Plant and Soil Effects of Plant Growth-Promoting Rhizobacteria

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Rhizobacteria that support plant growth are known as Plant Growth-Promoting Rhizobacteria (PGPR). It is believed that the use of microbes as bioinoculants, used together with chemical fertilisers, is the best strategy to increase plant growth and soil fertility. In sustainable agriculture, these microbes bring significant benefits to crops. In addition to colonising plant systems (epiphytes, endophytes and rhizospheres), beneficial microbes play a key role in the uptake of nutrients from surrounding ecosystems.

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1. Introduction

Rhizobacteria that support plant growth are known as Plant Growth-Promoting Rhizobacteria (PGPR) [1][2]. The diversity of phenotypic and genotypic characteristics of soil microbiomes makes them complex and difficult to characterise [3]. However, as the rhizosphere has become increasingly important to the bio-sphere in recent years, several PGPRs have been identified that, significantly, have a great impact on plant growth, primarily because they act as an ecological unit [4]. The PGPRs affect plant growth by solubilising insoluble phosphates, fixing atmospheric nitrogen and secreting hormones that control plant growth [5]. Furthermore, through induced systemic resistance (SRI), competition with nutrients, antibiotics, parasitism and the growth suppression of rhizobacteria are mechanisms that lead to increased plant resistance [6]. These communities are very diverse, and their actions can take many forms, including antagonistic action against pathogens in the soil and inducing systemic resistance against pathogens throughout the plant [7]. Plants can be indirectly aided in growing by antagonistic rhizobacteria because they produce various substances that can control pathogens [8]. If the inducing bacteria and the challenging pathogen remain spatially separated, inducing systemic resistance (ISR) can be compared to pathogen-induced acquired systemic resistance (SAR). Different plant species have induced resistance that makes uninfected parts of the plant more resistant to pathogen attacks [9]. The induction of resistance occurs via rhizobacteria either through salicylic acid-dependent SAR pathways or through the bacteria’s perception of jasmonic acid and ethylene. Among the many characteristics of rhizobacteria are their antagonistic effects and ability to trigger inflammatory responses. In recent years, many studies have examined the use of PGPR as substitutes for crop protection agents (fertilisers and pesticides) for plant growth promotion [10][11]. Rhizobacteria can alter soil structure, recycle essential elements, decompose organic matter, solubilise mineral nutrients and act as biocontrol agents for soil- and seed-borne pathogens [12][13][14]. A good understanding of plant growth-promoting rhizobacteria and their interaction with biological and abiotic factors is crucial for bioremediation techniques. This is also relevant for energy generation processes and biotechnological industries such as pharmaceutical, chemical and food industries [15], and rhizobacteria are also useful for reducing the use of chemical fertilisers. The main benefit of this approach is to increase the productivity and sustainability of agricultural systems and soil fertility [16]. The application of fungi, which increase plant defences through biocontrol strategies or can solubilise phosphorus and reduce iron deficiency, is also a strategy currently used in agriculture [16]. As a result, production costs can be reduced and the best soil and crop management practices are identified [17].

2. Plant and Soil Effects of Plant Growth-Promoting Rhizobacteria

Rhizobacteria that promote plant growth are well known and essential, and this growth enhancement is due to rhizobacteria's characteristics [18]. PGPRs can enhance plant growth and development through various mechanisms [19]. In particular, rhizobacteria produce a variety of substances that alter the entire microbial community in the rhizosphere, and they are capable of supplying nutrients (nitrogen, phosphorus, potassium and essential minerals) or producing plant hormones [20]. For example, the inoculation of rhizobacteria in *Astrophytum* spp. grown in biochar-enriched substrates improves vegetative and root growth and plant flowering [21]. By acting as biocontrol agents, environmental protectors and root colonisers, PGPRs can also indirectly promote plant growth by reducing the effects of pathogens [22][23]. Sustainable agriculture and plant cultivation can be threatened by the presence of microorganisms, with a deterioration in plant quality and production yields [24]. By fixing nitrogen, mineralising organic compounds, solubilising mineral nutrients and producing phytohormones, PGPRs also facilitate the plant uptake of nutrients and increase resistance to biotic and abiotic stresses. Many species are able to survive particular environmental conditions, such as high temperatures and drought [25]. As an indirect means of achieving soil fertility and plant growth, PGPRs are crucial to a sustainable and ecological approach. This can be achieved through various mechanisms, including antibiotics, HCNs, siderophores and hydrolytic enzymes, and as outlined before, PGPRs can be exploited to decrease the need for agrochemicals such as fertilisers and pesticides and increase soil fertility [26].

