CHAPTER: 2

REVIEW LITERATURE

2.1 Plant Growth-Promoting Rhizobacteria (PGPR)

Plant Growth-Promoting Rhizobacteria (PGPR) are a group of beneficial bacteria found in the rhizosphere-the soil region influenced by plant roots. These microorganisms engage in beneficial interactions with plants, boosting growth, nutrient uptake, and stress resistance (Santoyo et al., 2021). Key genera of PGPR include *Azospirillum*, *Rhizobium*, *Pseudomonas*, and *Bacillus*, each offering distinct advantages. For example, *Azospirillum* and *Rhizobium* are nitrogen-fixing bacteria, while *Pseudomonas* and *Bacillus* are recognized for their biocontrol properties, combating pathogens by producing antibiotics, enzymes, and siderophores (He et al., 2024). PGPR can enhance nutrient availability, produce phytohormones, and alleviate abiotic stress, benefiting plant growth. Additionally, they boost plant defence mechanisms, suppress harmful soil microbes, and promote soil health. PGPRs multifaceted benefits make them key to sustainable agriculture by reducing the need for chemical fertilizers and pesticides, thereby improving crop yields and resilience (Mishra et al., 2017).

2.1.1 Diversity of PGPR

PGPR represents a diverse range of bacteria that enhance plant health and growth. Prominent genera include *Azospirillum*, *Rhizobium*, *Pseudomonas*, and *Bacillus*, which are studied for their roles in nutrient cycling, phytohormone production, and pathogen suppression (Vejan et al., 2016). *Azospirillum* is noted for fixing nitrogen and promoting root development in cereals. *Rhizobium* forms symbiotic relationships with legumes, leading to nitrogen-fixing nodules that enrich soil fertility (Saikia et al., 2010). *Pseudomonas* species like *Pseudomonas fluorescens* are recognized for their ability to suppress pathogens through the production of secondary metabolites and siderophores. *Bacillus* species, such as *Bacillus subtilis* and *Bacillus amyloliquefaciens*, are valued for their ability to form spores, ensuring survival in harsh soil conditions, as well as their production of antibiotics and enzymes that protect plants from soil-borne diseases (Vân Bạch, 2021). Other PGPRs, such as *Enterobacter*, *Serratia*, and *Arthrobacter*, also contribute to nutrient solubilization, phytohormone production, and stress mitigation. This diversity allows PGPR to thrive in various environmental conditions and agricultural systems, making them essential for sustainable farming.

2.1.2 The Rhizosphere: A Hotspot for PGPR Activity

The rhizosphere is a critical area for PGPR activity, as it is rich in nutrients from root exudates such as sugars, amino acids, and organic acids. These exudates attract PGPR and activate beneficial traits like nutrient solubilization and phytohormone production (Beauregard and Pascale B, 2015). Once in the rhizosphere, PGPR uses mechanisms like biofilm formation to establish colonies on root surfaces, which enhances their persistence. Some PGPR even enter root tissues, forming endophytic relationships that allow closer interactions with plant cells. This close association improves nutrient uptake, stimulates root growth, and shields plants from pathogens and environmental stresses (Afzal et al., 2014). The nutrient-dense and biologically active rhizosphere is crucial for PGPR-mediated plant support, which underscores its importance in both natural and agricultural systems.

2.1.3 Key Roles of PGPR

PGPR play crucial roles in promoting plant health and productivity through both direct and indirect mechanisms. Directly, PGPR enhance nutrient availability by fixing nitrogen, solubilizing phosphorus, and mobilizing essential micronutrients through siderophore production (Etesami and Adl, 2020). They also produce phytohormones such as auxins, cytokinin, and gibberellins, which stimulate root and shoot growth. Additionally, the enzyme ACC deaminase produced by PGPR reduces ethylene production, alleviating stress-induced growth inhibition. Indirectly, PGPR protect plants by inhibiting soil-borne pathogens through antibiotics, lytic enzymes, and volatile organic compounds. PGPR also activate plant defence systems by inducing systemic resistance (ISR), helping plants resist diseases and pests (Meena et al., 2020). Furthermore, PGPR mitigate abiotic stresses, such as drought, salinity, and heavy metal toxicity, by modulating stress responses and producing protective metabolites (Khanna et al., 2022). PGPR (Plant Growth-Promoting Rhizobacteria) enhance sustainable agriculture by boosting crop growth, resilience, and yield through nutrient solubilization, nitrogen fixation, and stress mitigation. They suppress pathogens, reduce chemical fertilizer use, and support eco-friendly farming, advancing food security and environmental health.

