

## Contribution of PGPRs to plant growth

### Abstract

PGPRs play an important role in maintaining soil equilibrium. This environment is a living medium made up of essentially heterotrophic microorganisms, and is a major reservoir of rhizobacteria. It contains a complex and varied microflora that plays essential roles for the soil ecosystem and the soil's higher organisms. In the rhizosphere, in terms of biomass and taxon diversity, PGPRs are by far the most abundant in the soil. The aim of this study is to characterise the rhizobacteria and arbuscular mycorrhizal fungi (AMF) that occur naturally in the rhizosphere of millet as a function of different soil fertility management practices.

### I. Introduction

Rhizobacteria (PGPR, acronym for Plant Growth Promoting Rhizobacteria) are bacteria in the rhizosphere that are beneficial to plant growth and health. There are two main groups of PGPR: phyto-stimulators and phyto-protectants [1]. The term PGPR was first introduced at the end of the 1970s, when it was demonstrated by Kloepper and Schroth that strains of *Pseudomonas fluorescens* improved potato crop yields by up to 500% through the production of siderophores, iron chelators that deprive indigenous pathogenic bacteria of iron [1]. PGPRs are of major agronomic interest, as they could make it possible to reduce the use of chemical fertilisers and pesticides [2]. These are bacteria that actively colonise plant roots while increasing their growth and yield [3]. PGPRs can be used in two different ways: phyto-stimulation (sometimes called bio-fertilisation), when the PGPR directly stimulates plant growth, and phyto-protection (also called bio-control), when it inhibits the development of phyto-pathogenic organisms [4]. Plant growth-promoting rhizobacteria (PGPR) are considered an alternative to the use of chemicals in agriculture [5]. These PGPR are often used as model rhizobacteria [6]. They make up a significant proportion (up to 10%) of the cultivable rhizosphere microflora [7]. The aim of this study is to analyse the results of research showing the significant influence of PGPRs on plant growth, thereby contributing to a better understanding of the nutrition of cultivated plants.

### 2. Plant Growth Promoting Rhizobacteria (PGPR)

Rhizobacteria are microorganisms that directly stimulate plant growth directly by increasing the uptake of nutrients from the soil, inducing and producing plant growth regulators and activating induced resistance mechanisms in plants. They indirectly stimulate plant growth through their antagonistic effect on harmful microflora, by transforming toxic metabolites. The establishment of the PGPR-plant association is essential for the expression of beneficial effects.

Expression of beneficial effects. Rhizobacteria are bacteria with the ability to colonise roots intensively. Non symbiotic bacteria that meet this definition belong to different genera and species, the most extensively studied being :

**Comment [BB1]:** Ensure consistent use of terminology, especially the acronym PGPR. It should be defined clearly when first introduced, and subsequent references should be uniform.

**Comment [BB2]:** Emphasize why understanding PGPR is crucial for sustainable agriculture, potentially linking it to broader environmental or economic implications.

**Comment [BB3]:** "species species" should be corrected to "species".

Agrobacterium radiobacter, Azospirillum spp, Bacillus spp, Pseudomonas spp [8]. According to [8], the PGPR/plant relationship improves nutrient uptake, the same authors also concluded that the application of bacterial inoculations considerably improves N, P, and K uptake. Certain PGPR strains of the genera Pseudomonas, Bacillus, Paenibacillus, Rhodobacter and Azospirillum have recently been described for their direct positive effect on plant growth and increased crop yield [9]. PGPRs can promote host plant growth through various mechanisms such as nitrogen (N<sub>2</sub>) fixation and solubilisation of trace elements such as phosphate (P) [10]. Basically, RMPs are defined by three intrinsic characteristics [11].

- (1) they must be able to colonise the root ;
- (2) they must survive and multiply in the microhabitats associated with the root surface, in competition with other microbiota;
- (3) they must promote plant growth [12].

## 2.1. Diversity of RMPs in the rhizosphere

In the rhizosphere, bacteria are by far the most abundant microorganisms in terms of both biomass and taxonomic diversity [13]. [14] estimated that one gram of natural forest soil contains nearly  $1.5 \times 10^{10}$  bacteria. Generally speaking, it is now considered that one gram of soil contains several thousand species and that the abundance of these species can vary from  $10^8$  to  $10^{11}$  cells per gram of soil [15]. PGPRs can be classified into two types according to their degree of association with root cells. They are divided into extracellular (ePGPR) and intracellular (iPGPR) [16, 17, 18]. ePGPRs reside in the rhizosphere (mainly the rhizoplane) or in the intracellular space of the root cortex. iPGPRs, on the other hand, mainly reside inside nodules. The bacterial genera belonging to extracellular PGPRs are Azotobacter, Serratia, Azospirillum, Bacillus, Caulobacter, Chromobacterium, Agrobacterium, Erwinia, Flavobacterium, Arthrobacter, Micrococcus, Pseudomonas and Burkholderia. In contrast, endophytic bacteria belonging to intracellular PGPRs include Allorhizobium, Bradyrhizobium, Mesorhizobium, and Rhizobium, as well as Frankia species, which can fix atmospheric nitrogen in actinorhizal plants [19].

