DOI: https://doi.org/10.54083/978-81-980121-1-1-11

CHAPTER : 11

Role of Plant Growth Promoting Rhizobacteria in Disease Management

Bandana Hijam[1] and Oinam Washington Singh[2*]

[1]Department of Plant Pathology, Uttar Banga Krishi Viswavidyalaya, Cooch Behar, West Bengal (736 165), India
[2]College of Agriculture, Central Agricultural University (Imphal), Kyrdemkulai, Meghalaya (793 105), India

Abstract

The change in global climate over the past decades led to rapid increase of various new plant disease outbreaks. Utilizing synthetic chemicals for controlling diseases has always been the ultimate option for disease management. However, modern-day agriculture calls for a sustainable approach towards disease management which will improve crop health as well as be environmentally sound. Plant growth-promoting rhizobacteria (PGPR) play a crucial role in this approach. They are a free-living, diverse group of beneficial microorganisms that colonizes plant roots and improve plant health by suppressing soil-borne pathogens and inducing systemic resistance. They achieve this through various mechanisms, such as, antibiotic and siderophore production, that aid in pathogen control and promoting plant health, through competition with pathogens for resources, minimizing the pathogen population and also modulating plant defense responses through induce resistance via jasmonic acid and ethylene dependent pathways. Unlike synthetic chemicals, which have a negative impact on human health and the environment, PGPRs are natural and non-toxic. They can be used as an alternative to traditional synthetic agro-chemicals. They are effective in controlling soil-borne diseases and also act as bio-inoculants or biofertilizers to enhance crop yield. Bacterial strains like *Bacillus*, *Pseudomonas* and *Streptomyces* are known to exhibit effective control for soil-borne diseases in crops like rice, wheat and maize. Integrating PGPR into agricultural practices not only reduces the heavy reliance on synthetic chemicals but also, directly and indirectly, enhances the soil health and promotes environment-sound agriculture. This chapter explores the potential of PGPR as a key player in innovative and eco-conscious plant disease management strategies.

Keywords biopesticide, endophytes, disease management, PGPR, ISR, rhizobacteria

1. Introduction

The increasing challenges posed by climate change and the ever-increasing global population are exerting significant pressure on modern agriculture. As it has been estimated, by 2050, the world population will reach 9.7

---

*__Corresponding author's e-mail__: oinamw@gmail.com

In: Current Trends in the Diagnosis and Management of Plant Diseases. (Eds.) Dutta, P., Upamanya, G.K., Pandey, A.K., 2024. Biotica Publications, Tripura, India.

billion (Lal, 2016), food demand will also rise sharply, compounded by the impact of climate-related factors and other biotic stress such as diseases and pests, as well as abiotic stressors like salinity and drought. These factors are major threats to crop productivity and addressing them is critical to ensuring food security. Globally, plant pathogens and pests are responsible for reducing crop yields by 21-30% (Junaid and Gokce, 2024). For decades, synthetic chemicals, such as pesticides, insecticides and fungicides have been heavily relied upon to combat these threats. However, prolonged use of these chemicals will eventually lead to the development of new races of pathogen which have resistance to these chemicals, and reduced their effectiveness (Cloete, 2003). This chemical dependency also presents broader environmental and health risks, including soil degradation, long-term health hazards from chemical residues and disruptions to ecological balance. As a result, there is a growing need for sustainable agricultural practices that reduce chemical inputs, promote soil health and ensure long-term environmental and societal well-being. One promising strategy in sustainable agriculture is the use of PGPR. These beneficial microbes play a crucial role in supporting plant health by enhancing nutrient uptake, growth promotion and inducing protection against a range of plant diseases without harmful side effects (Mustafa *et al.,* 2019). PGPR are increasingly recognized as effective, environmentally friendly alternatives for plant disease management. Acting as bio-control agents, they offer several advantages over chemical interventions. They can be applied as microbial inoculants (biofertilizers) to boost crop yields, produce antibiotics, siderophores and cell wall-degrading enzymes and stimulate systemic resistance, enabling an active defense mechanism in plants against pathogens while enhancing overall plant growth (Harish *et al.,* 2019).