2.1.4 Importance of PGPR in Agriculture

PGPR are crucial for sustainable agriculture, addressing challenges like declining soil fertility, environmental degradation, and climate change. Through nitrogen fixation, phosphorus solubilization, and micronutrient mobilization, PGPR reduce reliance on chemical fertilizers, making farming more eco-friendly (Kour et al., 2020). Their ability to suppress pathogens and induce systemic resistance offers a sustainable alternative to chemical pesticides, reducing environmental contamination. Moreover, PGPR improve plant resilience to abiotic stresses, such as drought, salinity, and heavy metals, which are increasingly prevalent due to climate change (Al-Turki et al., 2023). By promoting root growth and optimizing water and nutrient uptake, PGPR contribute to higher crop productivity and improved food security. Their role in enhancing soil health and microbial diversity makes PGPR vital for long-term agricultural sustainability, offering a natural, cost-effective solution for both smallholder and commercial farming (Choudhary et al., 2018).

2.1.5 Mechanism of Action

PGPR enhance plant growth through a variety of direct and indirect mechanisms. Directly, PGPR fix atmospheric nitrogen, providing a vital source of nitrogen for plants in nitrogen-deficient soils. They also solubilize nutrients like phosphorus, potassium, and micronutrients, making them more available for plant uptake. In addition, PGPR produce phytohormones, such as auxins, cytokinin, and gibberellins, which regulate plant growth and stimulate root development (Arora et al., 2013). Another important mechanism is the production of ACC deaminase, which reduces stress-induced ethylene production and promotes root growth under stress conditions (Singh et al., 2015). Indirectly, PGPR protect plants by inhibiting soil-borne pathogens through antibiotics, lytic enzymes, and volatile organic compounds (Ali et al., 2015). They also activate plant defence systems by inducing systemic resistance, priming plants to better resist diseases and pests. Additionally, PGPR help plants tolerate abiotic stresses, such as drought, salinity, and heavy metal toxicity, by producing protective metabolites and modulating stress responses, thereby improving plant resilience (Sunita et al., 2020). These mechanisms collectively contribute to sustainable agriculture by increasing crop yields and promoting environmental health.

2.1.6 Role of *Bacillus* and *Pseudomonas* species as Plant Growth Promoters in Crop Production

Bacillus species play a vital role as plant growth promoters by enhancing nutrient availability, increasing resistance to pathogens, and improving stress tolerance. *Bacillus* species such as *Bacillus subtilis*, *Bacillus megaterium,* and *Bacillus amyloliquefaciens* fix nitrogen, solubilize phosphate, produce plant growth regulators like indole-3-acetic acid (IAA), and suppress harmful pathogens in the rhizosphere (Poveda and González-Andrés, 2021). Studies have shown that *Bacillus megaterium* improves phosphorus availability by solubilizing it, leading to better root growth and increased crop yields (Wyciszkiewicz et al., 2015). Additionally, *Bacillus* species protect plants from pathogens through the production of antimicrobial compounds and enhance stress resistance by producing exopolysaccharides (EPS), which help plants cope with drought and extreme temperatures (Yasmin et al., 2019).

Pseudomonas species, such as *Pseudomonas fluorescens*, are also effective plant growth promoters. These bacteria improve nutrient availability by solubilizing phosphorus and potassium, produce plant growth regulators, and protect plants from pathogens through the production of antibiotics and siderophores (Kumawat et al., 2017). *Pseudomonas* species also enhance stress tolerance by producing metabolites that protect roots and retain water during drought conditions (Beneduzi et al., 2012). Their biocontrol properties and ability to improve nutrient uptake and stress resilience make them valuable for increasing crop yields while reducing the need for chemical fertilizers and pesticides (Rajkumar et al., 2017). The use of *Pseudomonas* and *Bacillus* species as biocontrol agents and biofertilizers promotes sustainable farming practices by improving crop production and reducing environmental impact.

