Nanotechnology and Rhizobacteria: A Novel Strategy for Enhanced Plant Growth

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Abstract

The continuous use of chemical pesticides and fertilizers in agriculture has raised serious threats and concerns about environmental sustainability and food security. Scientists and researchers are looking into different approaches, like using beneficial microorganisms in biofertilizers. By facilitating better nutrient uptake and functioning as biological regulators, these microbial inoculants promote plant growth while lowering the demand for chemical inputs. Living microorganisms that colonize plant roots or soil to help transform nutrients into forms that plants can use make up biofertilizers. Through processes like the synthesis of phytohormones and nitrogen fixation, they can stimulate growth. Furthermore, applying nanotechnology to agriculture presents promising improvements for biofertilizers, which could increase their efficacy in a range of environmental circumstances. This review highlights the potential of nanoparticles (NPs) to support sustainable agricultural practices by improving the effectiveness of beneficial plant bacteria. These cutting-edge methods seek to establish a more sustainable and profitable agricultural system by lowering reliance on chemical pesticides and fertilizers.

Keywords: Plants, Plant growth-promoting bacteria (PGPB), Nanoparticles (NP), Biofertilizers

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Introduction

The need for food has grown due to population growth and economic development, which has resulted in an overuse of chemical pesticides and fertilizers to raise crop yields (Prasad, 2013; Sharma & Singhvi, 2017). Such approaches have led to ecosystem imbalance, biodiversity loss, water and soil contamination, and soil microbial depletion. Sustainable soil and water management techniques, biopesticides, and biofertilizers can all produce high agricultural yields with little harm to the environment (Kour et al., 2020). Rhizosphere and endophytic plant growth-promoting bacteria (PGPB) are useful biofertilizer ingredients that improve nutrient uptake, boost plant tolerance to stress, and provide phytopathogen protection (Singh et al., 2019). This potential is reflected in the global plant bio-stimulant market, which is expected to reach USD 3.0 million by 2022 at a growth rate of 12% per year (Peter et al., 2020).

Despite their promise, microbial biofertilizers face challenges such as instability and inconsistency under field conditions (Fadiji et al., 2024). Nanotechnology offers solutions through precision agriculture, leveraging NPs to address biofertilizer limitations like reproducibility, storage stability, and sensitivity to environmental factors (Duhan et al., 2017). Nanotechnology utilizes materials with unique properties arising from quantum confinement effects and highly reactive surfaces at the nanoscale. Compared to their macroscopic counterparts, nanomaterials exhibit novel characteristics due to their reduced size, higher surface area-to-weight ratio, and distinct shapes (Rastogi et al., 2019). By integrating nanomaterials with PGPBs, this technology promises to optimize crop systems while providing economic and environmental benefits, paving the way for sustainable agricultural development (de Moraes et al., 2021; Verma et al., 2024).

1. Application of Nanotechnology in Modern Agriculture

The concept of using agriculture techniques along with nanotechnology started in the late 20th century. In the starting era the nanotechnology was only considered for the application in material science and medicinal domains. As the population of the world is increasing day by day at a rapid speed, the importance and need of food security become and significant concern as a global problem (Kumar et al., 2020). Researchers are exploring environmentally friendly nanomaterials to enhance crop production. In agriculture, nanotechnology is applied in areas such as seed science, nano fertilizers, nonherbicides, water management, nanoscale carriers, biosensors, agricultural engineering, and animal science (Ditta & Ullah, 2022; Ghouri et al., 2020).

In smart agricultural systems use of nanomaterials improves nutrient absorption and allow for the regulated release and targeted distribution of molecules, which aid in early disease detection and safeguard the environment (Asrar et al., 2023). A traditional method that uses another synthetic form of NPs, nanoencapsulation, minimizes environmental effects while optimizing efficacy by enabling controlled release of agrochemicals (Chugh et al., 2021). In addition to improving plant uptake of nutrients, this method lowers the total amount of pesticides required, which supports a sustainable agricultural output (Mondéjar-López et al., 2024).