2. What are PGPRs: A General Overview

A plant/ plants grown in the field is not just a single organism but a complex community known as the phyto-microbiome, which includes various microorganisms such as fungi, bacteria, viruses and nematodes, associated with different plant structures like leaves, flowers, stems, fruits, and roots. The roots, in particular, host a diverse and intricate microbial community called the rhizomicrobiome, with nitrogen-fixing bacteria like rhizobia being a well-documented example (Jain *et al.,* 2020). This microbial community is integral for the plant's survival, aiding in nutrient acquisition and adaptation to environmental stressors. The rhizospheric soil region is directly influenced by plant roots, rich in nutrients due to plant exudates like amino acids and sugars. This area hosts a significantly higher concentration of bacteria, than in bulk soil (Kumar, 2019). These bacteria are known as rhizobacteria which can be beneficial, neutral or harmful, based on their impact on overall growth of the plant. When such rhizobacteria have a beneficial effect on plants, they are considered as plant growth-promoting rhizobacteria or simply PGPR. It constitutes only 2-5% of rhizobacteria present in the soil (Kloepper and Schroth, 1981), and they either live freely in the soil or form a symbiotic relationship with the plant. They mostly colonize the rhizosphere, rhizoplane, or even the root tissues and enhance plant growth. Among the various PGPR, genera like *Bacillus* and *Pseudomonas* are particularly prominent.

3. Classifications of PGPRs

3.1. Based on their root associations' nature, PGPRs are categorized into two types:

a. Extracellular PGPR (ePGPR): These group of bacteria are mostly resided in the root cortex, or the rhizosphere/rhizoplane region, *e.g.*, *Azotobacter*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *etc.*

b. Intracellular PGPR (iPGPR): These group of bacteria are located inside the root cells by forming specialized nodule structures, *e.g.*, *Rhizobium* spp., *Bradyrhizobium*, *Frankia* spp., *etc.*

3.2. Based on the function in plant growth and disease suppression, PGPR can be classified as:

a. Biofertilizers: PGPR that enhance plant nutrient uptake and improve growth through nitrogen fixation, phosphate solubilization, or mineralization of nutrients, *e.g.*, *Azotobacter, Phosphobacteria.*

b. Biopesticides: PGPR that suppress plant diseases by producing antibiotics, competing with pathogens, or inducing plant defenses, *e.g.*, *Bacillus* spp., *Pseudomonas* spp.

c. Phytostimulators: PGPR that promote plant growth by producing phytohormones or enhancing root development, *e.g.*, *Azospirillum*, *Bacillus* spp.

4. Mechanism of Disease Suppression by PGPR

PGPR are essential biocontrol agents in plant disease management, interacting with both pathogens and plants to suppress diseases. PGPRs employ direct and indirect mechanisms to manage plant diseases, which can range from producing antimicrobial compounds to competing for resources and space with pathogens. Additionally, they can induce resistance (ISR) in plants and activate various defense mechanisms to protect plants from invading pathogens while promoting plant growth as well. Let's explore these mechanisms in more detail:

4.1. Direct mechanism

4.1.1. Production of Antibiotics

One of the most significant mechanisms of PGPRs to combat plant pathogens is the production of antibiotics, which are organic compounds that, even in small concentrations, can inhibit the growth or disrupt the metabolism of pathogens. PGPRs produce a wide range of antibiotics, such as amphisin, butyro-lactones and 2,4-diacetylphloroglucinol (DAPG), which inhibits many plant pathogens, especially fungi and bacteria (Whipps 2001; Nielsen *et al.,* 1999; Nyfeler and Ackermann, 1992).

Some of the key antibiotics produced by PGPRs include:

- Cyclic lipopeptides: Effective in inhibiting various fungi and bacteria.
- Phenazines, phloroglucinols, pyrrolnitrin, pyoluteorin: These compounds inhibit pathogen growth by damaging membranes and inhibiting vital biological processes.
- Hydrogen cyanide (HCN): A volatile compound that disrupts respiration in pathogens.

The effectiveness of these antibiotics depends on external conditions like soil moisture, temperature and the availability of plant root exudates. Antibiotic production also varies based on the host plants and nutrient availability. For instance, glucose enhances DAPG production in certain Pseudomonas strains, while phosphate fertilizers can suppress antibiotic synthesis.

Examples:

- *Pseudomonas fluorescens* produces several antibiotics, including DAPG, HCN and pyoluteorin, which help suppress diseases like wheat's take-all disease (Kwak *et al.,* 2013).
- *Bacillus cereus* produces zwittermicin A and kanosamine, which suppress oomycete pathogens like *Fusarium* and *Pythium* (Shang *et al.,* 1999*)*.

4.1.2. Enzyme Production: PGPRs produce various enzymes that disrupts the growth and proliferation of fungi through degradation of their cell walls. Important enzymes include:

- Chitinase: Breaks down the chitin present in the fungal cell walls.
- β-1,3-glucanase: Degrades glucan, another component of fungal cell walls.

