Chapter 9
Nanotechnological Advances with PGPR Applications

A. R. Nayana, Bicky Jerin Joseph, Ashitha Jose, and E. K. Radhakrishnan

Abstract Plant growth promoting rhizobacteria (PGPR) are soil bacteria which have the potential for direct and indirect effects on plant growth. These organisms may have the capability to limit or replace the use of chemical fertilizers and inputs of toxic chemicals. Exploring PGPR in agriculture is, thus, one of the more promising techniques for increasing agricultural production without harming ecosystems. At the same time, nano-technological applications are greatly imparting their influence in agriculture. When compared against conventional fertilizers, nano-fertilizers play an effective role in promoting plant growth as they are rapidly absorbed by plants. Hence, nano-materials such as nano-fibers, nano-fertilizers and nano-pesticides may produce revolutionary effects in the agricultural sector. PGPR together with nanomaterials may thus be a favorable strategy for managing plant growth and productivity. The application of nanomaterials like silver, titanium, zinc oxide, silica, gold and others with PGPR holds great promise. However, there can be both positive and negative impacts of engineered metal nanoparticles on rhizobacteria. Hence, engineered nanoparticle (ENPs) must be studied further to explore their use as ecofriendly agents for field application. In this chapter we describe the effects of nanofertilizers with PGPR as an innovative method for improving crop productivity.

Keywords Agriculture · Biofertilizer · Nanofertilizer · Nanoparticle · PGPR

9.1 Introduction

In this period of climate change and resource limitation, challenges to crop production in terms of abiotic stress, nutritional deficiency and disease are considerable. Managing these challenges with conventional agrochemicals is no longer practical as they will only produce significant negative impacts on both the environment and

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human health. Hence, to successfully counteract the adverse impacts of climate stress and lower yields, sustainable and innovative approaches are essential. Plant growth promoting rhizobacteria (PGPR) are heterogeneous root-associated beneficial bacteria which are known for their ability to enhance plant growth by either direct or indirect phytostimulatory mechanisms. Direct mechanisms involve those related to mobilization of important nutrients such as phosphorous, zinc, sulfur and iron, and for promoting non-symbiotic nitrogen fixation along with production of various phytohormones like indole acetic acid (Glick 2012). Indirectly, PGPR reduce the deleterious effects of phytopathogens and protect the plant against biotic and abiotic stress conditions (Beneduzi et al. 2012). However, the variability in performance of PGPR under varied climate, weather parameters and soil characteristics is a major difficulty to exploring its field efficacy (Timmusk et al. 2017).

PGPR formulations are applied as suspensions to seeds, root surfaces or directly to soil (Mendis et al. 2018). It is difficult for a single microbial inoculant to perform consistently under varying agro climatic conditions and stresses; therefore, recent trends in PGPR applications adopt multiple inocula. Microbial consortia have proven to have higher efficiency than application of a single species (Pandey et al. 2012). Their survival and colonization, however, are dependent on the physical, chemical and biological nature of the recipient environment. Declining microbial diversity and numbers within the consortia can result in inefficient colonization of the rhizosphere of the host plant.

Microbial consortia can be prepared in liquid, organic, inorganic, polymeric, and encapsulated formulations for wider use (Bashan et al. 2014). The carrier of the consortia can provide the necessary microenvironment to ensure survival of organisms and also act as a niche for security against soil predators. Peat, coal, clay, waste plant materials, vermiculite, and residues of azolla are commonly employed for PGPR applications (Maiyappan et al. 2011).

Maintenance of adequate growth conditions over time in terms of nutrition and climate are major hurdles in transferring the developed consortia from the lab to the field. Failure to maintain the desired environs can considerably affect microbial counts, which in turn can adversely affect field results. Hence, introducing innovative and effective methods for field delivery of PGPR is important.

