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Bursa Technical University, Türkiye

*CORRESPONDENCE
Ikunda Herman Massawe
✉ ikunda.massawe@nm-aist.ac.tz

†These authors have contributed equally to this work

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Potential application of nanotechnology in formulating biofertilizers as a sustainable way for promoting plant growth: a systematic review

Ikunda Herman Massawe*, Ernest Mbega† and Akida I. Meya†

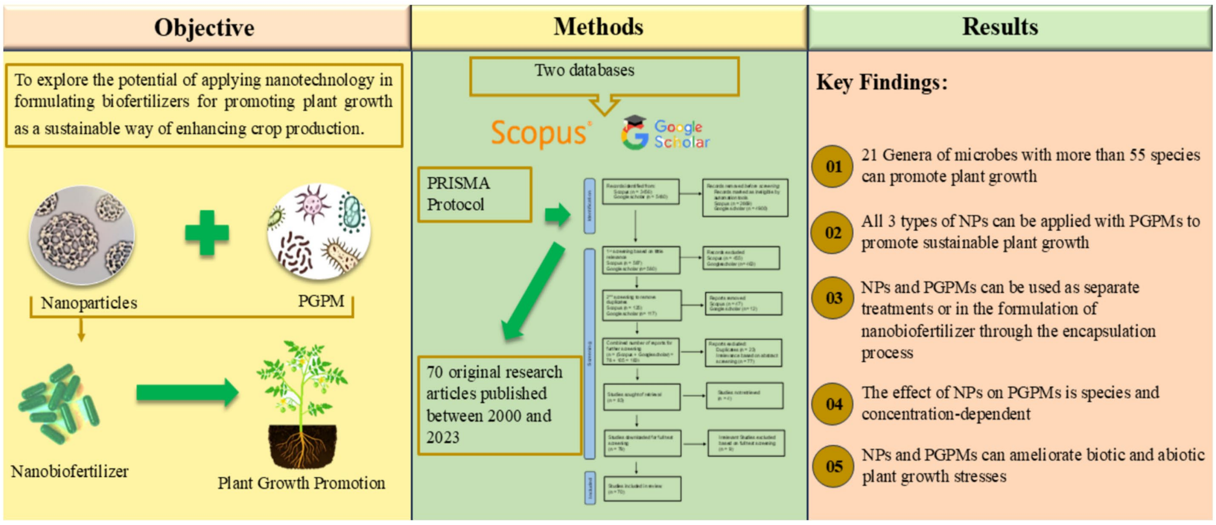
The School of Life Science and Bio-Engineering, Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania

Introduction: Nanoparticles and Plant Growth-Promoting Microbes are trending as sustainable means for supplying plant nutrients. The purpose of this review was to understand how these technologies have been applied together to enhance plant growth.
Methods: A PRISMA protocol was followed to explore relevant articles that reported the impact of nanoparticles on plant growth-promoting microbes or their influence on plant growth. By using the established search string, 70 original research articles published between 2000 and 2023 from Google Scholar and Scopus were obtained.
Results: The results show that 21 microbe genera with more than 50 species can promote plant growth. Free-living plant growth-promoting rhizobacteria are the most studied microbes, followed by arbuscular mycorrhizal fungi. Inorganic nanoparticles, such as ZnO, are the most extensively studied nanoparticles, followed by organic nanoparticles, primarily chitosan.
Discussion: Nanoparticles and plant growth-promoting microbes can be applied as separate treatments or by formulating nano-biofertilizer, and their combination ameliorates biotic and abiotic plant growth stresses. The effect of nanoparticles on plant growth-promoting microbes is concentration and species-dependent.

KEYWORDS
nanobiofertilizer, nanoparticles, plant growth-promoting microbes, plant growth, nanotechnology

1 Introduction

Sustainable agriculture is a priority in the current agricultural production systems, while increasing agricultural production remains to be a core focus to ensure world food demand is met (FAO, 2021; Marambe and Silva, 2012). It is undoubtedly right to say there is a need to ensure both aspects are achieved. It is argued that mineral fertilizers play a vital role in agricultural production as they contribute up to 40% of the productivity (Elizabath, 2019). On the contrary, inappropriate usage of mineral fertilizer is the major contributor of environmental pollution, such as air pollution, water pollution, soil nutrients depletion, and increased emissions of greenhouse gases in agricultural systems (Kumar et al., 2019). Therefore, there is a need to think of sustainable means of managing and supplying nutrients to plants. Plant growth-promoting microbe (PGPM) and nanoparticles (NPS) are some of the important sustainable ways for supplying plant nutrients and promoting plant growth. In this review, these two important game-changing aspects for sustainable plant nutrient supply and management are explored.



GRAPHICAL ABSTRACT

PGPMs have been extensively studied in agricultural systems and have proven to have positive functions as far as nutrient supply and plant growth are concerned (Dhawi, 2023). PGPMs are divided into three groups, namely: arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR), and rhizobia. PGPR are free-living rhizobacteria that promote plant growth by colonizing the roots' rhizosphere without forming any association with the plant, e.g., *Pseudomonas* spp., *Azospirillum* spp., *Azotobacter* spp., *Bacillus* spp., *Burkholderia* spp., and *Enterobacter* spp. (Jeyanthi and Kanimozhi, 2018; Lucy et al., 2004; Rai et al., 2018). AMF are symbiotic fungi that penetrate the cortical cells of plant roots, forming unique tree-like structures called arbuscules, e.g., *Rhizophagus* spp. and *Glomus* spp. (Kumar et al., 2022). PGPM promotes plant growth through mechanisms such as the production of phytohormones like Indole Acetic Acid (IAA), ethylene, cytokinin, and Abscisic Acid (ABA) that enable cell elongation, division, and expansion (Kumar et al., 2022). Also, these microbes are involved in N fixation and solubilization of P, K, and Zn, thus improving nutrient availability and supply (Rai et al., 2023a; Rai et al., 2023b; Singh, 2013). Other functions of PGPM include Phytoremediation, improvement of plant resistance to biotic and abiotic stresses such as soil salinity and drought (Ma et al., 2020; Singh, 2013). Application of PGPM in agriculture offers an alternative, sustainable means for plant nutrient supply and brightens the future of sustainable crop production (Singh, 2013).

