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Review Article

The Role of Plant Growth-promoting Rhizobacteria for Eco-benign Agriculture

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ABSTRACT

The evolution of life in all forms is dependent on agriculture for food production and sustenance. Microorganisms present in the soil such as plant growth-promoting rhizobacteria (PGPR) species are the family of rhizosphere bacteria that can promote food crops production by several key mechanisms such as phosphate solubilization, siderophore production, nitrogen fixation, phytohormone, and yield of volatile organic compounds, etc. The significance of PGPR in agriculture is gradually increasing as a natural nourishment factor to reduce or replace the use of chemical fertilizers and pesticides. Potential plant growth-promoting constituents provided at a larger quantity by the rhizosphere microorganisms are impacting the morphology of the plants, indirectly. In this review, we are focusing on its role in agriculture sustainability due to its high raise in global food production with a specific goal to reduce the use of synthetic chemical fertilizers and pesticides for health and environmental safety.

Key words: Agriculture, Biocontrol agents, Biofertilizer, Bio-mineralization, Nanotechnology, Phytohormone, Plant growth promoting rhizobacteria, Rhizosphere, Sustainability.

1. INTRODUCTION

In the current cultivation method, arbitrary use of nitrogen and phosphorus fertilizers has led to extensive pollution of soil, air, and water. Extreme usage of these chemicals employs hazardous effects on soil microorganisms; it pollutes our environment and also affects the fertility of soil [1]. Application of these fertilizers always leads to a decline in pH and exchangeable bases thus, making them unobtainable to crops, and hence, the crop production drops. To achieve sustainable agricultural concepts, crops produced are needed to be equipped with disease-resistant, salt-tolerant, drought-tolerant, heavy metal stress-tolerant features, and should have enhanced nutritional significance.

For enhancing the quality of crop production, there is a possibility to use soil microbes such as bacteria, fungi, and algae. Among which the most promising bacteria are plant growth-promoting rhizobacteria (PGPR). Without any environmental contamination, PGPR is used to promote the rate of plant health and plant growth [2]. Encouraging sustainable agriculture is very important by gradually decreasing the use of synthetic and harmful agrochemicals and more prominent utilization of biowaste-derived substances.

2. PLANT GROWTH-PROMOTING RHIZOBACTERIA (PGPR) AND ITS IMPORTANCE

The rhizosphere is a kind of soil atmosphere surrounding the plant root and is a zone of extreme microbial activity developing in a confined nutrient pool from which important macro-and micronutrients are abstracted [3]. "Plant growth-promoting rhizobacteria (PGPR)" is the term coined by Kloepper and Schrothon [4]. They are a gaggle of bacteria present within the rhizosphere. The term "plant growth-promoting rhizobacteria" indicates the colony of bacteria that are found in the root of plants (rhizosphere) and promotes plant growth. Depending on interaction with plants, they are often classified as symbiotic bacteria, like Rhizobium that resides within the intercellular spaces of plant cells and directly trades metabolites with plants [5].

3. DIFFERENT KINDS OF PGPR

PGPR is separated into two kinds, which are

- Bacteria that occupy the rhizosphere on the rhizoplane or within the gaps between the cortex cells are known as extracellular PGPR. It includes bacteria such as *Azospirillum, Bacillus, Caulobacter, Chromobacterium, Agrobacterium, Arthrobacter, Micrococcus, and Pseudomonas bacteria* [6]
- Bacteria that dwell inside the particular nodular structures of the root cells are known as intracellular PGPR. The endophytic microbes contain *Allorhizobium, Brady rhizobium, and Rhizobium,* as well as *Frankia* species, which fix atmospheric nitrogen specifically for higher plants [5].

4. PGPR ENHANCES PLANT GROWTH

PGPR has been known to promote plant growth by direct and indirect mechanisms (Figure 1).

5. DIRECT MECHANISM

In direct mechanism, PGPR has been shown to facilitate the growth and development of plants by increasing accessibility to nutrients by fixing atmospheric nitrogen, by organic compounds mineralization, and by solubilizing mineral nutrients. The presence of PGPR on the root surface increases the ion flux and causes the essential mineral uptake in plants [7].

