to be responsible for inhibiting mycelial growth [23–25].

3.2. Competition for Nutrients and Space

The efficient colonization of the root system by PGPRs is a crucial step in biocontrol processes. Plants release organic nutrients onto the root surface and into the rhizosphere, which creates diverse niches that attract a wide range of microorganisms [20,26]. Additionally, these nutrients function as chemical signals for motile bacteria to migrate towards the root surface [27,28]. PGPRs establish a strong and beneficial inter-relationship with plants via chemoreceptors, which enable them to sense chemo-attractants and form biofilms on roots for the long-term colonization of the rhizosphere [29,30].

In addition to physical sites, competition for nutrients at root surfaces represents an indirect but important strategy of PGPRs against pathogens that depend on limited external resources [31]. Iron nutrient competition is a crucial area of research focus. In aerobic soil, iron exists in insoluble forms that are almost or completely inaccessible for most microorganisms. However, PGPRs have evolved to acquire ferric iron through the production of siderophores, which enables the solubilization of iron and its increase its availability mineral or organic complexes [32,33]. Therefore, the production of siderophores by PGPRs provides them with a competitive advantage in colonizing roots and excluding plant pathogens from rhizosphere ecological niches.

3.3. Induced Systemic Resistance (ISR)

ISR refers to the plant's ability to resist a wide variety of attackers, including phytopathogenic bacteria and fungi [34]. This non-specific protection can be activated by PGPRs through elicitors. Most PGPRs employ a salicylic acid-independent pathway to activate ISR, involving jasmonate and ethylene [35,36]. PGPRs induce ISR responses by modulating physical and biochemical properties in plants, leading to a reduction in plant diseases [37,38]. ISR has been extensively studied in many PGPRs strains, particularly those from the genera, *Bacillus* and *Pseudomonas*, as well as other symbiotic groups of rhizobacteria [23,39–41]. However, the mechanisms underlying the beneficial effects of these bacteria, including their selection and interaction with plant immune systems, remain poorly understood. Further research is required to distinguish these mechanisms from those employed by pathogenic bacteria.

4. Conclusions and Prospects

Currently, the widespread use of agrochemicals in major field crops poses serious threats to the environment. However, PGPRs have multifarious beneficial activities for plant growth and could potentially be substitute for or supplement toxic chemicals due to their promising applications in organic farming, which can lead to sustainable agricultural practices [6,42,43].

The most studied PGPRs are members of the genera, *Azospirillum*, *Bacillus*, *Pseudomonas*, etc. However, most significantly, different species of PGPRs produce diverse bioactive substances and elicitors. The great advantage of suppressing multiple pathogens through a mixture is thus increased. Moreover, certain combinations of PGPR strains fail to have synergistic or comparable effects on both disease control and plant growth when compared to their individual counterparts [44]. Significant recent advances in the integrated fields of genomics, proteomics, metabolomics, and transcriptomics at the level of PGPR–PGPR and PGPR–host interactions open up opportunities for further research on synthetic microbiomes [45].

Recent developments in biotechnological and bioinformatics have made it much easier to obtain the whole-genome sequences of PGPRs, which can be utilized to investigate the molecular and biochemical mechanisms involved in plant–microbe interactions [46]. Various bioinformatics tools, such as genome mining and deep learning, are currently being used to rapidly identify promotion mechanisms [47]. Additionally, synthetic biology is playing a significant role in stable gene expression to aid the growth promotion and disease management of plants [42].

Many PGPRs possess the capability to enhance plant growth, and some of them have already been commercialized. However, screening for multi-trait potential strains requires further research. There is a significant potential to enhance the productivity of field crops via the strategic application of newly discovered PGPRs. Therefore, based on PGPR mixtures, biotechnological, and bioinformatics approaches, future research directions should focus on enhancing the biofertilization, biocontrol, bioremediation, and alleviation of both biotic and abiotic stresses.

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