Nanotechnology is, an emerging field that offers tremendous applications in all aspects of science including chemistry, biology, physics, materials science and engineering. The application of nanotechnology in the agricultural sector has gained immense attention due to its ability to enhance biotic and abiotic stress tolerance, disease detection and prevention along with refined nutrient absorption (Shalaby et al. 2016). Nanomaterials can improve nutrient utilization efficiency of plants when compared to conventional approaches. Nanoparticles (NPs) can boost plant metabolism by their defined physicochemical properties, and thereby enhance crop yield and provide nutrients to soil (Siddiqui et al. 2015).

Nanoparticles can generally be classified as carbon nanoparticles, metal nanoparticles, organic, and semiconductor nanoparticles (Buzea and Pacheco 2017). Among these, silver (Yin et al. 2012), titanium (Abdel Latef et al. 2018), zinc oxide (Laware and Raskar 2014), silica (Rastogi et al. 2019), carbon (Mohamed et al. 2018), boron

(Goudar et al. 2018; Shireen et al. 2018), gold (Shukla et al. 2015) and zeolite (Yılmaz et al. 2014) nanoparticles have been reported to have plant growth promoting effects. Nano-fertilizers are more effective than conventional chemical fertilizers as they do not cause problems with leaching and nutrient loss following application and only minimal amounts are required which thereby reduces risk of soil and water pollution.

Nanotechnology-based plant viral disease detection kits and nanobiosensors are gaining popularity by virtue of their improved efficacy in detection of various viral diseases (Chaudhary et al. 2018). Nanobiosensors can be used to detect even minute levels of fertilizers, herbicides, pesticides, insecticides, pathogens, moisture, and soil pH, thus supporting sustainable agriculture for enhanced crop production.

The rhizosphere is the zone surrounding the plant root and which contains abundant plant growth promoting microorganisms. Plants secrete various exudates into rhizosphere soil which attract microorganisms. The exudates and microbial communities also have the capability to produce various nano-size minerals in soil which have not yet been fully studied (Yu 2018). Reports are available on the plant growth promotion activity exhibited by nanoparticles in combination with various PGPR organisms. PGPR and nanotechnological applications can make the agriculture sector more powerful than conventional technologies used for crop improvement. By developing a conjugative approach of both NP and PGPR, there is immense potential to improve both yields and disease resistance of plants (Table 9.1; Figs. 9.1 and 9.2). Nanoparticles offering such potential are discussed in the following sections.

9.2 Titania Nanoparticles

Titania nanoparticles are widely used in cosmetics, agriculture, and the chemical and food industries. Titania in the form of titanium dioxide (TiO_2) nanoparticles has a positive effect on plants by its involvement in plant nitrogen metabolism and modulating ROS signaling (Abdel Latef et al. 2018). Application of low concentrations of nano-TiO_2 to roots or leaves can stimulate the crop, leading to the improved activities of certain enzymes (Lyu et al. 2017), enhanced chlorophyll content and thereby photosynthesis (Gao et al. 2008). This can also promote nutrient uptake (Larue et al. 2012), and improve stress tolerance (Karami and Sepehri 2018) and hence improve overall crop yield.

Titania nanoparticles impart an adhesive effect on bacteria as evident from the potent nanophase adhesion of *Pseudomonas fluorescens* 5RL and *Pseudomonas putida* TVA8 when compared to conventional titania (Park et al. 2008). Double inoculation of PGPR with sol gel-synthesized titania nanoparticles has been shown to enhance colonization of PGPR to about 25%. This occurs via formation of microniches around the root which are entirely different from the surrounding microbiome and thus allow beneficial bacteria to work as a functional unit leading to crop improvement (Timmusk et al. 2018). Establishment of significantly larger and