One of the promising applications of nanotechnology in agriculture is the formulation of nano fertilizers to address crop nutrition issues. Nano fertilizers are said to be an excellent replacement for bulk soluble fertilizers as they help in the slow release of nutrients, thereby improving nutrient use efficiency and reducing risks of environmental pollution (Elizabath, 2019). The major aspect of nanotechnology is the utilization of nanostructured molecules or atoms (nanoparticles) over the normal bulk materials. Examples of these nanoparticles (NPs) include Mesoporous silica NPs, Carbon nanotubes, Liposomes, Quantum dots, Metallic NPs such as selenium NPs, and Metal oxide NPs such as ZnO and TiO_2 (Mayurakshee et al., 2023; Rai et al., 2023a; Rai et al., 2023b). Nanoparticles can be used as (i) a source of plant nutrients when they are applied as they are, (ii) a means of delivery of nutrients to plants to ensure targeted uptake, and/or (iii) a coating to protect nutrient fertilizer and ensure a slow release of nutrients. In whichever way they are used, NPs offer a sustainable means of nutrient supply to the plants and help in protecting the environment from the adverse effects of mineral fertilizers (Elizabath, 2019). NPs are meant to reduce the quantity of fertiliser resources used, lessen nutrient loss, and improve crop quality and the overall yield (Mayurakshee et al., 2023).

Nanotechnology and biofertilizers can be integrated to form nanobiofertilizer with increased efficiency, stability, and functionality of PGPMs, thereby improving nutrient use efficiency, reducing nutrient losses, and increasing crop yield (Rai et al., 2023a; Rai et al., 2023b; Yadav and Yadav, 2024). This integration involves an encapsulation process where bacterial cells of PGPMs are coated with NPs, thereby protecting them from harsh environmental conditions, extending their shelf life, and enabling their gradual release (Oyediran et al., 2025). The main objective of this review is to explore the potential of applying nanotechnology in formulating biofertilizers for promoting plant growth as a sustainable way of enhancing crop production. To achieve this objective, the following key questions are addressed in this review:

i To what extent have NPs and PGPM been studied together as a technique for promoting plant growth and enhancing crop yield?
ii Which NPs and PGPM have been studied as plant growth and yield-enhancing agents?
iii In what ways can NPs and PGPM be applied together to enhance plant growth and yield?
iv What is the impact of NPs on the growth, viability, and functionality of PGPM?
v What is the impact of NPs and PGPMs on plant growth and yield?
vi What is the contribution of NPs and PGPM in ameliorating plant growth stress?

2 Materials and methods

Two databases, i.e., Scopus and Google Scholar, were used to search for relevant research articles to be included in this review. The search string used was: *"PGPR" OR "PGPB" OR "rhizobacteria" OR "biofertilizer" AND "nanotechnology" OR "nano technology" OR "nanobiofertilizer" OR "nano biofertilizer" AND "plant growth."* The search process and results are shown in the PRISMA chart below (Figure 1). The following steps were followed during the selection process:

- The First step was article identification. The search string *"PGPR" OR "PGPB" OR "rhizobacteria" OR "biofertilizer" AND "nanotechnology" OR "nano technology" OR "nanobiofertilizer" OR "nano biofertilizer" AND "plant growth"* was used to identify

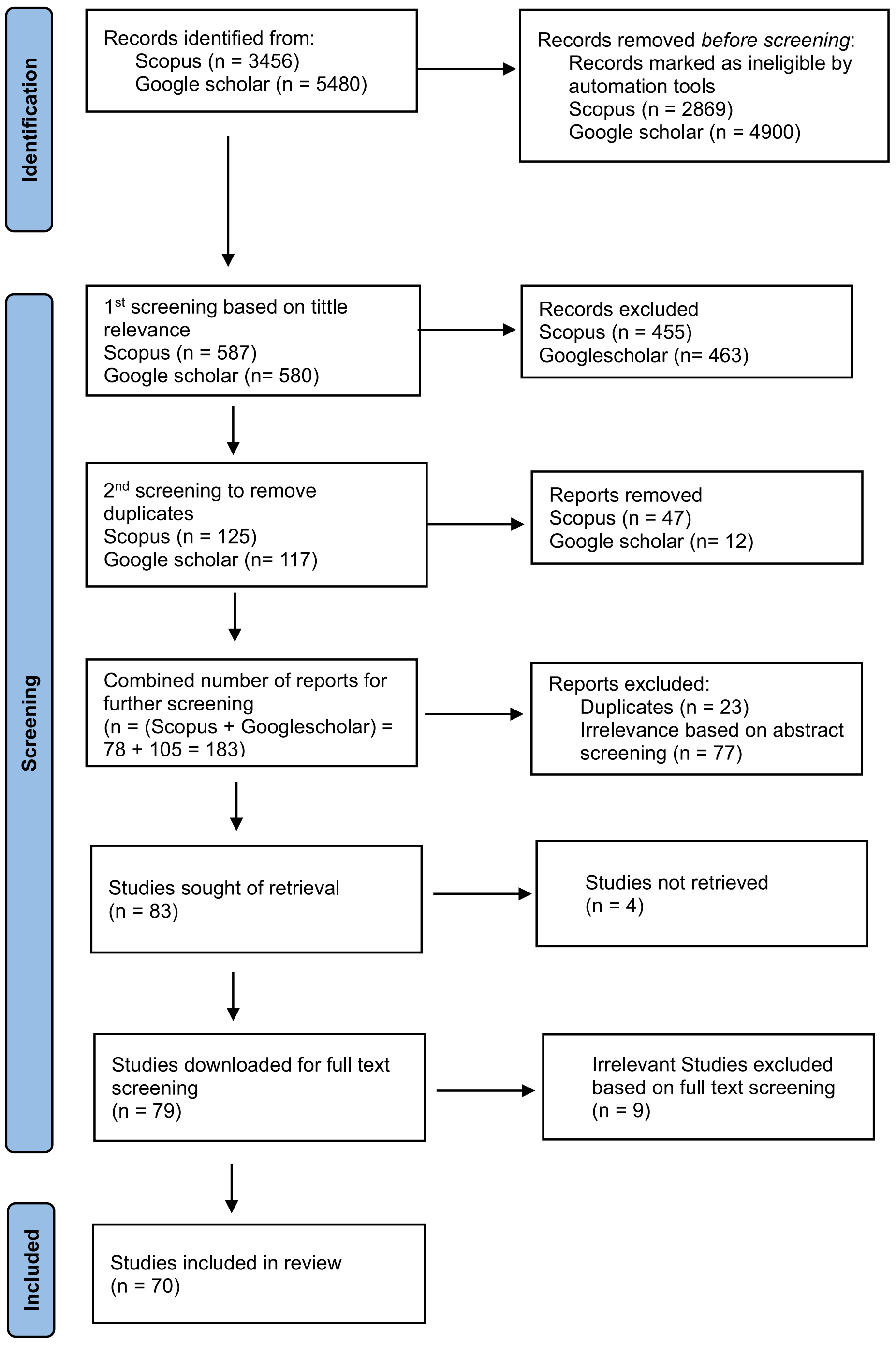


FIGURE 1
PRISMA flow chart showing the process of articles selection.

articles to be included in the review. The aim was to look for articles that focused on three main issues, i.e., plant growth-promoting bacteria, nanotechnology, and plant growth. In Google Scholar, the advanced search was performed, where articles that were published between 2000–2023 were included. Sorting of the articles was done based on relevance, English pages only were included, and any type of document was specified in the document type check box, including patents and citations. A total of 8,936 articles were identified, of which 3,456 were from Scopus and 5,480 from Google Scholar.