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5.1. Role of PGPR in Nutrient Fixation of Plants

Nutrient fixing PGPR acts as growth promoters for plants, as they can enhance the nutrient concentration by securing their supply for its productivity and plant growth [8]. Some PGPR has the potency to solubilize phosphate, ensuring an increased concentration of phosphate ions in the soil, which can be simply taken up by plants. *Kocuria* bacteria extracted from the soil acts as a phosphate solubilizer, a siderophore producer, and an Indole-3-Acetic Acid (IAA) producer [9]. PGPR can also be used as a biofertilizer as it has been proven to cause mineral nutrient solubilization (Table 1) and the use of PGPR as a biofertilizer can decrease the utilization of agrochemicals and can be used to improve eco-benign agriculture [10].

5.2. PGPR Regulators of Plant Growth and Phytohormones

Phytohormones are organic substances like auxins, gibberellins (GA), cytokinin, ethylene that wield influence on the biochemical, physiological, and morphological processes, which are found in extremely acute amounts [15,16]. The ability of PGPR rhizobacteria to secrete IAA is considered to play a vital role in the stimulation of root growth. Microbial auxin production is also important to promote root elongation and root branching in plants to mediate the water uptake in dry soil (Figure 2). Both auxin and cytokinin hormones are secreted by PGPR. Plant response to rhizobacterial inoculation can be defined by auxin to cytokinin ratio. The growth of *Paenibacillus polymyxa* in the bacterial media has been known to produce mostly all cytokinin. Microbial cytokinin production by *Pseudomonas fluorescens G20-18* has also been proven to regulate *Arabidopsis* development [17].

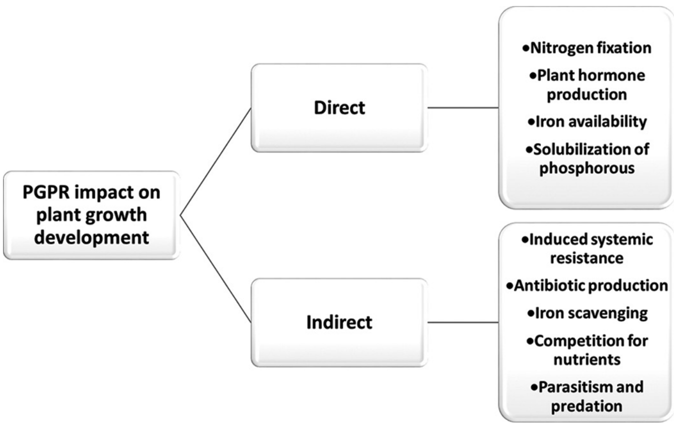

Figure 1: Outline of PGPR mechanisms in promoting eco-benign crop production and soil management [7].

5.3. Production of Siderophores

Under iron-limiting conditions, small organic molecules such as siderophores are formed by microbes that enhance the uptake of iron. Pseudomonas sp. PGPR, a group of organisms consume siderophores supplied by soil microorganisms present in the rhizosphere for fulfilling ions necessity and increase the uptake of iron in plants (Figure 2). An effective siderophore, for example, a complex of ferric-siderophore facilitates the uptake of iron by plants in the company of some metals, such as cadmium and nickel [15,16]. They are a major resource for providing the required amount of iron to the plant. However, research regarding siderophores is extremely limited.

6. INDIRECT MECHANISM

Indirect mechanisms include the method by which PGPR prevents/neutralizes the dangerous outcomes of phytopathogens by secreting explosive substances on plants that also boosts natural resistance towards plant host. This can be stated as a method that helps the plants to grow energetically under environmental stress (abiotic stress) or protect plants from infections (biotic stress) [18].