Table 9.1 Effects of selected nanoparticles with PGPR on plants

Nano particle	Method of synthesis	PGPR	Plant	Effect	References
Silica	Nanosilica synthesized from rice husk ash using alkaline extraction followed by acid precipitation	*Bacillus megaterium, Bacillus brevis, Pseudomonas fluorescens, Azotobacter vinelandii*	Maize (*Zea mays*)	Promoted seed germination percentage than conventional silica	Karunakaran et al. (2013)
	Nanosilica synthesized from rice husk using alkaline treatment followed by acid precipitation	–	Maize (*Zea mays*)	Increased bacterial biomass	Rangaraj et al. (2014)
Titania	Acidic hydrolysis of titanium ethoxide, ($Ti(OC_2H_5)_4$) modified with triethanolamine, $N(C_2H_4OH)_3$	*B.thuringiensis AZP2, P.polymyxa A26*	Wheat (*Triticum aestivum cv. Stava*)	Enhanced performance of PGPR and their colonization	Timmusk et al. (2018)
	Sol-Gel approach (Captigel method and applying TiBALDH precursor)	*B.amyloliquefaciens subsp. plantarum UCMB5113*	Oilseed rape plants (*Brassica napus*)	Helped adhesion of beneficial bacteria to roots of oilseed rape; protected plant from the fungal pathogen *Alternaria brassicae*	Palmqvist et al. (2015)
Silver	Chemical method using sodium borohydride ($NaBH_4$)	*Pseudomonas fluorescence, Bacillus cereus*	Maize (*Zea mays*)	Augmented PGPR and induced increase in root area, root length and root-shoot ratio of maize irrigated with municipal wastewater	Khan and Bano (2015)

(continued)

Table 9.1 (continued)

Nano particle	Method of synthesis	PGPR	Plant	Effect	References
Gold	Biosynthesized by *Bacillus subtilis* SJ15	*P. monteilii*	Cowpea (*Vigna unguiculata)*	Enhancement of IAA production in *P. monteilii*; improved the plant probiotic effect	Panichikkal et al. (2019)
Zeolite	Commercially purchased	*Bacillus* sp.	Maize (*Zea mays*)	Increased plant height, leaf area, number of leaves, chlorophyll and total protein	Khati et al. (2018)
Zinc Oxide	–	*Brady rhizobium japonicum, Pseudomonas putida, Azospirillum lipoferum*	Soybean (*Glycine max* L.)	Increased plant height, number of nodules per plant, grain yield and grain weight	Khoramdel (2016)
Chitosan	–	*Bacillus* sp.	Maize (*Zea mays*)	Increased seed germination, plant height and leaf area	Khati et al. (2017)

thicker bacterial clumps than a self-produced biofilm matrix is possible through application of titania nanoparticles (Timmusk et al. 2018). Titania nanoparticles are reported to act at the nano interface between the beneficial plant growth promoting bacterium *Bacillus amyloliquefaciens* UCMB5113 and oilseed rape plants (*Brassica napus*) – titania nanoparticles increased adhesion of beneficial bacteria to the roots of oilseed rape and protected the plant from the fungal pathogen *Alternaria brassicae* (Palmqvist et al. 2015). Analysis by SEM, EDS, CLSM, SDS-PAGE and fluorescence measurements confirmed the nanoparticle-mediated colonization which eventually enhanced bacterial biomass (Palmqvist et al. 2015). Titania nanoparticles provide an effective platform for PGPR colonization on the plant and hence can be used as a potential agent for PGPR development for sustainable agriculture.