- The second step was the pre-screening of the identified articles. The 8,936 articles that were identified were subjected to a pre-screening process. In Scopus, the pre-screening was done automatically, where searching was limited to include articles that were published between 2000 and 2023. Final published original journals, books, book series, or conference proceedings that are in English and open access only were included. In Google Scholar, pre-screening was done manually, where the open-access articles only were labeled as "Nano bio" and saved in my library. The pre-screening process led to the elimination of 7,769 ineligible articles and left 587 articles from Scopus and 580 articles from Google Scholar.
- After pre-screening, the screening process started, where the first screening was done manually in both databases. In this step, the documents in both databases were exported as a CSV file and saved. The screening was based on title relevance and removal of review articles. During this process, 918 articles were excluded, and the remaining 242 articles were subjected to further screening.
- The second screening process was then performed on 242 articles that passed the first screening. In this step, the screening was based on duplication, where a total of 59 duplicates were removed and leaving 183 articles.
- The Third screening process involved further removal of duplicates and irrelevant articles based on the abstract. In this step, the articles from both databases were combined, and articles that appeared in both databases were considered duplicates and removed. Then, abstracts were read, and irrelevant articles were removed. This step led to the elimination of 100 articles and left 83 articles.
- The 83 articles that passed the three screening stages were downloaded and saved. However, not all articles were retrieved; only 79 articles were successfully downloaded and saved.
- The saved articles were subjected to final screening based on full-text reading. Only 9 articles were irrelevant and were excluded. Therefore, the remaining 70 articles were considered for this review.

The inclusion and exclusion criteria used to determine the relevance of articles in each stage of screening are shown in Table 1.

TABLE 1 Inclusion and exclusion criteria used to select articles.

Criteria	Include	Exclude
Publication time	Articles that were published between 2000 and 2023	Articles that were published before 2000
Accessibility	Open-access articles	Closed articles
Type of article	Fully published, original peer-reviewed research articles	Review articles and preprints
Language	Articles in English	Articles not in English
Contents	• Articles that report the effect of NPs on PGPMs • Articles that report the effect of both NPs and PGPMs on plant growth promotion	• Articles that reported NPs only • Articles that reported PGPMs only

3 Results and discussion

3.1 Extent of research on the combined use of nanoparticles and plant growth-promoting microbes for plant growth promotion

This review focused on examining the interaction of two important emerging aspects of sustainable agriculture, i.e., nanoparticles (NPs) and plant growth-promoting microbes (PGPM). The 70 studies that are included in this review can be divided into six groups based on the objectives and nature of experiments that were carried out. The details on the designation of these studies are given in Figure 2. A total of 28 studies were conducted to test the effect of NPs and PGPR on the growth of plants as separate treatments and in their combination. Sixteen studies did the evaluation to determine the toxicological effects of NPs on PGPR. On the other hand, 10 studies did the encapsulation of PGPR on NPs and tested the effect of encapsulated PGPR on plant growth. Only 5 studies have evaluated the effect of commercially available nanobiofertilizer products. The remaining studies (11 studies) have conducted research on the toxicological effects of NPs on PGPR, and at the same time, evaluated the effect of NPs and PGPR on plant growth as either separate treatments or the encapsulated product.

Only six products were reported and tested (details of the products are shown in Table 2). Three products are nanobiofertilizers, and three are biofertilizers. These results imply that there is a huge demand for more research to develop products that will be available for farmers in the pace of promoting sustainable farming practices.

Furthermore, it is observed that there is an increasing number of research studies that are conducted on the subject matter year after year (Figure 3). Studies on PGPM as an alternative nutrient source for plant growth are not new, but the interaction between NPs and PGPR is a new trend in agricultural production. Based on the search criteria that were established during this review, in the years 2000–2007, there was no article that was retrieved. Only two articles were published in the years 2008–2011, and the number kept on increasing each year from 8, 16, to 44 in 2012–2015, 2016–2019, and 2020–2023, respectively.

3.2 Types of nanoparticles and plant growth-promoting microbes studied in the reviewed articles as plant growth and yield enhancers

3.2.1 Nanoparticles

According to Joudeh and Linke (2022), NPs are divided into three types based on composition, namely organic NPs, carbon-based NPs, and inorganic NPs. It was observed during this review that all three

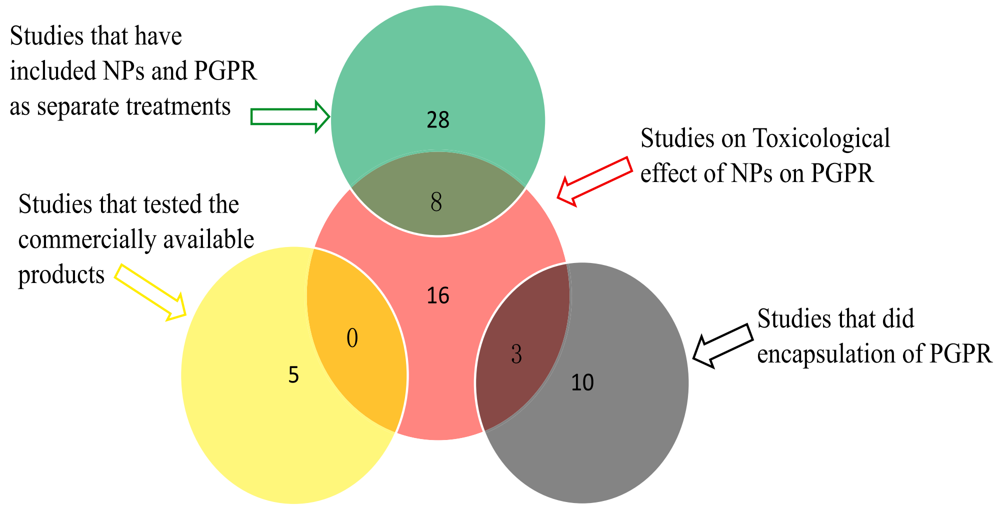


FIGURE 2
Designation of articles that were included in the review.

types of NPs can be successfully applied with PGPM to promote plant growth. Inorganic-based (ZnO and Silica) are the most studied NPs, followed by organic nanoparticles, mainly Chitosan and alginate. Carbon-based NPs are the least studied NPs, with only two studies reported in the selected articles. It was further observed that NPs can be used in a composite, i.e., more than one NPs can be applied together. A total of seven composite NPs were reported from different studies that were included in this review. The composite NPs studied were Chitosan polyvinyl alcohol, Laponite clay polyethylene oxide gel beads, Fe-coated nanofiber with activated carbon microbeads, Polymeric Fe, Chitosan coated mesoporous nano silica, polyvinylpyrrolidone-coated silver Engineered Nano Material, and Nano Fe Zn oxide.