6.1. Tolerance of Abiotic Stress

Extreme temperature, drought, high wind, salinity, floods, etc. are included under abiotic stress and have a high negative impact on biomass production (up to 70%) [19-21]. Tolerance to this abiotic stress involves deposition of stress metabolites because of several metabolic changes, for example, abscisic acid, poly-sugars, proline, glycine-betaine, and increased production of enzymatic and non-enzymatic antioxidants, superoxide dismutase, catalase, and ascorbate peroxidase. Which has gained deliberate consideration for reducing stress. *P. fluorescens* neutralizes the toxic effect of cadmium pollution due to their ability to scavenge cadmium ions from the soil, on barley plants [22].

6.2. Tolerance of Biotic Stress

Pathogens such as bacteria, viruses, fungi, nematodes, protists, insects, and viroid are responsible for causing biotic stress due to which there is a substantial decrease in agricultural yield. The major challenge of crop yield is to encourage the growth of stress-resistant crops [23]. Harmful effects on plants due to biotic stress includes population dynamics, co-evolution, natural habitat ecology, ecosystem nutrient cycling, and horticultural plant health. These issues can be resolved by using PGPR such as *Bacillus amyloliquefaciens, Bacillus thuringiensis, Paenibacillus,* and *Bacillus subtilis*. Several studies have also shown

Table 1: Mineral solubilization - nitrogen, phosphorus, and potassium by PGPR

Nitrogen fixation	Phosphorus solubilization	Potassium assimilation
1. The foremost pivotal nutrient for plant growth which is essential for crop production and disease management	1. The second most important nutrient crucial for energy transfer, photosynthesis, and respiration in plants [12]	1. The third major nutrient and plays a vital role in seed, root development, and growth rate
2. Two-thirds of the global nitrogen is fixed by PGPR biological nitrogen fixation	2. Solubilization and mineralization is done by phosphate-solubilizing bacteria	2. The potassium status is maintained by PGPR
3. Nitrogen is abstracted from the soil in the form of ammonium (NH_4^+) and nitrate (NO_3^-)	3. Plants take up the phosphates in the forms of Monobasic ($H_2PO_4^-$) and dibasic ($(HPO_4)^{2-}$) ions	3. Plants absorb potassium in its ionic form i.e., K^+
4. Nitrogen-fixing PGPR bacteria are *Rhizobium* and *Azotobacter,* etc., [11]	4. Phosphate solubilizing bacteria such as *Bacillus, Enterobacter, Pseudomonas, and Mesorhizobium,* etc., [13]	4. Potassium solubilizing PGPR are *Acid thiobacillus* sp. and *Bacillus*, etc., [14]

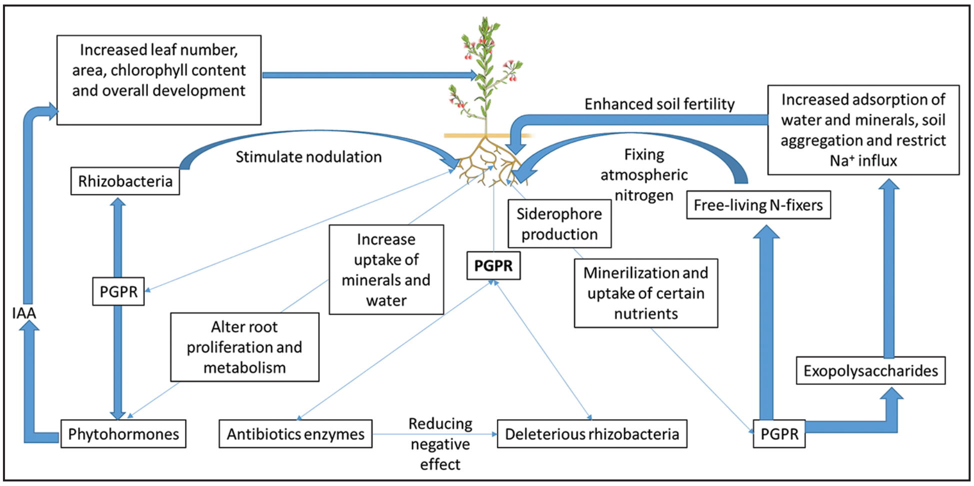

Figure 2: Overview of the role of PGPR in eco-benign agriculture [7].