2.2 PGPR in the Enhancement of Crop Production

Plant Growth-Promoting Rhizobacteria (PGPR) have shown considerable potential in improving crop production, as supported by a wealth of research. For example, studies on *Azospirillum brasilense* have indicated yield increases of up to 30% in crops like maize and wheat, largely due to its nitrogen-fixing abilities and the production of growth-regulating phytohormones, such as auxins and gibberellins (Revolti et al., 2018). Research on *Rhizobium leguminosarum* in legumes such as chickpeas has revealed a 20–50% increase in seed yields, attributed to enhanced nitrogen fixation and better root nodulation (Singh and Singh, 2018). In addition, *Pseudomonas fluorescens* has been noted for its ability to reduce disease incidence by 40–70% in tomato plants, because of its biocontrol properties and production of siderophores and antifungal compounds, leading to healthier plants and higher yields (Panpatte et al., 2016). Similarly, *Bacillus subtilis* has played an important role in protecting rice and other crops from soil-borne pathogens like *Rhizoctonia solani*, while boosting yield by up to 25% through improved nutrient uptake and enhanced root health (Jamali et al., 2020). Field trials that combine PGPR with biofertilizers have consistently shown improved crop productivity under both normal and stressed conditions, underlining the potential benefits of PGPR in sustainable agriculture by promoting crop yield and reducing reliance on chemical inputs.

Recent studies further emphasize the important role of PGPR in promoting plant growth, particularly in overcoming nutrient deficiencies and environmental stresses. For example, a 2023 study demonstrated that *Bacillus subtilis* not only stimulated root elongation and increased biomass in maize but also improved photosynthetic efficiency under drought conditions (Tao et al., 2019). This effect was attributed to the bacterium production of phytohormones like indole-3-acetic acid (IAA) and its ability to enhance nutrient uptake efficiency (De Andrade et al., 2023). Another study on *Azospirillum brasilense* revealed its capacity to enhance nitrogen assimilation in wheat, improving tillering and grain yields (Quatrin et al., 2019). Additionally, *Pseudomonas fluorescens* was found to solubilize phosphorus and alleviate salinity stress in rice, contributing to enhanced growth and productivity (Adnan et al., 2020). PGPR consortia, such as those combining *Bacillus amyloliquefaciens* and *Rhizobium leguminosarum,* have been shown to improve nodulation in legumes and increase resistance to pathogens like *Fusarium oxysporum* in tomatoes, resulting in higher yields and better fruit quality (Saharan and Nehra, 2011).

The combination of PGPR bio stimulants with compost has been shown to increase plant height, pod yield, and nutrient uptake. Co-inoculating PGPR strains has provided superior results compared to single inoculation, emphasizing the synergistic effect of microbial consortia (Malik et al., 2023). These treatments also improved soil health by enhancing the solubilization of key nutrients, such as phosphorus, contributing to more sustainable farming practices.

Furthermore, recent research highlights the significant role of PGPR in improving groundnut (*Arachis hypogaea* L.) production, both in terms of yield and quality. A study involving bacterial strains such as *Bradyrhizobium* and *Bacillus subtilis* showed that their combination with biochar led to a significant increase in seed protein, oil content, and iron levels (Eswaran et al., 2023). This improvement was linked to better nutrient availability and root colonization, enhancing groundnut growth and productivity under field conditions. Moreover, PGPR strains that produce IAA, siderophores, and ammonia were found to significantly promote nodulation, plant biomass, and overall yield compared to untreated controls (Harish et al., 2019).

2.3 Metal oxide nanoparticles in agriculture

Metal oxide nanoparticles (MONPs) are emerging as effective tools in agriculture, offering several potential advantages for enhancing crop productivity and sustainability. These nanoparticles, such as zinc oxide (ZnO), titanium dioxide (TiO_2), iron oxide (Fe_3O_4), and copper oxide (CuO), improve plant growth and yield by enhancing nutrient availability and uptake (Hashmi et al., 2024). For example, ZnO NPs provide essential zinc to plants, which supports enzymatic activity and chlorophyll synthesis (Ahmad et al., 2019). Similarly, Fe_3O_4 nanoparticles increase iron availability in the soil, helping to address iron deficiencies and promote robust plant growth (Zuniga Miranda et al., 2023).