3.2.2 Plant growth-promoting microbes

A total of 21 genera with more than 50 different species were observed to have a plant growth-promotion effect on different crops (Table 3). Two types of microbes were studied, these are, bacteria and fungi. In general, bacteria, specifically the free-living PGPR, are the most studied microbe (about 10 genera), followed by AMF.

PGPR are the root rhizosphere bacteria that can enhance plant growth through different mechanisms such as hormone secretion, phosphate solubilization, and nitrogen fixation (Hasan et al., 2024). These bacteria have a lot of benefits, including: increasing nutrient availability, shoot and root development, protection against several biotic and abiotic stresses such as salinity, drought, and heavy metals (de Andrade et al., 2023). According to the results obtained from this review, the most studied genera of bacteria in promoting plant growth are *Bacillus*, followed by *Pseudomonas*, *Azotobacter,* and *Azospirillum,* which were reported in 35, 28, 12, and 8 articles, respectively. The results further stipulate that *Pseudomonas* has the highest number of investigated species (14), followed by *Bacillus, Azospirillum,* and *Azotobacter,* which have 13, 3, and 2 species, respectively. *Rhizobium* with one species, namely *leguminosarum,* is the only symbiotic PGPR genus that was reported in four research articles.

On the other hand, the most investigated group of Fungi is arbuscular mycorrhiza fungi (AMF). AMF protects host plants against various stresses such as extreme temperature, salinity, water shortage, and toxic heavy metals, thereby promoting plant growth and yield (Cui et al., 2018). *Glomus* is the most reported genus of AMF with five species (*mosseae, fusculatum, clarum, intraradices,* and *etunicatum*), which were reported in 6 articles. Another AMF that was reported is *Piriformospora indica,* which was reported in only one study.

3.3 Ways nanoparticles and plant growth-promoting microbes can be applied together

NPs can be applied with PGPM to promote plant growth in two ways, i.e., as separate treatments applied individually and in combination, or by formulating nanobiofertilizer through encapsulation, where NPs are used as carriers and protection for PGPM. Out of 70 studies that were included in this review, 36 studies have evaluated the effect of NPs with PGPM as separate treatments, and 13 studies have done encapsulation and evaluated the effect of encapsulated PGPM on plant growth. The commonly reported method of encapsulation is electrospinning, followed by emulsion methods, and mostly, the organic and composite NPs are used for encapsulation. All the reported processes of encapsulation in the reviewed articles were successful.

3.4 Impact of nanoparticles on the growth and viability of plant growth-promoting microbes

NPs can influence the growth and functionality of PGPM or can inhibit their growth and reduce their activities (Verma et al., 2024). A total 27 articles out of 70 articles that were included in this review have reported the impact of different NPs on different PGPMs. The effect of NP on PGPM, based on the articles included in this review, is summarized in Table 4. It is observed that different NPs affect PGPM in different ways, and the effect of nanoparticles on PGPM

TABLE 2 Biofertilizers and nanobiofertilizer products that were tested and reported in the reviewed articles.

S/n	Name of product	Type	Contents	References
1	Azotovit	Biofertilizer	*A. chroococcum*	Tiranov et al. (2021)
2	Phosphovit	Biofertilizer	*B. mucilaginosus*	Tiranov et al. (2021)
3	Biomik	Nanobiofertilizer	*Azotobacter* spp., *Bacillus* spp., *Pseudomonas* spp., *Azospirillum* spp., 12% potassium, 32% humic acid, 0.1% molybdenum, 0.36% magnesium, 3.4% manganese, 2% fulvic acid, 0.36% calcium, 10% zinc, 9.5% iron, and some amino acids.	Eskandari et al. (2023)
4	Nitroxin	Biofertilizer	*A. chroococcum, A. lipoferum, Pseudomonas* spp.	Davod et al. (2011) and Eskandari et al. (2023)
5	Bioazar	Nanobiofertilizer	*Azotobacter* spp., *Pseudomonas* spp., nano Zn, Fe, and Mn	Zahedi (2014)
6	Haleax 2	Nanobiofertilizer	*Azospirillum*, *Azotobacter*, and *Klebsiella*	Sorial et al. (2022)

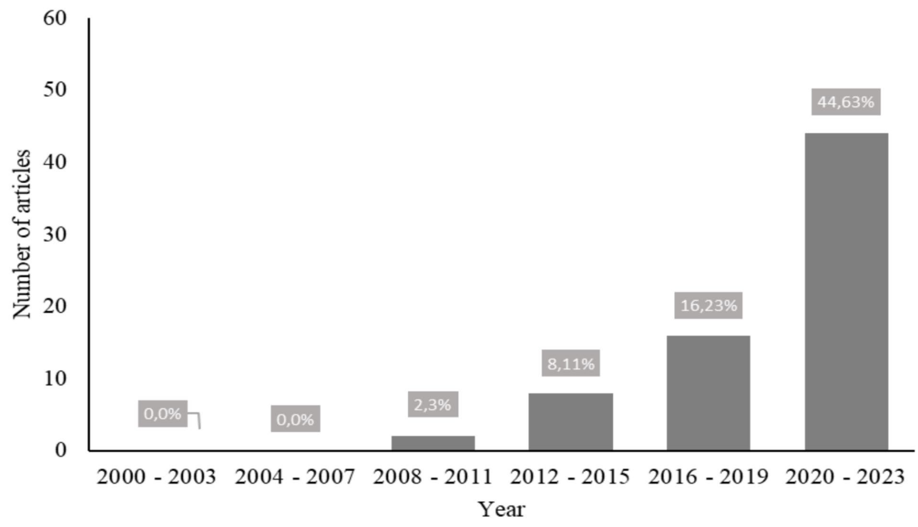


FIGURE 3
Distribution of reviewed articles in chronological order.

depends on the species of PGPM and the concentration of the NP. For instance, the studies on silver NP show that it suppresses the growth of most PGPM, but at higher concentrations, it increases production of IAA by *B. mojavensis* and reduces IAA production by *S. meliloti, P. mosselii,* and *A. chroococcum*. On the other hand, it is observed that TiO_2 nanoparticles increase the ability of *A. vinelandii* and *B. subtilis* to produce ABA and Cytokinin and increase adhesion of *P. polymyxa, A. faecalis, B. thuringiensis,* and *B. amyloliquefaciens* onto the roots of plants. However, at higher concentrations, TiO_2, CaO, ZnO, and Fe_2O_3 inhibit the growth of PGPM. While ZnO and CaO suppress the growth of PGPM. Gold NPs, Chitosan, SiO_2 NPs, Al_2O_3 NPs, and nanogypsum were observed to increase the growth and viability of PGPM. Other NPs such as SiO_2, CuO, and TiO_2 accelerate the production of IAA, Exopolysaccharides, ABA, GA, Cytokinin, and P solubilization.

