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Advances in Growth-Promoting Rhizobacteria Function on Plant Growth Facilitation and Their Mechanisms

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Abstract **Review Article**

In modern times, agriculture has been a major cause of environmental degradation due to both natural and artificial factors. However, there is a silver lining in the form of Plant Growth-Promoting Rhizobacteria (PGPR), a beneficial microbial community present in the rhizosphere soil of plants. PGPR can adjust soil pH, reduce the burden on plants, and accelerate their growth, making it an excellent choice for sustainable agriculture. This article delves into the mechanism of how PGPR promotes plant growth and highlights its impact under different environmental conditions. The aim is to promote the use of PGPR biofertilizers, which could revolutionize the field of agriculture and pave the way for a greener future.

Keywords: Plant growth-promoting rhizobacteria, growth-promoting mechanism; biological regulation.

1. INTRODUCTION

Agriculture serves as the foundation of human society, with soil being a crucial factor in agricultural production, playing a vital role in agricultural development [1]. Currently, soil is facing influences from both natural and non-natural factors, with human productive activities accounting for the vast majority of non-natural factors. The inadequate utilization efficiency of chemical fertilizers, at less than 40%, as humans rely on them to enhance agricultural productivity, has led to excessive accumulation of elements such as nitrogen and phosphorus in soil, causing water eutrophication [2]. The continual use of chemical pesticides also results in the loss of potassium and sulfur elements in soil, as well as soil compaction. Soil salinization is one of the main forms of soil degradation, with the total area of saline-alkaline soil worldwide reaching around 1 billion hectares, of which at least 20% of arable land is suffering from salinization erosion [3]. Most plants lack salt tolerance, with major food crops experiencing up to 70% yield reduction under salt stress [4].

According to the latest research findings, soil microbes play a crucial role not only in promoting healthy plant growth but also in significantly impacting soil quality. Plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhiza fungi (AMF) exhibit great potential in this regard [5]. This article summarizes the research progress on the role of PGPR in providing nutrients to plants, influencing plant hormonal balance, and alleviating plant stress, as well as its molecular mechanisms. By integrating and summarizing these research findings, the aim is to better understand the function of PGPR and provide a theoretical basis for further research on PGPR.

2. DEFINITION OF PLANT GROWTH-PROMOTING RHIZOBACTERIA

Among beneficial microorganisms in the soil, PGPR has received particular attention for its powerful functions, which can not only directly promote material cycling and encourage plant growth but also stabilize the soil environment. The term rhizosphere was first introduced by Hilnter in 1904 [6], referring to the specific range surrounding plant roots with minimal soil property differences, and the microorganisms existing within this range were defined as rhizosphere microorganisms. This category includes bacteria, fungi, and pathogens, with rhizosphere bacteria further classified as beneficial (2%-5%), harmful (8%-15%), and neutral (80%-90%) based on their impact on plants [7]. In around 1970, Vessey et al. first proposed the concept of PGPR, which inhabits the rhizosphere soil of plants, forming symbiotic relationships with them and performing various functions such as promoting plant growth, enhancing soil mineral utilization efficiency and absorption capacity, and suppressing the spread of plant pathogens [8].

There are a wide variety of PGPR species identified in soil, including more than 20 genera such as *Pseudomonas*, *Arthrobacter*, *Agrobacterium*, *Bacillus*, *Azoarcus*, and *Azospirillum*, all of which play crucial roles in plant growth and provide important biological support for the healthy development of plants [9]. Among them, *Pseudomonas fluorescens* are considered to be highly promising [10]. Based on the different colonization locations of PGPR in the plant rhizosphere, they can be divided into two types: intracellular PGPR (iPGPR) and extracellular PGPR (ePGPR). iPGPR can form nodules within the root cells of plants for direct nutritional exchange, such as nitrogen-fixing bacteria like Rhizobium and Frankia. On the other hand, ePGPR lives freely around plant roots or between root cells and cortex without forming specific nodules, either not touching the roots, attaching to the root surface, or existing between the cortex and cells of plants [6].