E.g., *Pseudomonas fluorescens* and *Bacillus cereus* produce these enzymes to target pathogens like *Fusarium oxysporum* and *Rhizoctponia solani*, leading to pathogen cell wall damage and inhibition (Chernin *et al.,* 1997; Benhamou *et al.,* 1996).

4.1.3. Volatile Organic Compounds (VOCs)

PGPRs also release volatile organic compounds (VOCs) that have antifungal and antibacterial properties. These VOCs include substances like 2-(benzyloxy)-1-ethanamine and cyclohexane, which suppress pathogen growth. HCN is a notable VOC, produced by various PGPRs, that controls phytopathogens by interfering with their cellular respiration.

E.g., *Bacillus* spp. emit VOCs with antifungal activity, contributing to the overall plant health and pathogen suppression (Siddiqui *et al.,* 2006).

4.1.4. Bacteriocin Production

PGPRs can produce bacteriocins, proteins that specifically target and kill closely related bacterial strains. Bacteriocins are highly effective against certain bacterial pathogens, but their action is often limited to closely related species (Holtsmark *et al.,* 2008; Compant *et al.,* 2005).

E.g., Colicins produced by *Escherichia coli* target other related strains, while pyocins from *Pseudomonas spp.* are effective against other bacterial species in the rhizosphere.

4.2. Indirect mechanism

a) Competition: In order to provide vital nutrients for microbial growth, plants emit organic acids, carbohydrates, and amino acids into the rhizosphere. PGPRs can outcompete pathogens for these carbon sources, creating a competitive advantage (Wang *et al.,* 2018). PGPRs also excrete novel metabolites into the soil, attracting beneficial microorganisms while suppressing harmful pathogens. *E.g.*, By promoting stronger root systems, rhizobacteria can create phytohormones such as cytokinin and indole-3-acetic acid (IAA), which can enhance the plant growth and lessen the impact of pathogens (Idris *et al.,* 2008).

b) Siderophore Production: Despite being an essential ingredient for many species, iron is frequently scarce in soil. Siderophores, which are molecules that bind and sequester iron, are produced by PGPRs, depriving pathogens of this vital nutrient (Kumar *et al.,* 2018). By outcompeting pathogens for iron, PGPRs limit their growth and ability to cause disease. *E.g.*, *Pseudomonas putida* produces pyoverdin, a siderophore that limits the growth of *Fusarium oxysporum* by sequestering iron in the rhizosphere (Buysens *et al.,* 1996).

c) Induced Systemic Resistance (ISR): PGPRs can “prime” plant defense systems through a process called ISR. In contrast to systemic acquired resistance which is induced by a pathogen, ISR is induced by beneficial microbes such as PGPRs and does not necessitate direct pathogen infection (Kuc, 1995). Signaling chemicals such as ethylene and jasmonic acid promote ISR, which strengthens the plant’s defenses against a variety of diseases, such as bacteria, viruses, nematodes, and fungi (Annapurna *et al.,* 2013). *E.g.*, *Pseudomonas fluorescens* induces ISR in plants, protecting them from cucumber mosaic virus and tobacco necrosis virus (Ryu *et al.,* 2003).

5. Prerequisites for Selecting Potent PGPRs for Developing Effective Bio-Formulation

To develop an effective bio-formulation using PGPR, the selected species must meet specific criteria to ensure they perform well under field conditions. These include:

a) Plant growth enhancement: The chosen PGPR strain should be highly effective in promoting plant growth.

b) Scalability: The species should be easy to culture on a large scale to support widespread use.

c) Rhizospheric competence: The PGPR should have strong rhizosphere competence, meaning it can easily establish itself and thrive in the root zone.

d) Competitive saprophytic ability (CSA): The strain must outcompete other microorganisms for nutrients and resources in the soil.

e) Multiple beneficial activities: It should exhibit a broad spectrum of beneficial activities, such as nutrient solubilization, hormone production and disease suppression.

f) Coexistence with other rhizobacteria: The PGPR must coexist harmoniously with other beneficial microorganisms in the environment.

g) Stress tolerance: It should withstand abiotic stresses, including heat, desiccation, radiation and oxidative conditions, to ensure survival in different environmental conditions.

h) Environmental safety: The PGPR should be environmentally safe, non-toxic and pose no harm to plants, animals, or humans.