These results show that there is a potential for using NPs in formulating biofertilizers to enhance the shelf life of bacterial cultures, plant growth, and productivity in agricultural fields (Perez et al., 2018). The concentrations of NPs should be observed during the formulation, as in most cases, higher concentrations of NPs reduce the viability of PGPM. Some NPs are toxic to PGPM; hence, precautions should be taken during disposal and application to prevent their effects on humans and the environment in general (Karunakaran et al., 2014).

3.5 Impact of nanoparticles applied with plant growth-promoting microbes on plant growth and yield

One of the promising applications of nanotechnology in agricultural production is in the improvement of biofertilizer formulation. The increased demand for safe and sustainable agricultural practices has pushed researchers to conduct research on the potential application of NPs along with biofertilizers in promoting plant growth. NPs can be applied with biofertilizers to promote plant growth in two ways, i.e., as separate treatments applied in combination or by formulating nanobiofertilizer through encapsulation, where NPs are used as carriers for PGPM.

Out of 70 investigated research articles, 54 articles have evaluated the effect of NPs with PGPM on the growth of different crops. A total of 13 studies did formulation of nanobiofertilizer by using NPs as carriers for PGPM, and 36 studies have tested the two (NPs and

TABLE 3 Plant growth-promoting microbes that were studied in the reviewed articles.

Types of microbes	Genus	No. of studies	Species
Rhizobacteria	*Rhizobium*	4	*Leguminosarum*
	Sinorhizobium	3	*Meliloti*
	Bacillus	34	*Amyloliquefaciens, pumilus, mojavensis, aryabhattai, velezensis, subtilis, thuringiensis, megaterium, licheniformis, coagulans, brevis, circulans, cereus*
	Lysinibacillus	1	*Macroides*
	Lactobacillus	2	*Casei*
	Serratia	2	*Marcescens*
	Pseudomonas	27	*Monteilii, allii, fluorescens, taiwanensis, putida, marginalis, rhodesiae, kilonensis, protegens, sesami, chlororaphis, aeruginosa, mosselii, koreensis*
	Methylobacterium	1	*Oryzae*
	Azospirillum	9	*Brasilense, lipoferum*
	Pantoea	5	*Agglomerans, dispersa*
	Klebsiella	2	*Pneumoniae*
	Azotobacter	12	*Chroococcum, vinelandii*
	Paenibacillus	5	*Elgii, polymyxa*
	Alcaligenes	1	*Faecalis*
	Nocardiopsis	1	ND
	Flavobacterium	1	ND
	Arthrobacter	2	ND
	Burkholderia	1	*Caribensis*
	Citrobacter	1	*Freundii*
Arbuscular mycorrhiza fungi (AMF)	*Glomus*	6	*Mosseae, fasciculatum, clarum, intraradices, etunicatum*
	Piriformospora	1	*Indica*

PGPMs) as separate treatments. The remaining 5 studies have evaluated the effect of commercially available nanobiofertilizers or biofertilizers with NPs on the performance of different crops.

A total of 25 crops were tested, as shown in Table 5. These crops are maize, rice, wheat, sugar beet, tomato, oilseed rape, common beans, triticale, pistachio, cabbage, peanuts, sunflower, eggplants, watermelon, ashwagandha, potato, soybean, rosemary, chili pepper, chick pea, radish, broccoli, grass pea, black eyed pea and fenugreek. Maize is the most investigated crop reported in 12 out of 53 research articles, followed by wheat and tomato, which are reported in 11 and 5 research articles, respectively. Sugar beet, black eyed pea, rice, and pistachio were reported in two articles only, while the remaining crops were reported only once.

The findings of this review revealed that treatments involving combined applications of NPs and PGPM were superior in promoting plant growth as compared to when the treatments were applied singly.

3.6 Contribution of nanoparticles and plant growth-promoting microbes in ameliorating plant growth stresses

In the course of determining the influence of NPs and PGPM on promoting plant growth, some researchers have gone further in exploring the possibilities of using these technologies as a means to overcome biotic and abiotic stresses for plant growth. Both NPs and PGPM have a beneficial impact in protecting plants against pathogens and abiotic stresses such as salinity, water stress, and heavy metals (de Andrade et al., 2023; Kumari et al., 2024).

Out of 54 studies that evaluated the effect of NPs and PGPM on the growth of crops, 20 studies have also evaluated their influence on ameliorating plant growth stresses. The biotic stresses reported in the articles included in this review are mainly the soil-borne pathogens, which are reported in 9 research articles. A study conducted by Guardiola-Márquez et al. (2023) and Timmusk et al. (2018) demonstrated that application of Fe-coated nanofiber with activated carbon microbeads along with *Paenibacillus polymyxa* and TiO_2 along with *B. thuringiensis* and *P. polymyxa* are effective in suppressing *Fusarium oxysporum* and *Fusarium culmorum* in chickpea and wheat, respectively. NPs and PGPM were also observed to be effective against *Cochliobolus sativus*, *Candida glabrata*, *Sclerotium rolfsii* and *Alternaria brassicae* in wheat, cabbage sprouts, rice, and oilseed rape, respectively. These results support the arguments made by Kumar et al. (2023) that the combined power of NPs and PGPR improves the plant's ability to resist disease-causing organisms. Similar findings were also reported by Perveen and Mushtaq (2019).

On the other hand, the abiotic stresses that were reported in the reviewed articles are drought/water stresses, cadmium accumulation, salinity stresses, and wastewater. The influence of NPs and PGPM in reducing salinity stress was reported in 8 articles, while five articles have reported their influence in reducing drought/water stresses. In all articles, NPs and PGPM have shown positive results in reducing the adverse effects of salt and water stresses on plants and promoting plant growth.

TABLE 4 Impact of nanoparticles on plant growth-promoting microbes.