2. Development of Nanotechnology-Based Biofertilizers

Bacterias such as *Pseudomonas*, *Bacillus*, *Rhizobium*, *Azospirillum*, *Arthrobacter*, *Burkholderia*, *Serratia*, *Flavobacterium*, *Enterobacter*, *Erwinia*, *Acinetobacter*, *Alcaligenes*, etc. support plant health through direct mechanisms such as nutrient uptake (nitrogen, phosphorus, iron) and hormone regulation (auxins, cytokinins, gibberellins) and indirect mechanisms like biotic stress resistance (antibiotics, antioxidants, volatile compounds) (Chandra et al., 2015). However, crops only use 30–50% of chemical fertilizers, which as a result, cause soil saturation and groundwater contamination (Khan et al., 2018). Biofertilizers containing live microorganisms such as phosphorus solubilizers and nitrogen fixers offer an environmentally benign substitute for chemical fertilizers and improve soil fertility, sustainability, and accessibility for small farmers.

Despite its advantages, PGPB application has drawbacks, such as the necessity for physical protection or a suitable microenvironment and the fall in the bacterial population following inoculation as a result of unpredictable soil conditions (Hossain et al., 2023). In order to get around this, PGPB needs carriers for transportation and storage, such as liquid media or peat. New materials, including nanostructures, are being explored to improve inoculum stability, reduce production costs, and enhance effectiveness in field applications. Nanomaterials, whenever applied at the scale of nanometers, have the potential to be the most effective carrier, improving the delivery and bioavailability of nutrients in different aspects (Saritha et al., 2022).

Nanoscale encapsulation and coating technologies are especially important in Nanomaterial-Based Biofertilizer formulations. Microbial cells and culture are protected against different stress environments by encapsulation of PGPB, a process of entrapment or enclosure of microorganisms by a nanomaterial (Vejan et al., 2019). These methods not only provide stability (ability to resist heat, UV light, and desiccation) and more shelf life to biofertilizer but also ensure the release of nutrients in a controlled and manageable way for plant (Jafari, 2017). Another very beneficial feature of enclosing PGPB with inorganic or organic NPs is that it allows very accurate timing of bacterial distribution to target organs (Khalid et al., 2020). For instance, research has shown that nano-urea may be successfully applied to pearl millet cultivation, resulting in notable improvements in nutritional content and dry matter buildup (Sharma et al., 2022).

3. Integrating Nanomaterial with Plant Growth-Promoting Bacteria for Enhanced Plant Productivity

Nanomaterials facilitate biofilm formation abilities to bacteria as well as support in the enhancement of biofilm formation and the enhancement of metabolite secretions (Mohanta et al., 2023). Small-scale NPs also help a bacterium to adhere properly to different surfaces. Carbon nanotubes have been tested and proven to provide antibacterial properties and trigger defense mechanisms in pathogen-infested tomatoes (Ning et al., 2024). Alpha amylases is essential for the breakdown of starch during the seed germination process. Zinc oxide NPs have been reported to increase its production during wheat and maize production (Srivastav et al., 2021). Researchers have studied two functional properties of two bacterial strains, *Pseudomonas* and *Azotobacter,* with NPs in a detailed manner (Yousaf et al., 2024). They have found that this formulation can influence the development of roots by colonization and plant growth by increasing phosphorus availability in soils (Ahmed et al., 2021; Patel et al., 2023). PGPBs (*Agrobacterium*, *Alcaligenes*, *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Caulobacter*, *Chromobacterium*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Klebsiella*, *Micrococcus Pseudomonas* and *Serratia*) microbial activity help the soil to solubilize and release plant growth promoting phytohormones (auxins, gibberellins, cytokinin, ethylene and abscisic acid) which help the plant in nutria uptake (Amara et al., 2015).

4. Innovative Ways to Increase Plant Productivity

4.1. Preserving the Rhizosphere Microbiome

Reducing rhizosphere microbiome disruption is essential for improving plant health and agricultural productivity. Bacterial colonies present in the rhizosphere are crucial to the cycling of nutrients, the prevention of disease, and the general growth of plants (Ayangbenro et al., 2022). The stability is maintained by frequently used methods like traditional farming, tillage, pesticide application, and monoculture. Unfortunately, the traditional method can eventually lower crop yields and make crops more susceptible to pests and diseases. Nowadays, several techniques are used to reduce rhizosphere microbiome disruptions. These include organic farming methods that support microbial diversity and soil health, conservation tillage, and cover crops. However, organic methods are resource-intensive and might not necessarily produce results right away (Crystal-Ornelas et al., 2021). With nanotechnology, researchers can create customized fertilizer and biopesticide delivery systems that limit chemical runoff and eliminate the need for broad-spectrum treatments by employing NPs (Ullah et al., 2024).