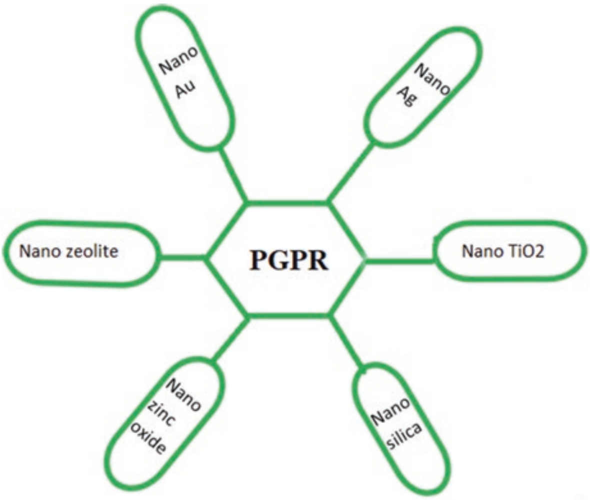

Fig 9.1 PGPR and commonly used nanoparticles

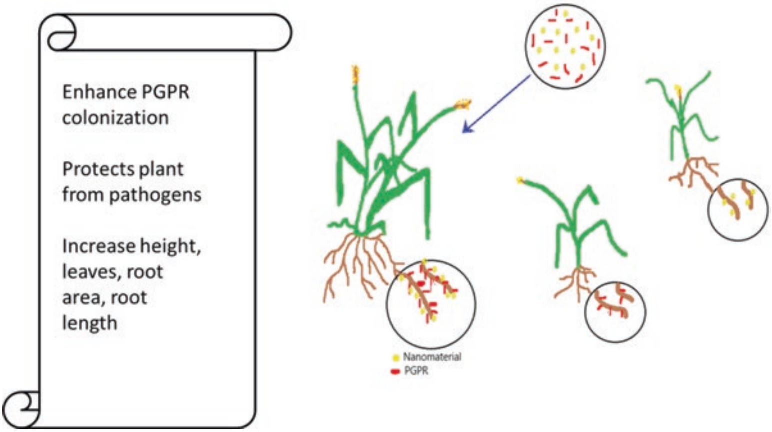

Fig 9.2 Combined action of nanomaterials with PGPR

9.3 Silica Nanoparticles

Silicon and silica nanoparticles are well established plant growth promoters. Silica nanoparticles have the capability to enter the plant and influence metabolic activities either directly or indirectly (Rastogi et al. 2019). Application of silica nanoparticles can lead to the formation of a film on the epidermal cell wall following absorption, which can provide additional structural leaf colour to the plant (Strout et al. 2013) and increase resistance to fungal, bacterial, and nematodal infections (Rastogi et al. 2019). The nano-silica layer can also reduce plant transpiration, which thereby makes plants more resistant to drought, high temperature, and humidity (Ashkavand et al. 2015). These modifications allow for improved plant growth and yield under adverse environmental conditions.

Nano-silica oxide has a significant impact on seed germination (Siddiqui and Al-whaibi 2014). Silica nanoparticles are also used as an effective nano-pesticide (Aa et al. 2016), nanoherbicide, and nanofertilizer in sustainable agriculture. Studies by Karunakaran et al. (2013) showed nanosilica to have a favorable effect on both beneficial bacterial populations and nutrient value of soil. Nanosilica synthesized using rice husks was proven to enhance the microbial population greater than that of sodium silicate, which inhibited plant growth promoting rhizobacteria. This effect may be due to the hydration properties of the nanosilica surface, which could facilitate attraction to the microbial surface (Gordienko and Kurdish 2007). In a study by Rangaraj et al. (2014) nanosilica treatment induced the populations of phosphate solubilizing bacteria and nitrogen fixers, where silica indirectly acted as a substrate for the bacteria.

Silica and PGPR individually are reported to be potent agents for crop improvement (Suriyaprabha et al. 2012; Ramprasad et al. 2015). Hence, the combination of these inputs has the potential to replace traditional fertilizers and to be used as an efficient agent for biofertilizer development.

9.4 Silver Nanoparticles

The wide acceptance of silver nanoparticles (AgNPs) is attributed to its well-known antibacterial activity (Radhakrishnan 2017). AgNPs are used in many applications from medical devices (Gherasim et al. 2018) to sports socks and washing machines, to deter microbial growth. Utilization of this nanoparticle occurs in almost all fields but especially in medical, dentistry, clothing, catalysis, mirrors, optics, photography, electronics, and the food industry (Dargo et al. 2017). Silver nanoparticles are also gaining attention and acceptance in the agricultural sector (Babu et al. 2014), but their ecotoxicological properties and underlying risks must be considered (Mao et al. 2018).