S/n	NP	Impact on PGPM	References
1	Silver nanoparticles	Suppressed the growth of *P. fluorescens* and *B. cereus.* Reduced the abundance of soil bacteria. Increase production of IAA by *B. mojavensis* at Higher concentrations. Reduction of IAA production by *S. meliloti, P. mosselii,* and *A. chroococcum*	Chavan et al. (2022), Chavan and Nadanathangam (2019), and Khan and Bano (2016)
2	Gold NP	No impact on *P. putida* but accelerated the growth of *P. fluorescens, P. elgii,* and *B. subtilis.* Increased production of IAA by *P. monteilii* at 50 μg/mL	Panichikkal et al. (2019) and Shukla et al. (2015)
3	Chitosan	Preserved the viability of *A. brasilense* and *P. fluorescens* for a long time. Positive response on *P. taiwanensis, Pantoea agglomerans* in terms of compatibility, growth, viability, and cell morphology. Increased survivability of *Methylobacterium oryzae* after 9 months of storage	Agri et al. (2021) and Perez et al. (2018)
4	Silica NP, SiO_2	Changed the morphology of *P. polymyxa* and triggered the production of exopolysaccharides. Increased the ability of *A. vinelandii* and *B. subtilis* to produce ABA and Cytokinin. At 100 ppm, the ability of *B. cereus* to solubilize P and produce GA and the activities of catalase and superoxide dismutase enzymes were enhanced. No inhibitory effect on *B. velezensis* growth. Nontoxic toward *B. megaterium, A. vinelandii, P. fluorescens,* and *B. brevis* at below 1,000 mg L − 1 concentration.	Chobotarov et al. (2017), Ferrusquía-Jiménez et al. (2022), Fetsiukh et al. (2021), Karunakaran et al. (2014), and Moradi Pour et al. (2022)
5	CuO	Increased IAA production by *P. chlororaphis.* At 50 μgmL-1 IAA production by Rhizobium spp. increased by 11%, which later decreased with increasing concentration. At 150 μgmL-1 reduced IAA, HC, NH3, and siderophores production by Rhizobium spp. No effect on *S. meliloti, A. chroococcum, P. mosselii, B. thuringiensis.*	Ahmed et al. (2020), Dimkpa et al. (2012), and Oves et al. (2014)
6	ZnO	Inhibited IAA production by *P. chlororaphis*. Changed soil bacterial abundance and diversity. At 500 ppm reduced the growth of *P. allii, P. marginalis, P. protegens,* and *P. sesami* while at lower concentrations, the viability was maintained after 1 month of storage. Decreased IAA production and increased biofilm formation by *B. thuringiensis* and *B. megaterium*. ZnO showed a greater inhibitory effect than TiO_2-NPs on IAA production by *P. aeruginosa, P. fluorescens,* and *B. amyloliquefaciens*. At 150 μgmL-1 reduced IAA, HC, NH_3, and siderophores production by rhizobium. Sensitive to *S. meliloti, A. chroococcum, P. mosselii,* and *B. thuringiensis.*	Ahmed et al. (2020), Chavan et al. (2022), Chavan and Nadanathangam (2019), Dimkpa et al. (2012), Guardiola-Márquez et al. (2023), Haris and Ahmad (2017), Matyszczuk and Krzepiłko (2022), and Oves et al. (2014)
7	TiO_2	Increased the ability of *A. vinelandii* and *B. subtilis* to produce ABA and Cytokinin. Changed soil bacterial abundance and diversity. Has no effect on *B. velezensis, S. meliloti, A. chroococcum, P. mosselii* and *B. thuringiensis.* Increased adhesion of *P. polymyxa, A. faecalis, B. thuringiensis,* and *B. amyloliquefaciens* onto the roots of plants. At higher concentrations, it decreased *P. aeruginosa, P. fluorescens,* and *B. amyloliquefaciens* cell viability. In direct contact, it inhibited the growth of *R. leguminosarum, A. chroococcum, S. meliloti, P. dispersa, S. marcescens, P. aeruginosa, K. pneumoniae,* and *B. subtilis,* while in the presence of rich growth medium, the inhibition was eliminated.	Ahmed et al. (2020), Chavan et al. (2020, 2022), Chobotarov et al. (2017), Haris and Ahmad (2017), Moradi Pour et al. (2022), Palmqvist et al. (2015), and Timmusk et al. (2018)
8	Fe_2O_3	At 150 μgmL-1 it reduced IAA, HC, NH_3, and siderophores production by rhizobium spp. At 250 ppm and 500 ppm, it reduced the growth of *P. allii, P. marginalis, P. protegens,* and *P. sesami,* but at lower concentrations, the viability was maintained even after 1 month of storage.	Guardiola-Márquez et al. (2023) and Oves et al. (2014)
9	Nanoclay, natural char micro-particles (NCNPs), alginate	NCNPs + alginate and nanoclay + alginate carriers maintained the population of *P. putida* and *P. kilonensis.* NCNPs + alginate carrier increased the ability of *P. kilonensis* to solubilize P. After 6 months of storage, *P. kilonensis* maintained a higher population in all carriers.	Safari et al. (2020)
10	Al_2O_3	Can be tolerated by *S. meliloti, A. chroococcum, P. mosselii, and B. thuringiensis*. It increased the microbial population of the soil.	Ahmed et al. (2020) and Karunakaran et al. (2014)
11	Nano gypsum	At a concentration of 50 ppm, enhanced growth of *P. taiwanensis* and *P. agglomerans*	Sharma and Chaudhary (2019)
12	PVP-coated silver ENM.	They were less toxic to *B. amyloliquefaciens, S. meliloti,* and *P. putida* as compared to ions.	Lewis et al. (2017)
13	CaO NP	Toxic to *P. polymyxa*. Higher concentrations, i.e., above 1,000 ppm, are toxic to *B. subtilis, B. licheniformis,* and *Rhizobium* spp.	Jha et al. (2018)

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TABLE 5 The impact of nanoparticles and plant growth-promoting microbes on crop growth and yield.