Nanomaterials have a strong potential to significantly impact the strength of the rhizosphere microbiome and make plants more resilient. Nanomaterials' unique properties have also been linked to improved soil physicochemical properties, which support microbial communities in soil. Studies have reported that NPs can improve water holding capacity, soil pH and nutrient availability, microbial biomass and diversity (de Oca-Vásquez et al., 2020). A study done in the past has demonstrated that the combination of nanogypsum and *Pseudomonas taiwanensis* not only improves soil structure but also enhances plant overall health by promoting beneficial microbial interactions without causing toxicity (Chaudhary et al., 2021).

4.2. Mitigating Effects of Heat and Drought Stress

Extreme temperatures and drought conditions are very crucial in the context of climate change because they present serious obstacles to plant growth and agricultural productivity (Raza et al., 2019). These conditions can make a crop suffer, make it vulnerable to pests, and affect the overall food security by lowering crop yields. However, the scalability and efficacy of these drought-resistant plant varieties, better irrigation techniques, and soil management strategies that improve moisture retention in harsh environments are frequently constrained (Shiferaw et al., 2013).

Nanomaterials (NMs), along with PGPB, have emerged as a promising strategy to enhance plant resilience under extreme weather conditions (Savanur et al., 2021). Nanomaterials can help a plant to withstand different stress environments through multiple mechanisms.

One of the mechanisms is to facilitate the controlled release of nutrients by PGBGs (Thabet & Alqudah, 2024). Secondly, it can minimise nutrient fixation in the soil and make essential elements more accessible to plants (Khalid et al., 2022). Third, it creates a more favorable environment for root development and microbial activity (Zhang et al., 2020). For example, NPs have been reported to increase phosphate-solubilizing bacterial abundance and play a critical role in making phosphorus available to plants (Cheng et al., 2023). This enhances nutrient uptake and improves overall soil health and plant growth under adverse conditions.

4.3. Reduction of Soil Contamination

Researchers are finding new ways to reduce contamination from the environment by using nanomaterial. They have discovered their significant potential in enhancing soil health and mitigating heavy metal toxicity. NPs made up of zinc oxide and silver have been found to improve heavy metal contaminations present in soil, such as iron (Rizwan et al., 2019). *Staphylococcus aureus* is resistant to chromium, and it can transform toxic chromium (Cr VI) into Cr III in soil, which is a less harmful state (Ahmad et al., 2022). The iron NPs act in a way that they can upregulate chlorophyll content and mitigate oxidative stress caused by chromium toxicity (Ulhassan et al., 2022). These capabilities of bioremediation capabilities of heavy metals in soil are crucial for restoring contaminated land and supporting plant growth.

4.4. Soil Remediation

Soil remediation involves improving the nutrient value in soil for plant growth and good water retention. This can be done commonly using three different methods, which are chemical, phytoremediation, and bioremediation. All these traditional methods have some limitations associated with them For example chemical methods can result in secondary pollution when improperly managed, and bioremediation can be slow and ineffective in removing heavy metals (Rajendran et al., 2022). Studies done in the past for exploring some alternatives have resulted in the introduction of NPs in bioremediation efforts by promoting plant growth and facilitating the breakdown of contaminants. Silver NPs applied with *Bacillus cereus* and *Pseudomonas fluorescens* in a contaminated environment have successfully remediated soil for plant growth. Silver NPs boost enzyme activities linked to stress responses, including catalase and peroxidase, and improve root morphology (Danish et al., 2022). The enhanced enzymatic activities due to microbial interactions and nanomaterial applications contribute to improving soil fertility.