Treatment of fenugreek seedlings with biosynthesized silver nanoparticles was found to have beneficial impact on growth parameters such as number of leaves, root length, shoot length, and wet weight (Jasim et al. 2017).

Biologically synthesized silver nanoparticles are less toxic when compared with chemically synthesized AgNPs (Sharma et al. 2015). Silver nanoparticles are effective in facilitating the penetration of water and nutrients through the seed coat. AgNPs accelerated seed germination and seedling growth in *Boswellia ovalifoliolata* (Savithramma et al. 2012). In a study by Khan and Bano (2015), silver nano particles augmented PGPR activity by increasing root area, root length and root-shoot ratio of maize. Phytohormones are commonly applied to promote plant growth, and silver nanoparticles are now known to be an efficient tool to enhance phytohormones to a greater extent. Upon treatment with AgNPs, PGPR were reported to induce abscisic acid (ABA) levels by 34%, indole acetic acid (IAA) to 55% and gibberlic acid (GA) to 82% (Khan and Bano 2015).

Silver nanoparticles can have significant impact on the diversity of soil bacteria even when applied at minute levels. The fungal endophyte mediated synthesis of plant secondary metabolites such as taxol, podophyllotoxin, polyketides, terpenes and peptides (Mishra and Sarma 2018) can be enhanced effectively through a wide range of elicitors (Stierle and Stierle 2016). Among these, nanoelicitors comprising silver nanoparticles are found to be highly efficient (Jasim et al. 2017). Thus, exploring the potential of silver nanoparticles as a nanoelicitor for endophytic fungi can enhance the yield of desired secondary metabolites manyfold.

9.5 Gold Nanoparticles

Gold nanoparticles are among the most commonly synthesized and studied metal nanoparticles (Rashid et al. 2014). Synthesis includes chemical, biological and physical methods (Herizchi et al. 2014; Shah et al. 2014). Among these, biological methods are the most environmentally friendly and most commonly employed (Raghuvanshi et al. 2017), utilizing both plant extracts (Aljabali et al. 2018) and microorganisms (Roshmi et al. 2015). Plant growth promoting *Bacillus thuringiensis* strain PG-4 has been described as an effective agent for biosynthesis of gold nanoparticles (Raghuvanshi et al. 2017).

Considering its negligible toxicity (Rashid et al. 2014), gold nanoparticle-based formulations have become a huge attraction to the agricultural sector (Pestovsky and Martínez-antonio 2017). There are reports of enhancement of growth and yield of *Brassica juncea* (Arora and Sharma 2012) and *Arabidopsis thaliana* (Kumar et al. 2013) upon treatment with gold nanoparticles.

Enhanced growth of the PGPR *Pseudomonas* and *Bacillus* in the presence of 6.25 μg/mL gold nanoparticles was reported by Shukla et al. (2015). In addition, IAA production by *P. monteilii* was enhanced when treated with gold nanoparticles (Panichikkal et al. 2019). IAA is a major phytohormone that plays important roles in vascular tissue differentiation, root initiation, flowering, fruit ripening, leaf senescence and the abscission of leaves and fruits thus leading to overall plant growth (Basheer 2017). The exact mechanism behind enhancement of growth and IAA production by PGPR in the presence of gold nanoparticles has not yet been determined. A suggested mechanism involves penetration of the cell surface by nanoparticle aggregates without inducing any further toxic effect (Shukla et al. 2015). This attachment of nanoparticles can alter the shape and size of the bacterial cell and might accelerate its growth (Phenrat et al. 2009).