Crop	NP	PGPM	No. of articles	Response	References
Sugar beet	SiO_2, ZnO	*G. intraradices, P. koreensis, B. coagulans*	2	Combined application of ZnO and AMF increased chlorophyll contents, carotenoids, superoxide dismutase, root, and sugar yields. Combined application of PGPR and Si-NP impacts the growth and yield under combined stressors of high soil salinity and saline water irrigation.	Alharbi et al. (2022) and Mir Mahmoudi et al. (2023)
Wheat	SiO_2, ZnO, FeO, FeZnO, CuO, TiO_2, MnO, Fe-coated nanofiber with activated carbon microbeads	*A chroococcum, A. lipoferum, P. putida, B. subtilis, L. casei, B. pumilus, G. mosseae, Flavobacterium* spp., *B. coagulans, B. cereus, B. thuringiensis, P. polymyxa, A. faecalis, B. aryabhattai, A. brasilense.*	11	The application of nano Zn-Fe oxide increased grain yield in the highest salinity level. PGPR with CuO-NPs treatments showed a strong anti-genotoxic effect against NaCl stress. Increased N uptake by wheat grains upon treatment with PGPR and ZnO-NPs. Application of biofertilizers and nano-silicon improved wheat grain yield under water stress conditions. Nanobiofertilizer application increased crop growth and improved yield and yield components through extending the growing period.	Ahmadi Nouraldinvand et al. (2023), Alharbi et al. (2023), Babaei et al. (2017), Fetsiukh et al. (2021), Hasan and Saad (2019), Hosseinpour et al. (2022), Merinero et al. (2022), Muhammad et al. (2022), Timmusk et al. (2018), Verma et al. (2021), and Zahedi (2014)
Tomato	Chitosan coated mesoporus nano silica, ZnO, SiO_2, nano clay, FeO, Chitosan	*M. oryzae, B. subtilis, L. casei, B. pumilus, A. vinelandii, B. megaterium, P. allii, P. marginalis, P. protegens, P. sesami, C. freundii.*	5	Increased root and shoot fresh and dry weight upon application of NPs and PGPR. Increased seedlings' vigor and plant health.	Chanratana et al. (2018), Guardiola-Márquez et al. (2023), Hosseinpour et al. (2020) Isfahani et al. (2019), and Pavlicevic et al. (2022)
Oilseed rape	TiO_2	*B. amyloliquefaciens*	1	TiO_2 NP increased adhesion of beneficial bacteria on to the roots of oilseed rape and protected the plants against infection	Palmqvist et al. (2015)
Black eyed pea	Gold, Laponite clay, polyethylene oxide gel beads	*P. monteilii, P. fluorescens, P. taiwanensis, P. rhodesiae, P. putida*	2	AuNPs increased plant growth. A combination of hydrogel PNC and PGPR resulted in vigorous growth of seedlings	Panichikkal et al. (2019) and Snigdha et al. (2021)
Rice	Alginate, ZnO	*L. macroides, B. cereus, Pseudomonas* spp.	2	Encapsulated PGPR increased the shoot and root length of seedlings Combined application of ZnO NPs and PGPR increased nitrogen-protein content and protein expression	Akhtar et al. (2022) and Panichikkal et al. (2021)
Maize	Calcium phosphate, SiO_2, Chitosan, Zeolite, ZnO, Fe_2O_3, TiO_2, Silver, Rock phosphate.	*G. mosseae, P. indica, P. taiwanensis, P. agglomerans, P. allii, P. marginalis, P. protegens, B. cereus, B. pumilus, P. fluorescens, A. brasilense, B. subtilis*	12	Calcium Phosphate NPs with *G. mosseae* and *P. indica* promote root elongation and plant growth. NPs applied with PGPR enhanced chlorophyll content, carotenoid content, sugar content, soluble protein content, phenol content, and flavonoid content, as well as yield, plant height, and number of leaves. PGPR and chitosan enhanced seed germination. NPs and PGPR increased cob length and weight, grain yield, and weight	Agri et al. (2021), Chaudhary et al. (2021a), Chaudhary et al. (2021b), Guardiola-Márquez et al. (2023), Jalal et al. (2023), Khan and Bano (2016), Khati et al. (2018), Kukreti et al. (2020), Kumar et al. (2020), Rane et al. (2015), Shafiq et al. (2022), and Yasmeen et al. (2022)
Common bean	SiO_2, polyamine, nano seaweed.	*Azospirillum* spp., *Azotobacter* spp., *Klebsiella* spp.	1	SiO_2 and PGPR increased leaf area, relative water content, proline concentration, and seed weight	Sorial et al. (2022)
Triticale	FeO	*A. chroococcum, P. putida*	1	Combined application of FeO at 1.0% or 5.0% levels and PGPR increased chlorophyll, carotenoid, P, N, and Fe contents in the plant	Sepehrzadegan and Alizadeh (2021)

(Continued)

TABLE 5 (Continued)

Crop	NP	PGPM	No. of articles	Response	References
Pistachio	Sodium alginate, SiO_2, carbon nano tubes	*B. subtilis, P. fluorescens, B. velezensis*	2	Encapsulated PGPR increased shoot and root lengths and weight	Pour et al. (2019, 2022)
Cabbage sprouts	Selenium	*Nocardiopsis* spp.	1	Seed priming with NPs and PGPR increased sprout growth (fresh and dry weights) and glucosinolate accumulation.	AbdElgawad et al. (2023)
Peanuts	Calcium, Boron	*B. megaterium, G. mosseae, G. fusculatum, G. clarum*	1	Improved plant height, 100-seed weight, shelling percentage, seed yield, oil content, and seed protein	Abdelghany et al. (2022)
Sunflower	ZnO	*B. mucilaginosus, A. chroococcum*	1	Improved sunflower yield productivity	Alamery and Ahmed (2020)
Eggplant	Nano potassium	*A. chroococcum, G. mosseae*	1	Triple interaction of treatments increased Plant height, leaf number and area, chlorophyll content, dry weight, and leaf content of N%, P%, K%, and Fe% & Zn%	Jumaah et al. (2019)
Watermelon	Chitosan-coated mesoporous nano silica, nano clay	*A. vinelandii, B. megaterium*	1	Increased P and N content, chlorophyll, viability, antioxidative potential, and total plant mass	Pavlicevic et al. (2022)
Ashwagandha	Silver	*B. mojavensis*	1	Increased Root, shoot length, dry biomass, and leaf area	Danish et al. (2022)
Potato	Silver	*A. chroococcum, A. lipoferum, Pseudomonas* spp.	1	Increased tuber diameter, number of tubers per plant, average weight of each tuber, and tuber yield when NPs were applied with PGPMs	Davod et al. (2011)
Soybean	Polyvinyl alcohol	*P. agglomerans, B. caribensis*	1	Increased germination, leaf number, length, and dry weight of the root and shoot.	De Gregorio et al. (2017)
Rosemary	NI	*Azotobacter* spp., *Bacillus* spp., *Pseudomonas* spp., *Azospirillum* spp., *A. chroococcum, A. lipoferum, G. intraradices, G. etunicatum*	1	Increased the essential oil percentage	Eskandari et al. (2023)
Chill pepper	SiO_2	*B. cereus*	1	Co-application of NPs and PGPR increased seed germination, plant height, number of leaves, and fruits	Ferrusquía-Jiménez et al. (2022)
Chick pea	Fe-coated nanofiber with activated carbon microbeads	*P. polymyxa*	1	Increased biomass, root length, chlorophyll, and protein contents.	Verma et al. (2021)
Radish	ZnO, FeO	*P. allii, P. marginalis, P. protegens, P. sesami*	1	Increased Plant height, Leaf diameter and fresh weight	Guardiola-Márquez et al. (2023)
Broccoli	ZnO, FeO	*P. allii, P. marginalis, P. protegens, P. sesami*	1	Increased Plant height, Leaf diameter, and fresh weight	Guardiola-Márquez et al. (2023)
Grass pea	SiO_2	*A. lipoferum, P. putida*	1	Increased root weight and volume, number of active nodules, percentage of active nodules, nodule dry weight, and chlorophyll index	Seyed Sharifi and Narimani (2023)
Fenugreek	Zeolite, Chitosan	NI	1	Increased plant height, leaf number, leaf area, fresh weight, chlorophyll, sugar, soluble leaf protein, and catalase activity	Kumari et al. (2020)