5. Impact of Nanomaterial and Plant Growth-Promoting Bacteria on Global Plant Production

5.1. Nutrient Efficiency

A stable amount of nutrients in the soil and their uptake by plants is necessary for proper development. Nanomaterials paired with PGPB are reported to increase plant nutrient uptake to a very stable amount. They help in various ways to fulfill this requirement, for example, by maintaining physicochemical characteristics, Ph, substrate availability, or water holding capacity of soil (Elsakhawy et al., 2022). It can also help in increasing microbial diversity and better aeration for nutrient transportation in rhizosphere (Agarwal et al., 2024). *Pseudomonas* specie is associated with phosphate solubilization when combined with NPs and make phosphorous readily available for the plant to absorb (Safari et al., 2020). In addition to increasing phosphorus availability, this synergistic relationship promotes beneficial microbial colonization of roots, which improves wheat growth in infected *Fusarium culmorum* soil (Kashisaz et al., 2024).

Applications of nanoparticles can further show a positive effect on the availability of nitrogen in soil. Zinc oxide NPs and PGPB stimulate siderophores and make plants able to perform iron chelation and nutrient uptake (Khan et al., 2024). A study showed that titanium dioxide NPs facilitate PGPBs to adhere to plant roots and create persistent biofilms to support nutrient uptake (Vidya et al., 2024). Stable biofilm formation and bacterial colonization reduce the effect of stress on plants in unfavorable environmental conditions. Silica NPs improve mechanical resistance in plant cell wall which provides extra protection against biotic stress and also stimulates phosphorous uptake for plant (Wang et al., 2022). Copper oxide NPs have been found to stimulate indole acetic acid (IAA) synthesis in certain PGPB strains (Karunakaran et al., 2024). IAA promotes root elongation and branching in plants and provides support for nitrogen absorption from the soil. The role of nanomaterials extends to nitrogen fixation as well. With enhanced microbial activity due to nanomaterial application there is a notable increase in nitrogen-fixing bacteria populations in the rhizosphere.

5.2. Pest and Disease Resistance

Pest and disease management is very critical for a plant to survive in its natural environment as it can possess various threats to plant development. For agriculture sustainability this concern is very problematic because of its compromises the crop yield and quality. World population is expected to become 8.5 billion people by the year 2030 therefore in order to fulfil food requirement it is very necessary to find a solution to this global issue (Oluwole et al., 2023). No double there are traditional methods available for pest and disease control such as using chemical pesticides but they have serious disadvantages as well. Chemicals used in pesticides are very harmful for untargeted biotic life like birds, cattle and insects (Naz et al., 2023). They also give rise to generation of super bugs in pest making them resistant to these chemical pesticides (Venkatesan et al., 2022). Microbial biofertilizers face several limitations, including slow action, host specificity and reduced efficacy under extreme environmental conditions (O'Callaghan et al., 2022). Additionally, they often have a short shelf life and require proper storage.

Nanotechnology-based approaches offer effective solutions to challenges in agriculture and the food industry, including increasing food demand, ensuring food safety, managing plant diseases, and addressing climate change. A number of studies have reported the significant potential of nanoparticles to be used as an effective antimicrobial agent. Nano chitosan is highly renowned for its unique potential to microbial colonies, specifically *Meloidogyne incognita* and the associated root galls, achieving reductions between 45.89% to 66.61% in nematode densities and 10.63% to 67.8% in gall density, respectively (Upadhayay et al., 2023). The combination of nanogypsum and *Pseudomonas taiwanensis* has been reported to work to improve soil structure and health and ultimately, it supports plants with more robust defense mechanisms against pests and diseases (T. Ahmed et al., 2023). Strong antibacterial qualities are exhibited by certain nanomaterials, such as carbon nanotubes, which can also trigger plant defense systems against diseases like *Alternaria solani* in tomato crops (González-García et al., 2021). These results highlight the dual function of NPs as agents that protect against microbial diseases and stimulate growth.