## 2.2. Taxonomic diversity of rhizobacteria

PGPR colonise the rhizosphere using root exudates as nutrient substrates, but unlike other rhizospheric bacteria they in turn have a beneficial effect on the plant via a multitude of mechanisms (Figure 1). The enormous taxonomic and genetic diversity of rhizobacteria means that they are heavily involved in numerous environmental functions in the soil. Certain PGPRs are involved in plant health and growth, the most extensively studied being rhizobial and mycorrhizal symbioses. The soil microbial component also plays an active role in the biogeochemical cycles of sulphur, phosphorus, iron and nitrogen. As far as the latter is concerned, their involvement in atmospheric nitrogen fixation, ammonification, nitrification and denitrification processes is well established [20]. PGPRs are among the main players controlling the decomposition of organic matter. Due to their metabolic plasticity, these soil microorganisms are also involved in the degradation and immobilisation of pollutants (pesticides) brought in from agricultural or industrial sources. At soil level, the distribution of microorganisms is heterogeneous and is conditioned by the organisation of the soil (texture, structure, composition, etc.) according to [21, 22]. The

**Comment [BB4]:** Consider discussing the implications of PGPR in sustainable agriculture, including their potential to reduce chemical fertilizers and pesticides. In short

**Comment [BB5]:** Ensure consistent use of abbreviations, such as RMPs (Root Microbial Populations) and PGPR, throughout the text to avoid confusion.

**Comment [BB6]:** The notation " $1.5 \cdot 10^{10}$ " should be corrected to " $1.5 \times 10^{10}$ " for clarity and proper scientific formatting.

estimated that one gram of natural forest soil contains nearly  $1.5 \times 10^{10}$  bacteria."

**Comment [BB7]:** Consider separating the sections on bacterial abundance and PGPR classification for better coherence.

**Comment [BB8]:** The statistical data presented adds depth to the discussion, but clearer context and structure would enhance readability.

**Comment [BB9]:** Cite recent studies or reviews that explore the implications of PGPR diversity on agricultural practices or plant health to enrich the discussion.

distribution of microorganisms in the soil is also highly dependent on nutrient resources and their spatiotemporal distribution. Consequently, the presence of a particular trophic niche will strongly structure the distribution of microorganisms in the soil [21,22]. [23] have classified RMPs into four sub-groups according to their modes of action:

- Bio-fertilisers (increase in the availability of nutrients to the plant);
- Phyto-stimulators (increase in plant growth, ability to produce phytohormones);
- Rhizoremediators (degradation of organic pollutants);
- bio-pesticides (disease control, production of fungicidal and antibiotic metabolites).

Cultivable micro-organisms, with a diversity of genera and species, belong mainly to the following three phyla: Proteobacteria, Firmicutes and Actinobacteria [20]. At present, many bacterial genera include PGPRs, revealing very diverse taxa [5].

**Comment [BB10]:** Ensure that citations are correctly formatted. For example, "according to [21,22]" should be revised to clearly attribute the sources.

**Comment [BB11]:** Discuss shortly the implications of PGPR diversity in agricultural practices, emphasizing how different genera and species might be utilized for specific crop needs or environmental conditions.