6. Commercialization of PGPR

PGPR has gained considerable attention due to its wide-ranging benefits in enhancing plant growth. Substantial research has explored various PGPR strains, many of which have shown remarkable results in promoting plant health. Despite this progress, commercialization of these strains is urgently needed and collaboration between scientists and industries is vital for this process. To facilitate large-scale field applications, PGPR must be formulated with suitable carriers for mass production. The development of PGPR powdered formulations began in the 1980s and have proven particularly valuable for seed treatments and soil applications. Common bioformulations are used extensively in horticulture and agriculture to treat plant diseases, including those based on liquid and talc (Ahangar *et al.,* 2012; Manikandan *et al.,* 2010; Vidhyasekaran and Muthamilan, 1999). However, these formulations often face challenges, including short shelf life, storage difficulties, inconsistent quality and reduced performance in the field. To address these limitations, bioformulations with better shelf lives were developed by incorporating vegetative cells of antagonistic organisms as active ingredients. Further developments have produced solid formulations that have been effectively tested to control sheath blight of rice in controlled settings (Wiwattanapatapee *et al.,* 2013). Use of nanoparticles as carrier molecules in the formulation will significantly enhance the shelf life, and guaranteeing efficient distribution to specific plant systems. Longer-lasting formulations are especially preferred since they enable PGPR to become established in the soil, last longer, increase soil fertility, and shield plants from dangerous infections. In order to fulfill the demands of the developing world, high-yield crops and environmentally friendly fertilizers are essential. Many PGPR products are already commercially accessible and in use in various countries in Europe, despite these obstacles. These products offer a variety of advantages for improved plant growth as biopesticides, rhizoremediators, phytostimulators, and biofertilizers (Antoun and Prévost, 2005). *Azospirillum*, *Pseudomonas*, *Bacillus*, *Burkholderia*, *Azotobacter*, *Rhizobium*, and *Serratia* are well-known commercially available PGPR strains (Nandakumar *et al.,* 2001).

7. Integrating Nanotechnology in PGPR for Sustainable Agriculture

Modern agricultural practices can benefit from advanced techniques like nanotechnology and genetic manipulation to enhance the performance of PGPR strains. Genetic engineering modifies the DNA of PGPR to improve their stress resistance, nutrient uptake and chemical production. Tools like CRISPR-Cas9 enable precise genetic alterations, allowing PGPR to better support plant health. In nano-agriculture, nanosized particles such as nanofertilizers offer innovative solutions to improve nutrient uptake and crop productivity. These particles have special physical, chemical, and biological characteristics that help protect plants, detect diseases, track growth, improve food quality, boost output, and cut down on waste. For example, compared to traditional fertilizers, nanofertilizers are more effective. They reduce nitrogen loss through leaching, lower emissions and improve soil incorporation over time. Controlled-release nanofertilizers have been shown to mitigate the toxic effects of excessive traditional fertilizer use, promoting better soil health (Rani *et al.,* 2020). Traditional PGPR bio-fertilizers often experience significant loss due to air exposure, environmental intolerance and runoff, which increases application costs. Nanoencapsulation technology can help resolve these issues by shielding PGPR from environmental stress, enhancing their longevity and distribution and enabling controlled release in fertilizer formulations. In the U.S., nanomaterials are employed in targeted delivery systems, precision farming and controlled-release pesticides, with nanosensors monitoring soil conditions to optimize irrigation and fertilization (Nayan *et al.,* 2020). In China, nanoparticles enhance soil fertility and crop health (Khanm *et al.,* 2018), while Japan focuses on smart nanomaterials to improve seed germination and nutrient absorption (Siddiqui, 2015). The integration of nanomaterials with PGPR offers substantial benefits. Nanoparticles can deliver PGPR-produced chemicals directly to plant roots, improving nutrient availability and stress tolerance (Yadav *et al.,* 2012). Smart nanomaterials, capable of adapting to environmental changes, ensure precise delivery of growth-promoting substances while minimizing environmental impact. Modern nanotechnology and genetic engineering have the potential to completely transform agriculture, making it more productive, sustainable, and able to supply the world's food needs. This synergy holds great promise for addressing the challenges of modern agriculture and supporting a growing population.

8. Conclusion

PGPRs offer us a promising alternative over traditional chemical pesticides in plant disease management, harnessing natural processes to combat pathogens. Their ability to enhance plant growth, induce resistance and directly suppress disease-causing agents makes them a valuable component in achieving sustainable agriculture. While current research is largely confined to controlled environments, pre-treated soil, pot cultures and greenhouse systems, expanding studies to real-world conditions and integrating PGPRs with other biocontrol methods could unlock their full potential. With the evolution of new disease outbreaks due to the rapidly changing climatic scenario, present-day agriculture targets for a climate resilient, sustainable environmentally sound approach towards disease control, PGPRs offer us a promising role in advancing eco-friendly and effective plant disease management solutions.