9.6 Nanozeolites

Zeolite, a crystalline aluminosilicate, is one of the most common minerals present in sedimentary rocks. Among the 40 naturally-occurring zeolites, the most well-known are clinoptilolite, erionite, chabazite, heulandite, mordenite, stilbite, and phillipsite. The maintenance of moisture content and pH of soil has been carried out effectively for years by Japanese farmers with the aid of zeolites (Ramesh and Reddy 2011). Zeolites have pores and channels within their crystal structure along with a high cation exchange capacity (CEC) which is beneficial in agriculture (Mahesh et al. 2018). They make up a class of excellent nutrient carriers, enhancing soil nutrient levels, which in turn increase crop yield and also nutrient utilization efficiency. Other common applications include use as a carrier of slow-release fertilizers, insecticides, fungicides, and herbicides, and also as a trap for heavy metals (Sangeetha and Baskar 2016).

The nanozeolites with few side effects, make them a powerful tool in agriculture as compared to bulk zeolite material (Khati et al. 2018). The ability of nanozeolites to enhance the organic carbon content of the soil and to stabilize micro and macro-aggregates are superior to that of bulk zeolite (Mirzaei et al. 2015).

Composites of zeolites possess a greater water retention capacity, water absorbance, equilibrium water content and swelling ratio when compared to nanozeolites used alone (Lateef et al. 2016). This may encourage utilization of nanozeolite-based composites as an environmentally-friendly fertilizer. Thus, crop productivity can be improved by a combined application of nanozeolite and PGPR.

9.7 Nano Zinc Oxide

Zinc is an essential micronutrient required by all organisms including plants, animals and humans. The human genome encodes approximately 3000 zinc-containing proteins having structural and functional roles (Process 2013). Zinc acts as a catalytic and structural cofactor in all classes of enzymes, namely oxidoreductases, transferases, hydrolases, lyases, isomerases and ligases (Mccall et al. 2000). These enzymes play a pivotal role in cellular regulation where they act either as an extracellular stimuli or intracellular messengers (Maret 2017).

Zinc is a key factor in photosynthesis (Wang et al. 2009), protein synthesis (Obata and Umebayashi 1988), phytohormone synthesis (e.g. auxine, ABA) (Atici et al. 2005), seedling vigor (Boonchuay et al. 2013), sugar formation (Mousavi 2011), membrane function and defense against disease and abiotic stress (e.g., drought) (Ma et al. 2017; Dang et al. 2008). Zinc deficiency can result in severe yield loss with plant death in acute cases (Hafeez 2014). Zinc deficiency is often observed in fields despite its abundance (Sharma et al. 2013). Owing to its relative insolubility, application of zinc fertilizer is the sole method to overcome this issue.

Both zinc sulfate and EDTA-Zn chelate are commonly used to meet this deficiency (Cakmak and Kutman 2018).

Nano fertilizer formulations have enhanced performance compared to traditional fertilizers, as they release the required nutrients in controlled manners which, along with their small size and large surface area, promote its activity. Zinc oxide nanoparticles at concentrations of 20 and 30 μg ml^{-1} reduced the flowering period in onion and ensured better growth of plants along with production of healthy seeds (Laware and Raskar 2014). Zinc oxide nanoparticles can, however, exert negative impacts on plants. Treatment of zinc oxide nanoparticles on tomato plants negatively affected both plant growth and chlorophyll content which, in turn, affected photosynthetic rate (Wang et al. 2018). A supernatant of ZnO nanoparticle suspensions containing Zn^{2+} was not found to affect growth of tomato; hence, toxicity is attributed to ZnO nanoparticles.