MONPs also exhibit antimicrobial properties, which help control plant diseases and reduce reliance on chemical pesticides. For example, CuO nanoparticles have shown effectiveness against fungal pathogens, contributing to healthier crops (Gaba et al., 2022). However, the application of MONPs raises concerns about their potential toxicity to plants, soil microbes, and the broader environment. Ongoing research is focused on optimizing MONP formulations and application methods to maximize their agricultural benefits while minimizing environmental and ecological risks (Chaudhary et al., 2019). As agricultural practices evolve, MONPs show promise in addressing global challenges related to food security and environmental conservation.

2.3.1 Metal Oxide Nanoparticles with PGPR

The integration of MONPs with PGPR offers a promising strategy to enhance sustainable agricultural practices. MONPs like ZnO, Fe_3O_4, and TiO_2 act as nano-nutrients, improving the availability of essential elements, while PGPR facilitates nutrient uptake and stimulates plant growth through mechanisms like nitrogen fixation, phytohormone production, and stress alleviation (Arora et al., 2024).

When combined, MONPs and PGPR work synergistically, promoting plant growth and increasing yield. For example, ZnO NPs help alleviate zinc deficiencies in plants, enhancing the activity of PGPR such as *Pseudomonas fluorescens* and *Bacillus subtilis*. This combination boosts root development and microbial colonization (Nayana et al., 2020). Additionally, the antimicrobial properties of MONPs, such as CuO, complement the biocontrol capabilities of PGPR, reducing soil-borne pathogens and nurturing healthier plants. Studies indicate that these combinations not only increase crop yields but also reduce the need for chemical fertilizers and pesticides, supporting environmentally friendly agricultural practices.

Recent research highlights the effective application of MONPs combined with PGPR to improve plant growth and resilience under stress. Studies on ZnO NPs and *Pseudomonas fluorescens* have shown significant improvements in wheat growth in zinc-deficient soils, due to enhanced nutrient availability and microbial activity (Thounaojam et al., 2021). Similarly, Fe_3O_4 nanoparticles combined with nitrogen-fixing PGPR such as *Rhizobium leguminosarum* have been shown to enhance nodulation and nitrogen assimilation in legumes, resulting in higher biomass and yields (Oves et al., 2014). Another study found that CuO nanoparticles combined with *Bacillus subtilis* not only boosted plant growth but also reduced fungal infections in crops like tomatoes and peppers (Duhan et al., 2017). This synergy between MONPs and PGPR harnesses the antimicrobial properties of nanoparticles and the biocontrol effects of PGPR to protect crops from pathogens.

MONPs also improve nutrient uptake, stress resistance, and metabolic efficiency in plants. For example, ZnO NPs promote maize growth by increasing zinc bioavailability and chlorophyll synthesis, while Fe_3O_4 nanoparticles enhance photosynthesis and iron assimilation in soybeans. CuO nanoparticles strengthen the antimicrobial defence in crops like *Arabidopsis* and tomato (Agrahari et al., 2020). These applications demonstrate how MONPs can be innovative tools for sustainable agricultural development, improving plant physiological and biochemical processes.

The combination of advanced nanotechnology and traditional agricultural practices can enhance nutrient cycling and boost crop productivity. However, careful management is necessary to minimize potential environmental risks and ensure the sustainable use of MONPs in agriculture.

Nanomaterials, including metal, organic, carbon, and semiconductor nanoparticles, have shown potential plant growth-promoting effects (Farooqui et al., 2016; Siddiqui et al., 2015). Silver nanoparticles (Siddiqi and Husen, 2021), titanium, zinc oxide (Saberi-Rise and Moradi-Pour, 2020), silica (Karunakaran et al., 2013), calcium, boron (Meier et al., 2020), gold (Panichikkal et al., 2019), and zeolite nanoparticles (Khati et al., 2018) have all been reported to enhance plant growth. Research has shown that combining Bacillus strains with silver nanoparticles can greatly benefit the growth and health of maize plants (*Zea mays*). According to Kumar et al. (2020), this combination not only promotes the growth of roots and shoots but also protects the plants by preventing fungal infections. This dual action makes it an effective solution for improving plant growth while reducing the risk of disease.