9. References

Ahangar, M.A., Dar, G.H., Bhat, Z.A., 2012., Growth response and nutrient uptake of blue pine (*Pinus wallichiana*) seedlings inoculated with rhizosphere microorganisms under temperate nursery conditions. *Annals of forest research*, *55*(2), 217-227.

Annapurna, K., Kumar, A., Kumar, L.V., Govindasamy, V., Bose, P., Ramadoss, D., 2013. PGPR-induced systemic resistance (ISR) in plant disease management. *Bacteria in agrobiology: disease management*, 405-425.

Antoun, H., Prévost, D., 2006. Ecology of plant growth promoting rhizobacteria. *PGPR: Biocontrol and biofertilization*, 1-38.

Benhamou, N., Kloepper, J.W., Quadt-Hallman, A., Tuzun, S., 1996. Induction of defense-related ultrastructural modifications in pea root tissues inoculated with endophytic bacteria. *Plant physiology*, *112*(3), 919-929.

Buysens, S., Heungens, K., Poppe, J., Hofte, M., 1996. Involvement of pyochelin and pyoverdin in suppression of *Pythium*-induced damping-off of tomato by *Pseudomonas aeruginosa* 7NSK2. *Applied and environmental microbiology*, *62*(3), 865-871.

Chernin, L.S., De La Fuente, L., Sobolev, V., Haran, S., Vorgias, C.E., Oppenheim, A.B., Chet, I., 1997. Molecular cloning, structural analysis and expression in Escherichia coli of a chitinase gene from *Enterobacter agglomerans*. *Applied and environmental microbiology*, *63*(3), 834-839.

Cloete, T.E., 2003. Resistance mechanisms of bacteria to antimicrobial compounds. *International Biodeterioration & Biodegradation*, *51*(4), 277-282.

Compant, S., Duffy, B., Nowak, J., Clément, C., Barka, E.A., 2005. Use of plant growth-promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action and future prospects. *Applied and environmental microbiology*, *71*(9), 4951-4959.

Harish, S., Parthasarathy, S., Durgadevi, D., Anandhi, K., Raguchander, T., 2019. Plant growth-promoting rhizobacteria: harnessing its potential for sustainable plant disease management. *Plant growth promoting Rhizobacteria for agricultural sustainability: from theory to practices*, 151-187.

Holtsmark, I., Eijsink, V.G., Brurberg, M.B., 2008. Bacteriocins from plant pathogenic bacteria. *FEMS microbiology letters*, *280*(1), 1-7.

Idris, H.A., Labuschagne, N., Korsten, L., 2008. Suppression of Pythium ultimum root rot of sorghum by rhizobacterial isolates from Ethiopia and South Africa. *Biological Control*, *45*(1), 72-84.

Jain, S., Jain, J., Singh, J., 2020. The rhizosphere microbiome: Microbial communities and plant health. *Plant microbiome paradigm*, 175-190.

Junaid, M.D., Gokce, A.F., 2024. Global agricultural losses and their causes. *Bulletin of Biological and Allied Sciences Research*, *2024*(1), 66-66.

Khanm, H., Vaishnavi, B.A., Shankar, A. G., 2018. Rise of nano-fertilizer ERA: Effect of nano scale zinc oxide particles on the germination, growth and yield of tomato (*Solanum lycopersicum*). *International Journal of Current Microbiology and Applied Sciences, 7*(5), 1861–1871.

Kloepper, J.W., Schroth, M.N., 1981. Plant growth-promoting rhizobacteria and plant growth under gnotobiotic conditions. *Phytopathology*, *71*(6), 642-644.

Kuc, Joseph., 1995. Induced systemic resistance—an overview. *Induced resistance to disease in plants*, 169-175.

Kumar, P., Thakur, S., Dhingra, G.K., Singh, A., Pal, M.K., Harshvardhan, K., Maheshwari, D.K., 2018. Inoculation of siderophore producing rhizobacteria and their consortium for growth enhancement of wheat plant. *Biocatal Agric Biotechnol* 15: 264–269.

Kumar, V.V., 2019. Influence of the rhizospheric microbiome in plant health management. *Microbiome in Plant Health and Disease: Challenges and Opportunities*, 215-230.