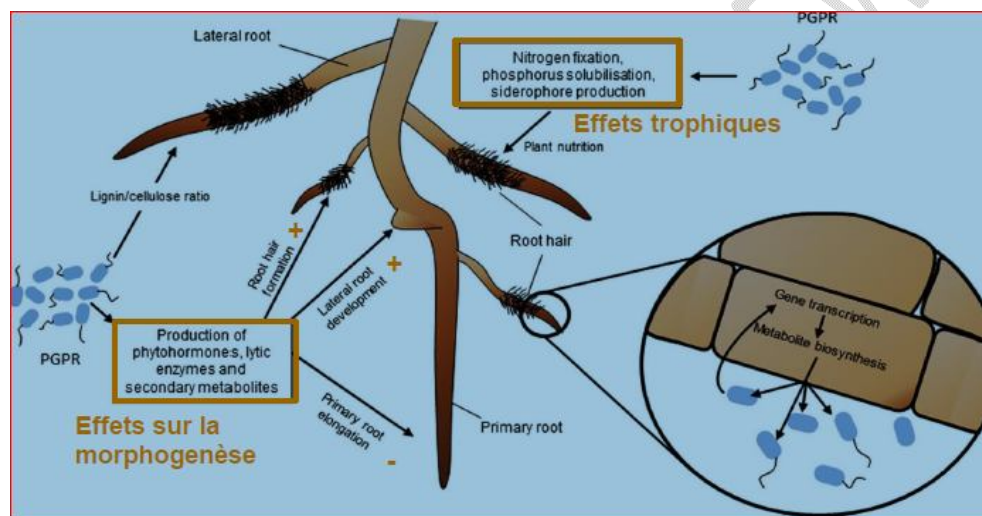


Figure 1: Effects of rhizobacteria on root system architecture and root function [24].

### 3. Mechanisms of action of PGPR

The beneficial effects of PGPRs on plant growth result from different mechanisms exerted by rhizobacteria whose modes of action are direct or indirect, although the difference between the two is not always obvious.

Indirect mechanisms are generally those that occur outside the plant, whereas direct mechanisms are those that occur inside the plant and directly affect its metabolism. These mechanisms (Figure 2) may be active simultaneously or sequentially at different stages of plant growth:

1. Solubilisation of phosphates, nitrogen fixation and mineral nutrients, making these foods available to the plant;
2. The production of phytohormones such as 3-indoleacetic acid (IAA);
3. The repression of pathogenic soil microorganisms (through the production of hydrogen cyanide, siderophores, antibiotics, and/or competition for nutrients [25]. In addition, PGPRs can contribute to improving plant resistance to biotic and abiotic stresses (salinity, dryness and heavy metal toxicity) on the basis of their activities. [23] have classified PGPRs as biofertilisers (increasing the availability of nutrients to plants), phytostimulators (improving

**Comment [BB12]:** While the text provides useful information, it could benefit from clearer organization, particularly in distinguishing between direct and indirect mechanisms.

plant growth, usually through the production of phytohormones), rhizoremediators (degrading organic pollutants) and biopesticides (controlling disease, mainly through the production of antibiotic and antifungal metabolites).

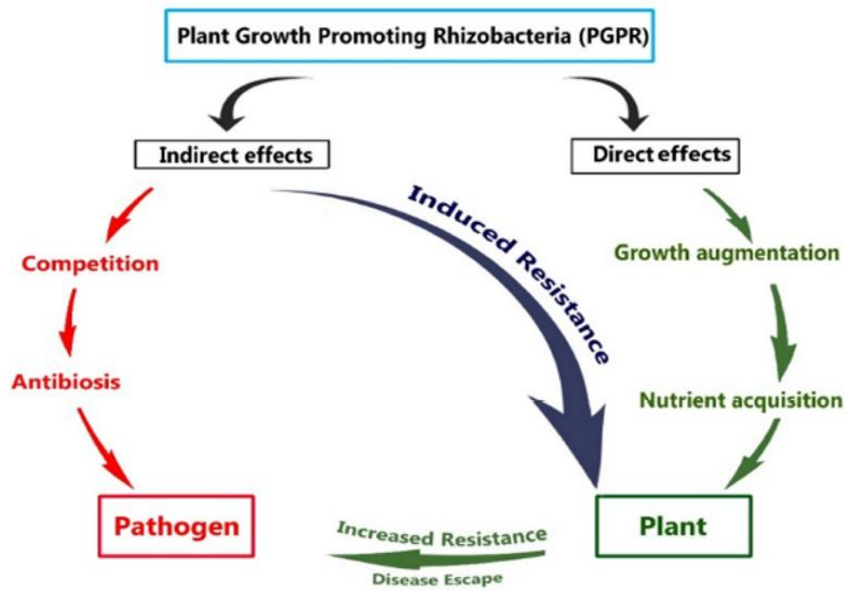


Figure 2: Overview of the two direct and indirect modes of RMPs [26].

## **Conclusion**

This review has revealed the role played by PGPRs in the plant rhizosphere. The rhizosphere is home to various microorganisms that interfere with the plant. PGPRs promote the growth of host plants through mechanisms such as nitrogen fixation and the solubilisation of trace elements such as phosphate. The beneficial effects of PGPRs on plant growth result from different mechanisms exerted by rhizobacteria whose modes of action are direct or indirect, although the difference between the two is not always obvious. Certain PGPRs are involved in plant health and growth, the most widely studied of which are rhizobial and mycorrhizal symbioses. The soil microbial component also plays an active role in the biogeochemical cycles of sulphur, phosphorus, iron and nitrogen. As far as nitrogen is concerned, the strong involvement in the fixation of atmospheric nitrogen, ammonification, nitrification and denitrification processes no longer needs to be demonstrated.

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