ZnO NPs are reported to enhance the plant defense response by increasing transcription of genes related to antioxidant enzymes (Wang et al. 2018). Numerous zinc-solubilizing bacteria have been reported, which are capable of solubilizing zinc in soil (Kamran et al. 2017). Mumtaz et al. (2017) showed that inoculation of zinc solubilizing bacterial isolates to result in improved growth of maize. Zinc solubilizers also of have the capability to produce zinc nanoparticles. Sultana et al. (2019) reported the production of zinc nanoparticles by zinc solubilizing strains of *Pseudomonas, Bacillus* and *Azospirillum.*

Seed inoculation with PGPR along with nano zinc oxide, significantly increased plant height, number of nodules per plant, grain yield and grain weight (Khoramdel 2016). ZnO nanoparticles exhibit a dose-dependent enhancement in siderophore production of bacteria (Haris and Ahmad 2017). An environmentally-friendly dose of Zn nanoparticles along with PGPR could very well revolutionize the agriculture sector.

9.8 Nano Carbon

Use of carbon nanomaterials in agriculture has both negative and positive feedbacks (Mukherjee et al. 2016). They are widely used for plant growth promotion, plant protection, plant transformation and for nanodiagnostics in the agricultural sector (Al-whaibi and Mohammad 2017). Nano Fullerenes (nC_{60}) are reported to have little impact on the soil microbial community (Tong et al. 2007). It is possible; however, that application of PGPR along with suitable nano-carbon or fullerenes can have a future application.

9.9 Nano Boron

Boron, a trace element, plays an important role in plant growth such as cell division, elongation, nitrogen and carbohydrate metabolism, sugar transport, cytoskeletal proteins, ion fluxes (H^+, K^+, PO_4^{3-}, Rb^+, Ca^{2+}) across membranes and phenol metabolism and transport (Shireen et al. 2018). Maziah et al. (2010) reported that inoculation of plant growth promoting rhizobacteria, *Bacillus sphaericus* UPMB10 in modified MS medium containing boron improved the growth and root biomass of banana plantlets compared to control. Nanoboron nitride fertilization increased seed and stalk yield of sunflower (*Helianthus annuus* L) (Goudar et al. 2018). PGPR mediated boron uptake in boron-limited conditions would be a great achievement for the field of agriculture. Use of boron nanomaterials in PGPR formulations may offer promising applications.

9.10 Nano Chitosan

Chitosan, a natural biomaterial, can be formed by the deacetylation of chitin. In plants, chitosan induces biotic and abiotic stress tolerance and control of plant diseases, and promotes growth (Malerba and Cerana 2016). Nano chitosan in combination with plant growth promoting rhizobacteria (*Bacillus spp*) in maize has been reported to enhance plant height, leaf area, seed germination and increased organic acid production in response to stress tolerance (Khati et al. 2017). Thus, the use of natural biopolymers in PGPR formulation can potentially have an immense impact in PGPR inoculant technology.

9.11 Advances of Nanotechnology with PGPR

Nanotechnology has revolutionized the agricultural sector with its wide range of applications. This includes application of more efficient and targeted use of inputs, thereby increasing nutrient uptake by plants, disease control and its detection, storage and packaging (Prasad et al. 2017). An emerging trend of bio-nano-encapsulation using plant beneficial microorganisms and nano particles has paved a unique way of development in current agriculture scenarios.

Understanding potential toxicity of nanoparticles together with microbes is crucial for optimizing their application. In such cases the use of nanoparticles derived from biopolymers such as proteins, carbohydrates can offer a significant role.

9.11.1 Nano Encapsulation of PGPR

The use of nanomaterials for the delivery of macro- and micro-nutrients to plants is trending (Jampílek and Kráľová 2017). Nanoencapsulation also has the capability to protect crops from disease-causing organisms, insects, and other pests (Castañeda et al. 2014). De Gregorio et al. (2017) showed that immobilization of *Pantoea agglomerans* and *Burkholderia caribensis* in nanofibers did not alter the viability or beneficial properties of either rhizobacteria. The immobilized PGPR were associated with increased seed germination, and length and dry weight of soybean roots.