5.3. Enhancing Soil Health

Use of nanomaterial in agriculture leads to improvements in soil health and microbial diversity. The efficiency of PGPB enhanced with nanomaterials in advancing sustainable farming methods is demonstrated by a number of scientific studies. For example, combined effects of PGPB strains (*Azospirillum lipoferum* and *Pseudomonas fluorescens*) and the cyanobacterium *Nostoc piscinale* on maize growth were examined and results over two years indicated that the addition of *N. piscinale* (0.3 g/L) and *A. lipoferum* enhanced grain yield by 31.53% in the second year and 33.20% in the first (Solomon et al., 2023). Furthermore, compared to untreated controls, treated plots showed improved microbial biomass and nutrient availability, as evidenced by increases in soil pH, humus content, and nitrogen levels. In a study *Curtobacterium oceanosedimentum* strain caused a significant increase in root and shoot length of chili plants by 58% and 60% even under the cadmium stress applied in a pot experiment (Patel et al., 2022). Chromium-resistant bacteria alongside NPs can also improve in rice quality by upregulating chlorophyll content and mitigating oxidative stress damage (Basit et al., 2023). These studies provide solid evidence regarding different ways of improving soil and crops health by using NPs.

6. Limitations for Use of Nanomaterial-based Biofertilizers in Agriculture

Nanomaterial combined with PGPBs no doubt provides a significant opportunity for modern agriculture and enhancing crop output, but unfortunately, some limitations hinder the widespread application of this technology. One of the main challenges is the production and adoption cost of nano-based PGPBs industry due to the requirement of advanced architecture at a large scale. The production comprises advanced techniques that require expertise and infrastructure investment, making it impossible for small-scale farmers to obtain (A. Ahmed et al., 2023). A study highlighted that the cost of producing certain nano formulations can reach up to $1,000 per kilogram, which may deter farmers from transitioning to these innovative practices, especially in regions where traditional farming methods are deeply entrenched (Kesisoglou et al., 2007). Another factor is the toxicity associated with NPs, as it could raise serious environmental concerns. Nanomaterials when left for a long period in soil can cause bioaccumulation in plants and microorganisms present in soil. Studies have found that certain types of NPs, such as silver NPs, can act as a toxic agent for the bacterial population in soil, even if it is present a very small quantity (Kafeel et al., 2022). Titanium dioxide NPs can also adversely affects the Earthworm population that acts as a natural cultivator in soil (Makarenko & Makarenko, 2019). Insects like earthworms are crucial for the maintenance of the health and structure of soil. Additionally, the stability of NPs in various environmental conditions must be ensured to maximize their benefits when applied to crops. Stability is a major hurdle in this regard as storage and transportation logistics can complicate the development of nanoparticles at a large scale. Stability and viability of bacterial colonies during storage and transportation is crucial for their effectiveness to be used as a biofertilizer as the effectiveness can be compromised after a few weeks if not stored in proper environment (Ahmad et al., 2008).

Nanotechnology use in agriculture is a modern techniques and yet the standardization of regulatory frameworks for this is very limited at this stage (Soltani & Pouypouy, 2019). This makes it more complicated for a farmer to implement it as a normal practice. Regulatory uncertainty is a main reason for hesitation among industrials and stakeholders to invest and adopt this modern technology. A report from the European Commission noted that a fewer number of European Union member states have established specific regulations for nanomaterials in agriculture (Amenta et al., 2015).

These challenges must be addressed through research and policy development so that the potential benefits associated with the integration of nanotechnology with PGPBs can be obtained efficiently for sustainable agriculture.

Conclusion

PGPBs provide an effective solution to counter the limitations of chemical fertilizers. However, this requires first obtaining accurate knowledge and understanding of specific plant-microbe interactions. Since different nanomaterials have shown beneficial effects on both PGPB and plant growth, nanotechnology becomes an important tool to improve the effectiveness of microbial biofertilizers. Integration of specific nanomaterials with beneficial bacteria, the viability and environmental resistance of these microbes can be improved which ultimately enhance plant growth. Despite these advantages, concerns regarding the impact of NPs on bacterial metabolism and potential risks to the environment, food safety, and human health necessitate thorough investigation. Factors such as the type of bacteria, characteristics of nanomaterials (including size and concentration), plant species, and environmental conditions play crucial roles in these interactions. Despite these advantages, challenges such as potential ecological risks, cost-effectiveness, and large-scale applicability must be addressed to ensure the safe and effective use of these technologies. Most current research has been conducted under controlled conditions, highlighting the need for field experiments to validate findings. More research and field trials are still needed to implement this technology on a large scale. With continued research and technological advancements, the integration of nanomaterials and PGPB has the potential to revolutionize global agricultural practices, driving sustainable development and food security

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