Additionally, the use of nano titanium dioxide (TNs) has been found to improve the performance of plant growth-promoting rhizobacteria (PGPR). Timmusk et al. (2018) explain that TNs help these beneficial bacteria attach more effectively to plant roots. This stronger attachment makes it easier to apply PGPR in agricultural fields and ensures they can provide their full range of benefits to the plants. Together, these advancements highlight how nanotechnology can enhance the use of beneficial microbes in agriculture, leading to healthier and more productive crops.

Table 2.1: Effect of various nanoparticles on plant with PGPR.

S.no	**Nanoparticles /Nanomaterials**	**Plant (Common and Scientific name)**	**PGPR**	**Effects**	**Reference**
1.	Molybdenum nanoparticles	Wheat (*Triticum*)	*Bacillus sp*. strain ZH16	Helps to increase in morphological characteristics, nutrients availability and balance of ionic condition in wheat plants	(Ahmed et al., 2022)
2.	Silicon dioxide nanoparticles	Wheat (*Triticum*)	*Azospirilluml ipoferum and Azospirillum brasilense Bacillus sp.*	improved physicochemical parameters, the growth and yield of wheat; improved relative water content, increased nutrients uptake, antioxidant enzymes- such as catalase, superoxide dismutase and peroxidase increased their up regulation with (81.69%), (60.49%), (55.99%) respectively.	(Akhtar et al., 2021)
3.	Silicon nanoparticles nanoparticles	Lemon balm (*Melissa*	(*Pseudomonas fluorescens and P. putida)*	the free radical scavenging activities of plant extracts emphasized	(Hatami et al., 2021)

		officinalis L)			
4.	Magnesium oxide nanoparticles	Radish (*Raphanus sativus L*.)	-	Enhanced secondary metabolite production; Increase in total phenolic and dry biomass	(Hussain et al., 2019)
5.	Silver nanoparticles	-	*Azotobactervinelandii*	Ag NPs effects differently at particles size 10nm and 50 nm. Inhibited the growth of bacteria and facilitate the rate of cell apoptosis. effective against nitrogenase activity and ROS detection.	(Zhang et al., 2018)
6.	Silver nanoparticles	-	*Nitrosomonas europaea*ATCC19718	It restricts the biosynthesis of protein, gene expression and production of energy.	(Yuan et al., 2013)
7.	Iron nanoparticles	-	*Paracoccus* sp.	Excess amount of Iron (II) generates oxidative damage to the cells, and adhered to cell membranes and changed bio nitrification of the strain.	(Jiang et al., 2015)
8.	Silver Nanoparticles and Iron oxide nanoparticles	-	Soil microbial activity	Silver NPs reduced soil microbial metabolic activity, nitrification potential and the influences of ammonia	(He et al., 2016)

				oxidizing bacteria. In contrast, Iron oxide nanoparticles promote the soil microbial metabolic activity and positively influence on C and N cycle. nitrification.	
9.	Gold nanoparticles	Cow pea *(Vigna unguiculata* L.)	*P. monteilii*	increased growth, enhanced production of IAA	(Panichikkal et al., 2019)
10.	Zero Valent Iron nanoparticles	White willow (*Salix alba L*.)	*Pseudomonas fluorescens.*	low doses (150mg/kg) enhanced root length and leaf area per plant. It had no negative effect on plant growth and various parameters. high dose (300mg/kg) reduced plant growth, induced stress, no positive effect on heavy metal uptake.	(Mokarram-Kashtiban et al., 2019)
11.	Magnesium oxide nanoparticles	Radish (*Raphanus sativus L*.)	-	Helps to enhanced plant growth, secondary metabolites, free radical scavenging activity, and phytoaccumulation of lead	(Salas-Leiva et al., 2021)