Maintaining viable counts of bacteria is a major concern when dealing with PGPR application in the field. Nanofibers and other nanomaterials can be a promising ecofriendly agent for inoculum development in which PGPR exerts its beneficial plant growth promoting traits and nanofibers protect bacteria and seeds from local abiotic stresses (Fig. 9.3).

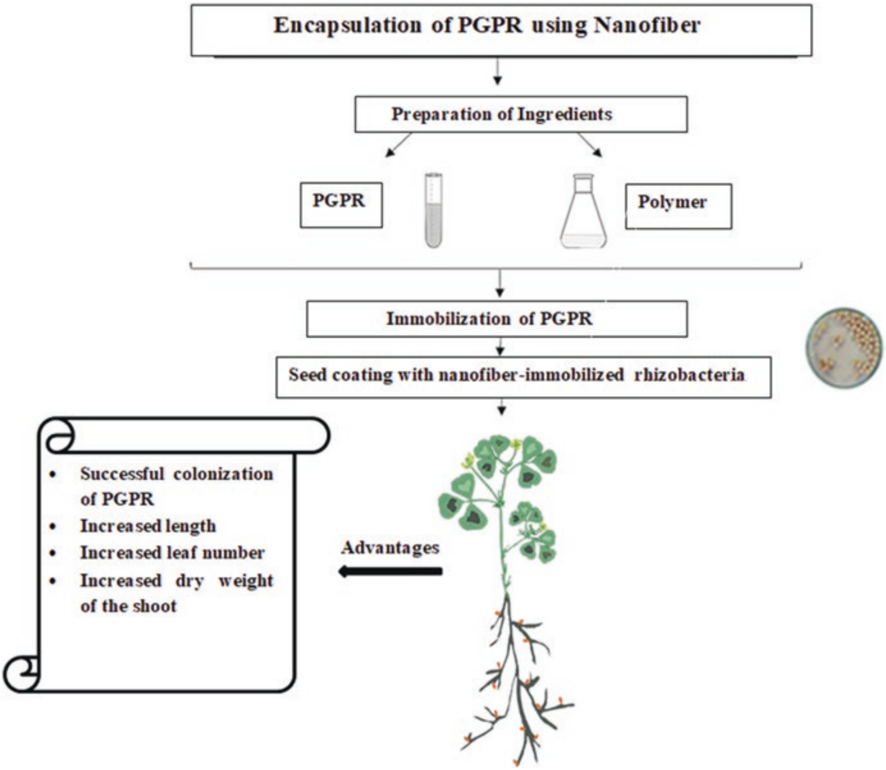

Fig 9.3 Benefits of encapsulation of PGPR using nanofiber

9.11.2 Nanobiofertilizers with PGPR

Nano-fertilizers have the potential to replace traditional fertilizers. They can increase nutrient use efficiency, reduce soil toxicity, minimize the potential negative effects associated with over dosage and reduce frequency of application (Qureshi et al. 2018). Slow-release nanofertilizers which release nutrients and plant growth promoting rhizobacteria were formulated by Mala et al. (2017); blending of nanofertilizer with neem cake, a byproduct of neem (*Azadirachta indica*) and PGPR was carried out. This slow release fertilizer system can accelerate the enzyme action during germination and increase seed vigour index (Mala et al. 2017). Use of PGPR facilitates the efficient use of NPK fertilizer and, hence, combined action can enhance overall crop yields.

9.12 Conclusions

Nanoparticles combined with PGPR have the potential to create a promising future for the upcoming age of agriculture. Nanoparticle interactions with PGPR can promote root colonization, phytohormone and secondary metabolite synthesis, and overall enhancement of the performance of rhizobacteria. Nano encapsulation of PGPR and nanobiofertilizer with PGPR are also trending. These eco-friendly compounds offer immense potential to replace traditional fertilizer practices. PGPR nanotechnology can be exploited as a low-input, sustainable and environmentally-friendly technology for management of plant stress and disease management. Future innovative technologies in this area will revitalize the agricultural sector.

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