Table 2: Gist of beneficial and harmful effects of PGPR

Beneficial properties	Harmful properties
PGPR organisms living in the soil environment enhance plant nutrition. Most of the rhizobacterial species can advance plant tolerance and allow plants to survive under disastrous environmental situations	*Rhizobacteria*, despite playing an important factor in preserving soil potency and in promoting plant growth and development, have some harmful effects [30]
The bacteria that produce cyanide is considered a growth promoter. The secretion of cyanide is called to be a feature of some *Pseudomonas* species [6]	Though, this negative effect only occurs under some specific conditions and by specific traits. Thus, the variety of a specific strain is of utmost significance in gaining maximum benefits [30,31]
Auxin production by PGPR causes a positive impact on plant growth. The efficiency of auxin varies on its concentration, at low concentrations, it increases the plant growth [28]	At high concentrations, Auxin produced by PGPR causes negative effects on plants as it prevents root growth [31]
Rhizobitoxine can alleviate the negative effect of stress-induced ethylene production on nodules and also acts as an inhibitor of ethylene synthesis [29]	Rhizobitoxine induces foliar chlorosis in soybeans and in some legumes too [29]

that the plants can be protected by soaking their roots or seeds overnight in PGPR cultures which provide resistance to various forms of biotic stress [19].

7. FORMATION OF VOLATILE ORGANIC COMPOUNDS (VOCs)

Enhancement of plant growth, abiotic/biotic stress tolerance, and induction of systemic resistance against plant pathogens are mainly due to VOCs produced by PGPR. VOCs produced by many bacterial species of different genera modifies plant growth, including *Bacillus, Pseudomonas, Serratia*, *Arthrobacter*, and *Stenotrophomonas*. The best-known VOCs synthesized by *Bacillus* are acetoin and 2, 3-butanediol, which are responsible for the development of plant growth [19].

8. SECRETION OF DEFENSIVE ENZYMES

PGPR enhances the plant's growth by secreting metabolites that can control phytopathogenic organisms [24]. PGPR secretes enzymes such as β-1, 3-glucanase, ACC-deaminase (1-aminocyclopropane-1-carboxylate deaminase), and chitinase, which are usually concerned with lysing the microbial cell walls and neutralizing pathogens. Most of the fungal cell wall components comprise β-1, 4-N-acetyl-glucosamine, and chitin. Henceforward, β-1, 3- glucanase- and chitinase produced by PGPR can provide defense against fungal pathogens and regulate plant growth [25].

9. KEY ROLE OF PGPR AS BIOFERTILIZER

Biofertilizers have become an important feature of organic farming and a serious factor for the final production of agriculture globally. Cellulolytic microorganisms are promoted by biofertilizers which are a combination of living cells and latent cells. They strengthen the nutrients' accessibility and absorption by the plants [26]. Biofertilizer was formulated by the combination of PGPR such as *Pseudomonas* sp. and *Bacillus* sp. with manure which can promote plant growth. They are considered to be the efficient biocontrol agents and among those, *Bacillus subtilis* and *Bacillus cereus* are the foremost effective bacterial species. PGPR in biofertilizers provides a valuable rhizosphere for plant growth and altering nutritionally essential components of biological processes, for instance, increases the provision of N, P, K which promotes soil fertility [27]. PGPR has several beneficial and harmful effects on crop production which are shown in Table 2.

10. CONCLUSION

Due to the rise in the human population, there is always an escalating demand for food all over the world. To increase the agricultural produce, people have become the prey of chemical fertilizers and pesticides. Soil and agriculture are bearing the burden of mankind and it has become never-ending greed. Considering its good impacts (Figure 2), encouragement should be given on its implementation in daily live agricultural practices Within the rhizosphere, PGPR processed with nanoparticles coated with gold, aluminum, and silver were shown to improve the plant growth, by acting as the potable nano-fertilizers and nano-fungicide. The nano bio-fertilizers are used to regulate the delivery of the fertilizer into the target cell without any undesirable damage and can condense effectively by micro-encapsulation [32].

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