Kwak, Y.S., Weller, D.M., 2013. Take-all of wheat and natural disease suppression: a review. *The Plant Pathology Journal*, *29*(2), 125.

Lal, R., 2016. Feeding 11 billion on 0.5 billion hectare of area under cereal crops. *Food and Energy Security*, *5*(4), 239-251.

Manikandan, R., Saravanakumar, D., Rajendran, L., Raguchander, T., Samiyappan, R., 2010. Standardization of liquid formulation of *Pseudomonas fluorescens* Pf1 for its efficacy against *Fusarium* wilt of tomato. *Biological control*, *54*(2), 83-89.

Mustafa, S., Kabir, S., Shabbir, U., Batool, R., 2019. Plant growth promoting rhizobacteria in sustainable agriculture: from theoretical to pragmatic approach. *Symbiosis*, *78*, 115-123.

Nandakumar, R., Babu, S., Viswanathan, R., Sheela, J., Raguchander, T., Samiyappan, R., 2001. A new bio-formulation containing plant growth promoting rhizobacterial mixture for the management of sheath blight and enhanced grain yield in rice. *Biocontrol*, *46*, 493-510.

Nayana, A.R., Joseph, B.J., Jose, A., Radhakrishnan, E.K., 2020. Nanotechnological advances with PGPR applications. *Sustainable Agriculture Reviews, 41*, 163–180.

Nielsen, T.H., Christophersen, C., Anthoni, U., Sørensen, J., 1999. Viscosinamide, a new cyclic depsipeptide with surfactant and antifungal properties produced by *Pseudomonas fluorescens* DR54. *Journal of Applied Microbiology*, *87*(1), 80-90.

Nyfeler, R., Ackermann, P., 1992. Phenylpyrroles, a new class of agricultural fungicides related to the natural antibiotic pyrrolnitrin.

Rani, R., Bernela, M., Malik, P., Mukherjee, T., 2020. Chapter 9. Nanofertilizers applications and future prospects. In R. K. Sindhu, M. Chitkara, & S. I. Sandhu (Eds.), *Nanotechnology: Principles and Applications* (pp. 145–163). Jenny Stanford Publishing.

Ryu, C.M., Hu, C.H., Reddy, M.S., Kloepper, J.W., 2003. Different signaling pathways of induced resistance by rhizobacteria in *Arabidopsis thaliana* against two pathovars of *Pseudomonas syringae*. *New Phytologist*, *160*(2), 413-420.

Shang, H., Chen, J., Handelsman, J., Goodman, R.M., 1999. Behaviour of *Pythium torulosum* zoospores during their interaction with tobacco roots and *Bacillus cereus*. *Current Microbiology*, *38*, 199-204.

Siddiqui, I.A., Shaukat, S.S., Sheikh, I.H., Khan, A., 2006. Role of cyanide production by *Pseudomonas fluorescens* CHA0 in the suppression of root-knot nematode, *Meloidogyne javanica* in tomato. *World Journal of Microbiology and Biotechnology*, *22*, 641-650.

Siddiqui, M.H., Al-Whaibi, M.H., Mohammad, F., 2015. Nanotechnology and plant sciences: Nanoparticles and their impact on plants. *Nanotechnology in Plant Sciences: Nanoparticle Impact on Plants, 10*, 1–303.

Vidhyasekaran, P., Muthamilan, M., 1999. Evaluation of a powder formulation of *Pseudomonas fluorescens* Pf1 for control of rice sheath blight. *Biocontrol Science and Technology*, *9*(1), 67-74.

Wang, Z., Jiang, M., Chen, K., Wang, K., Du, M., Zalán, Z., Kan, J., 2018. Biocontrol of *Penicillium digitatum* on postharvest citrus fruits by *Pseudomonas fluorescens*. *Journal of food quality*, *2018*(1), 2910481.

Whipps, J.M., 2001. Microbial interactions and biocontrol in the rhizosphere. *Journal of experimental Botany*, *52*(suppl_1), 487-511.

Wiwattanapatapee, R., Chumthong, A., Pengnoo, A., Kanjanamaneesathian, M., 2013. Preparation and evaluation of *Bacillus megaterium*-alginate microcapsules for control of rice sheath blight disease. *World Journal of Microbiology and Biotechnology*, *29*, 1487-1497.

Yadav, T.P., Yadav, R.M., Singh, D.P., 2012. Mechanical milling: A top-down approach for synthesis of nanoparticles and nanocomposites. *Nanoscale Science & Nanotechnology, 2*(1), 22–48.