12.	Zero Valent Iron nanoparticles	White clover (*Trifolium repens*)	PGPR	Increases plant photosynthesis, plant growth and phytoremediation performance	(Zand et al., 2020)
13.	Silver nanoparticles	Wheat (*Triticum*)	*Burkholderia* sp., *Bacillus cereus, Bacillus* spp.,	raised sugar production and translocation to grains. biocontrol potential against yellow rust	(Bano, 2020)
14.	Graphite and Silica nanoparticles	Potato (*Solanum tuberosum*)	*Lysinibacillus* sp., *B.subtilis,* and *P.fluorescens*	Isolated PGPR reduced the wilt disease caused by *R. Alstoniasolanacearum,* and mechanism of biocontrol affected by the formulation of NPs	(Djaya et al., 2019)
15.	Titanium dioxide nanoparticles	Beans (*Phaseolus vulgaris L.*)	*Bacillus subtilis* Vru1	Helps to increase the vegetative growth parameters of plant and the level of metabolites production such as indole-3-acetic acid,	(Saberi-Rise and Moradi-Pour, 2020)
16.	Gold nanoparticles		*P. fluorescens, B.subtilis,* and *P.putida*	in *P. putida* no significant impact was observed due to Au NPs. On the contrary, significant increase was observed in the case of *P. fluorescens,* and *B. subtilis,*	(Shukla et al., 2015)

				P. Elgii has potential to be used as a nano biofertilizer	
17.	Nano zeolite	Maize (*Zea mays*)	*Bacillus spp.*	enhancing growth, plant health domain and crop productivity.	(Khati et al., 2018)
18.	Silver nanoparticles	Onion seedlings (*Allium cepa*)	*Bacillus pumilus* and *Pseudomonas moraviensis*	It increased the sugar and proline contents. maximum increase in protein content of bulb, decreased the leaf flavonoids but had significant increase in the bulb flavonoid contents.	(Jahangir et al., 2020)
19.	molybdenum nanoparticles	Chickpea (*Cicer arietinum L.*)	*Bacillus subtilis*	improved the physiological status of the plant, increasing structural diversity of the microbial community of the rhizosphere through changes in the activity of root exudates	(Raffi and Husen, 2019)
20.	Iron oxide nanoparticles	(*Brassica napus L.*)		enhancing growth and agronomic traits by reducing ROS damage and improving oxidative defense system	(Palmqvist et al., 2017)
21.	Iron oxide nanoparticles	Thale cress (*Arabidopsis thaliana*)		Inhibitory effects on development.	(Bombin et al., 2015)

22.	Iron nanoparticles	Cow pea *(Vigna unguiculata* L.)		Increased seedling growth	(Rahimi et al., 2016)
23.	Silicon dioxide nanoparticles	Perennial ryegrass (*Loliumperenne*)		improved mineral nutritional value and other quality indexes	(Mahdavi et al., 2016)
24.	Silicon dioxide nanoparticles	Tomato (*Solanumlycopersicum*)		enhances seed germination	(Iqbal et al., 2021)
25.	Silicon dioxide nanoparticles	Maize (*Zea mays*)	*Azotobacter,* *B. megaterium, B. brevis,* and *P. fluorescens*	SiO_2 particles had nontoxic effect on PGPRs at to 1000 mg L^{-1}	(Karunakaran et al., 2013)
26.	Zinc oxide nanoparticles	sorghum		mitigated the negative influences on drought stress (40% of field moisture capacity)	(Dimkpa et al., 2019)
27.	Zinc oxide nanoparticles	*Brassica napus*		showed improvement in plant growth at 10 mg/L, while at higher concentration	(Rahmani et al., 2016)

				(1000 mg/L) resulted in toxic effects	
28.	Zinc oxide nanoparticles	*Allium cepa L.*		at higher concentration of ZnO, the rate of seed germination decreased and at lower concentration seed germination rate increased	(Laware and Raskar, 2014)
29.	Calcium Phosphate Nanoparticles	strawberry		nano-CaP NPs at 15 ppm is very important to improve quality and storability of fruits and gave good appearance with the lowest values of weight loss, and zero decay percentage	(Zakaria et al., 2018)
30.	Calcium Phosphate Nanoparticles	Rice		help in reduction of the quantity of fertilizer in crops and contributing to reduces fertilizer wastage due to agricultural malpractices	(Upadhyaya et al., 2017)

2.4 Co-application of ZnO NPs and PGPR in plants

The combined application of ZnO NPs and PGPR creates a synergistic system that significantly boosts plant growth and productivity. ZnO NPs serve as a highly bioavailable source of zinc, an essential micronutrient for enzymatic functions and photosynthesis. When integrated with PGPR such as *Pseudomonas fluorescens* or *Bacillus subtilis*, these

NPs enhance zinc solubilization and uptake, improving nutrient efficiency (Jalal et al., 2023).