3.MECHANISMS OF PLANT GROWTH-PROMOTING

PGPR exhibits various growth-promoting effects, including direct modulation of the physiological functions of plants, such as stimulating the synthesis and secretion of plant hormones, promoting techniques like phosphorus solubilization, potassium releasing, and nitrogen fixation, enhancing the efficiency of plants' absorption and utilization of specific nutrients, thereby contributing to the healthy growth of plants. Furthermore, PGPR can also trigger the internal mechanisms of plants, such as strengthening plants' resistance to viruses and bacteria, improving plants' drought and saline-alkaline tolerance, and facilitating the healthy growth of plants.

3.1. DIRECT MECHANISMS

3.1.1. NITROGEN FIXATION

Nitrogen is crucial for the healthy growth and development of plants, and it mostly exists in the form of inert in surface water and soil, making it difficult to be directly utilized. Some PGPRs have the ability to fix nitrogen, as they can decompose nitrogen in surface water and soil into more easily absorbable forms of nitrate and ammonia through the action of nitrogenase enzymes, and this function depends on their respective genes (BNF nif) [11]. Additionally, PGPR can also utilize NO_3^- as an electron acceptor through denitrification, converting it to NO_x, which is further oxidized to NH_4^+ [12]. Zhao *et al*., identified nitrogen-fixing microorganisms from the rhizosphere of early maturing grass in the Gannan grassland plateau, demonstrating that these nitrogen-fixing bacteria significantly increased soil nitrogen content and nitrogen-fixing microorganism population, thus playing a crucial role in soil health [13]. Tang discovered a nitrogen-fixing soybean growth-promoting rhizobacteria present in the tissues and root zone soil of soybeans, which was named Bacillus safensis after identification [14].

3.1.2. PHOSPHATE SOLUBILIZATION

Phosphorus, as an essential nutrient for plants, can be provided to plant growth metabolism by applying chemical fertilizers. However, its absorption efficiency is low; most of the phosphorus easily reacts with metal ions (such as calcium, iron, and aluminum) in the soil, forming insoluble phosphates, which hinder plants from directly utilizing phosphorus, thereby impeding normal plant reproduction and development. The utilization of phosphorus has become one of the bottlenecks for plant growth and development [15]. Plants can only absorb soluble phosphorus in the form of monovalent ($H_2PO_4^-$) or divalent (HPO_4^{2-}) ions. PGPR can transform insoluble phosphates such as tricalcium phosphate and hydroxyapatite into soluble phosphorus that plants can absorb by secreting organic acids like formic acid, citric acid, or chelators such as iron carriers. Among them, PGPRs that solubilize phosphorus through organic acid secretion are known as phosphate-solubilizing bacteria (PSB) [16]. Lin *et al*., successfully extracted four high-quality Pseudomonas species phosphate-solubilizing bacteria from rhizosphere soil samples of highland meadow grass and small fescue through their research [17]. These bacteria can significantly improve the local environment and enhance plant resistance. Currently, the main types of phosphorus-solubilizing bacteria discovered include rhizobia, Bacillus, and Pseudomonas species [18].

3.1.3. SIDEROPHORE PRODUCTION

Iron, as a plant micronutrient, promotes photosynthesis, enhances material transport, and provides nutritional support for normal plant growth. However, bioavailable iron is relatively scarce in soil. Both Fe^{3+} and Fe^{2+} forms of iron exist in soil, and they are easily oxidized into insoluble states such as carbonates, hydroxides, or oxides, making it difficult for plants or microorganisms to directly utilize them [19]. Some microorganisms produce low molecular weight iron chelators, which are generally synthesized by non-ribosomal peptide synthetases or polyketide synthases. These organic chelators have a high affinity for trivalent iron and can bind to surrounding iron elements, converting Fe^{3+} to plant-available Fe^{2+}. Additionally, some plants secrete acidic or phenolic substances to dissolve Fe^{3+} and reduce it to Fe^{2+} under the action of reductases. Subsequently, the Fe^{2+} is absorbed by the high-affinity cells of the root epidermis, enters the root nutrient transport system, and provides the necessary iron elements for plants [20]. Moreover, compared to pathogens, the high-affinity iron chelators secreted by PGPR facilitate easier access to iron, thereby restricting the growth of iron-deprived pathogens and alleviating plant diseases [21].