3. Mechanisms Activated Directly by Plant Growth-Promoting Rhizobacteria

In terms of plant growth, phytohormones play a critical role. These are plant hormones that affect the plant's response to its environment. These hormones are produced at one point in the plant and then transferred to another part of the plant, where they are used to promote growth [1]. Roots and leaves grow due to the physical responses caused by these hormones [27]. Some essential plant hormones are auxins, gibberellins, ethylene, cytokinins and abscisic acid [28]. Rhizobacteria produce these phytohormones. In addition to auxins and gibberellins, ethylene, cytokinins and abscisic acid are important phytohormones [29]. Several naturally occurring auxin-like molecules have been described as products of bacterial metabolism in *Azospirillum* sp. cultures. In addition to indole-3-acetic acid (IAA) (between 5 and 50 lg mL^{-1} typically produced according to culture conditions and strain), indol-3-butirric acid (IBA) [30] and phenylacetic acid (PAA) [31], considered in sensu stricto as real auxins, many other indolic compounds (precursors and/or catabolites) have been identified in *Azospirillum* sp. supernatants, including indole-3-lactic acid (ILA), indole-3-ethanol and indole-3-methanol, indole-3-acetamide (IAM) [32], indole-3-acetaldehyde [33], tryptamine (TAM), anthranilate and other uncharacterized indolic compounds [34].

In plant roots and shoots, cytokinins (CKs) play a role in cell division [30]. Among their benefits, there is the growth of cells, the differentiation of cells, apical dominance, axillary bud development and leaf senescence [35][36]. Plants synthesise this hormone, but yeast strains and PGPR strains can also prepare it. In addition, some phytopathogens can synthesise cytokinins. It has been reported that *Azotobacter* species, *Pantoea agglomerans* strains, *Rhizobium* species, *Rhodospirillum rubrum* strains, *Bacillus subtilis* strains, *Pseudomonas fluorescens* strains and *Paenibacillus polymyxa* species all produce the cytokinin hormone [37][38]. Some rhizobacteria are able by their actions to mitigate the effects of different types of stress, such as water, salt and heat stress [39]. A class of important plant hormones, gibberellins (GA) control various developmental processes in plants. Their functions include stem elongation, dormancy, germination, flowering and flower development. Several cytokinin-producing polymeric protein receptors synthesise gibberellin, a phytohormone involved in breaking dormancy and other aspects of germination. Gibberellin is the most crucial phytohormone synthesised by some PGPRs. The production and regulation of gibberellin and cytokinin are extremely important [40]. PGPRs and plants produce a variety of phytohormones, including indoloacetic acid. In addition to cell division, other proprieties like gene expression, organogenesis, pigmentation, root development, seed germination, stress resistance, tropical responses and photosynthesis play an essential role in plant cellular responses [41]. Plants and bacteria influence the amount of indole-3-acetic acid (IAA) required to promote plant growth vigorously. The amount of IAA required to promote plant growth depends on the plant and bacterial species. PGPRs produce indole-3-acetic acid, which is responsible for root elongation and the formation of roots. Nearly all plants produce ethylene as a growth hormone, which is key in many physiological changes [42]. Plants respond to biotic and abiotic stresses negatively, affecting root growth and plant growth [43]. The PGPR enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase can regulate ethylene production. Inoculation with PGPRs can maintain plant growth and development under stressful conditions, such as drought, salinity, cold and soil pollution, and plants synthesise abscisic acid [25]. This growth hormone activates stress-resistance genes. Abscissic-acid-producing strains, such as *Bacillus licheniformis* Rt4M10, *Azospirillum brasilense* sp. 245 and *Pseudomonas fluorescens* Rt6M10, increase the internal ABA content of plants. As a result, the plants become more resilient to drought. The unavailability of nitrogen can limit plant growth, but phosphorus is also essential for life [44].

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