PGPR further amplifies the benefits by producing phytohormones, solubilizing phosphates, and inducing systemic resistance to environmental stress. Studies indicate that this combination improves root and shoot biomass, enhances photosynthetic activity, and increases crop yield, while reducing the reliance on chemical fertilizers. This synergistic effect highlights the potential of combining ZnO NPs with PGPR to foster sustainable agricultural practices.

Recent research has also explored the effects of ZnO NPs in combination with *Bacillus hynseii*, another PGPR. ZnO NPs, known for their antimicrobial properties and ability to mitigate abiotic stresses, work alongside *Bacillus hynesii* to improve nutrient uptake and promote phytohormone production (Rehman et al., 2019). This synergy has led to improvements in plant physiological parameters, including increased chlorophyll content, enhanced root and shoot biomass, and better overall stress resilience. Studies show that ZnO NPs facilitate nutrient availability in the rhizosphere, improve interactions between PGPR and plant roots, and activate stress-response pathways, reducing oxidative stress by modulating antioxidant enzyme activity (Singh et al., 2022).

Such advancements emphasize the dual benefits of ZnO NPs in agriculture and also reducing the need for chemical inputs while enhancing crop productivity through microbial synergy (Zhou et al., 2023). This combined approach is opening new pathways for sustainable agricultural practices that address global food security challenges, particularly in the context of climate change and resource limitations.

The integration of ZnO NPs with *Priestia megaterium*, a PGPR known for enhancing soil enzyme activities and nutrient availability, has also shown promising results. Studies highlight that when paired with ZnO NPs, *P. megaterium* promotes root colonization and supports robust plant growth, even under saline conditions, improving both soil fertility and plant health (Shi et al., 2023).

Additionally, ZnO NPs combined with *Pseudomonas aeruginosa* (a close relative of *P. sonengensis*) have been studied for their effects on plant growth and disease management.

ZnO NPs not only promote plant growth by enhancing nutrient uptake and root colonization but also provide biocontrol against plant pathogens due to their antimicrobial properties. PGPRs like *Pseudomonas aeruginosa* contribute to plant health by enhancing immune responses and supporting overall growth (Verma et al., 2024).

Further studies on chemically synthesized ZnO NPs, typically in the range of 70–80 nm, have demonstrated their potential in promoting plant growth when applied with PGPR. The ZnO NPs improve seed germination, enhance photosynthetic pigment production, and boost antioxidant activity. However, it is important to note that the effects can vary based on the concentration and synthesis method. Higher concentrations of ZnO NPs may reduce seed germination rates, indicating the accurate application (Sánchez-Pérez et al., 2023).

Recent studies on the use of ZnO NPs and PGPR for groundnut (*Arachis hypogaea*) growth have shown significant improvements in seed germination, root length, and shoot biomass. ZnO NPs help stimulate antioxidant enzyme activities, enhancing the plant's resistance to oxidative stress, while PGPRs contribute by solubilizing phosphates, producing phytohormones like indole-3-acetic acid (IAA), and improving soil microbial ecosystems. This synergistic effect results in increased plant vigor and yield, while reducing the need for chemical fertilizers, thereby promoting more sustainable agricultural practices (Hamzah et al., 2022; Prasad et al., 2017).

Studies suggest that while ZnO NPs improve nutrient uptake and stress resilience, PGPRs play a crucial role in mitigating potential stress caused by NPs, ensuring the maximum benefit without harm to the plant (Alhujaily et al., 2022). Additionally, the antioxidant properties of plants treated with ZnO nanoparticles (ZnO NPs) help them handle environmental stress better, making this method more sustainable.