3.1.4. PHYTOHORMONE PRODUCTION

Plant hormones themselves cannot directly provide plants with the necessary nutrients, but they can modify, inhibit, or promote plant growth and development at specific concentrations, thereby altering the growth and development of plants [22]. In addition to plant hormones synthesized by plants themselves, PGPR can also synthesize plant hormones or affect the synthesis of plant hormones, mainly including auxins, cytokinins, and gibberellins, as well as ACC-deaminase and ethylene, all of which help regulate plant growth and development to achieve optimal plant growth effects. Auxin, also known as indole-3-acetic acid, has long been regarded as the core hormone of plants, promoting cell division and differentiation and alleviating adverse environmental impacts. Currently, most known strains capable of synthesizing IAA are concentrated in genera such as Pseudomonas, Bacillus, and Rhizobium [23]. PGPR mainly synthesizes IAA through the precursor tryptophan, mediated by the indole-3-pyruvic acid decarboxylase encoded by the ipdC gene [24]. Gibberellins not only regulate plant development but also affect root growth and root hair density. Abscisic acid is a chemical that inhibits plant growth and metabolism, it can reduce the content of gibberellins and activate the plant’s stress-resistant genes. In addition, ethylene plays an important role in activating seeds, forming stomata, root growth, and other physiological processes. When plants face environmental stress, they release large amounts of ethylene to suppress their growth.

3.2. INDIRECT MECHANISMS

The utilization of microorganisms for disease control, as a form of biological control, represents an eco-friendly strategy. The primary indirect mechanism by which rhizobacteria promote plant growth is through their role as biocontrol agents [25]. Generally, competition for nutrients, niche exclusion, induced systemic resistance, and the production of antifungal metabolites are the key modes of biocontrol activity in PGPR. Numerous rhizobacteria have been identified as producers of antifungal metabolites such as HCN, phenazines, pyrrolnitrin, 2,4-diacetyl phloroglucinol, nicotinamide, and tensin. Interactions between certain rhizobacteria and plant roots can induce plant resistance against pathogenic bacteria, fungi, and viruses, a phenomenon known as induced systemic resistance (ISR). Furthermore, ISR involves signaling pathways mediated by jasmonate and ethylene in the plant, which subsequently trigger the host plant’s defense responses against various plant pathogens [26]. Various bacterial components, such as LPS, flagella, siderophores, cyclic lipopeptides, 2,4-diacetyl phloroglucinol, homoserine lactones, and volatile compounds like acetoin and 2,3-butanediol, have been found to induce ISR [27].

4. CONCLUSION

The rapid development of modern agriculture has led to the overuse of biochemical fertilizers and pesticides, resulting in various environmental pollutions such as compaction, land degradation, and toxicity, which have negative impacts on crop yield. PGPR technology has been proven to effectively inhibit these pollutants and improve soil texture, enhance plant resistance, and effectively prevent the spread of diseases and pests. Although progress has been made in understanding the mechanism of plant growth promotion by PGPR, there is still insufficient understanding of the interaction, causality, and molecular mechanism between PGPR and plant growth promotion, especially in terms of other element transformation mechanisms, which requires further research. The interplay of plant hormones, causality, and molecular mechanisms also need to be further elucidated. Therefore, future efforts should focus on: (1) in-depth exploration of different types of PGPR; (2) perfecting the mechanism of PGPR in soil element transformation; (3) studying the interactions between multiple PGPR and the rhizosphere; (4) investigating the effects of PGPR colonization on soil and plants, as well as the molecular mechanisms of growth promotion and stress alleviation in plants.

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