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4 Conclusion

A number of research studies have been conducted to explore the potential application of nanoparticles together with Plant growth-promoting microbes to promote plant growth and enhance crop yield. There is a potential for applying NPs with PGPMs to enhance plant growth and yield. The two technologies can be applied as either separate treatments applied in combination or by formulating nanobiofertilizer through encapsulation, where NPs are used as carriers and protection of PGPMs. Different NPs affect PGPMs in different ways, and the effect of NPs on PGPMs depends on the species of PGPM and the concentration of the NP. Higher concentrations of NPs affect PGPMs negatively; hence, precautions should be taken during the formulation. Combined application of NPs and PGPM helps to ameliorate plant growth stresses such as diseases, salinity, and drought, thereby promoting plant growth and yield.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

IM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. EM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

AbdElgawad, H., Magdy Korany, S., Reyad, A. M., Zahid, I., Akhter, N., Alsherif, E., et al. (2023). Synergistic impacts of plant-growth-promoting Bacteria and selenium nanoparticles on improving the nutritional value and biological activities of three cultivars of Brassica sprouts. *ACS Omega* 8, 26414–26424. doi: 10.1021/acsomega.3c02957

Abdelghany, A. M., El-Banna, A. A. A., Salama, E. A. A., Ali, M. M., Al-Huqail, A. A., Ali, H. M., et al. (2022). The individual and combined effect of nanoparticles and biofertilizers on growth, yield, and biochemical attributes of peanuts (*Arachis hypogea* L.). *Agronomy* 12:398. doi: 10.3390/agronomy12020398

Agri, U., Chaudhary, P., and Sharma, A. (2021). In vitro compatibility evaluation of agriusable nanochitosan on beneficial plant growth-promoting rhizobacteria and maize plant. *Natl. Acad. Sci. Lett.* 44, 555–559. doi: 10.1007/s40009-021-01047-w

Ahmadi Nouraldinvand, F., Seyed Sharifi, R., Siadat, S. A., and Khalilzadeh, R. (2023). Effects of bio-fertilizers and nano-silicon on phosphorus uptake, grain yield and some physiological traits of wheat (*Triticum aestivum* L.) under withholding irrigation conditions. *Environ. Stresses Crop Sci.* 16, 711–726. doi: 10.22077/ESCS.2023.4931.2090

Ahmed, B., Ameen, F., Rizvi, A., Ali, K., Sonbol, H., Zaidi, A., et al. (2020). Destruction of cell topography, morphology, membrane, inhibition of respiration, biofilm formation, and bioactive molecule production by nanoparticles of ag, ZnO, CuO, TiO2, and Al2O3 toward beneficial soil bacteria. *ACS Omega* 5, 7861–7876. doi: 10.1021/acsomega.9b04084

Akhtar, N., Khan, S., Jamil, M., Ur Rehman, S., Ur Rehman, Z., and Rha, E. S. (2022). Combine effect of ZnO NPs and bacteria on protein and gene's expression profile of rice (*Oryza sativa* L.) plant. *Toxics* 10, 305–325. doi: 10.3390/toxics10060305

Alamery, A. A., and Ahmed, N. A. (2020). Effect of biofertilizers and zinc nano particles on growth, yield and oil percentage of sunflower (*Helianthus annuus* L.). *Plant Arch.* 20, 4648–4652.

Alharbi, K., Hafez, E., Omara, A. E. D., Awadalla, A., and Nehela, Y. (2022). Plant growth promoting Rhizobacteria and silica nanoparticles stimulate sugar beet resilience to irrigation with saline water in salt-affected soils. *Plants* 11:117. doi: 10.3390/plants11223117

Alharbi, K., Hafez, E. M., Omara, A. E. D., Rashwan, E., and Alshaal, T. (2023). Zinc oxide nanoparticles and PGPR strengthen salinity tolerance and productivity of wheat irrigated with saline water in sodic-saline soil. *Plant Soil* 493, 475–495. doi: 10.1007/s11104-023-06245-7

Babaei, K., Sharifi, R. S., Pirzad, A., and Khalilzadeh, R. (2017). Effects of bio fertilizer and nano Zn-Fe oxide on physiological traits, antioxidant enzymes activity and yield of wheat (*Triticum aestivum* L.) under salinity stress. *J. Plant Interact.* 12, 381–389. doi: 10.1080/17429145.2017.1371798

Chanratana, M., Han, G. H., Melvin Joe, M., Roy Choudhury, A., Sundaram, S., Halim, M. A., et al. (2018). Evaluation of chitosan and alginate immobilized *Methylobacterium oryzae* CBMB20 on tomato plant growth. *Arch. Agron. Soil Sci.* 64, 1489–1502. doi: 10.1080/03650340.2018.1440390

Chaudhary, P., Khati, P., Chaudhary, A., Gangola, S., Kumar, R., and Sharma, A. (2021a). Bioinoculation using indigenous Bacillus spp. improves growth and yield of *Zea mays* under the influence of nanozeolite. *3 Biotech* 11, 1–11. doi: 10.1007/s13205-020-02561-2

Chaudhary, P., Khati, P., Gangola, S., Kumar, A., Kumar, R., and Sharma, A. (2021b). Impact of nanochitosan and Bacillus spp. on health, productivity and defence response in *Zea mays* under field condition. *3 Biotech* 11:237. doi: 10.1007/s13205-021-02790-z

Chavan, S., and Nadanathangam, V. (2019). Effects of nanoparticles on plant growth-promoting bacteria in Indian agricultural soil. *Agronomy* 9:140. doi: 10.3390/agronomy9030140

Chavan, S., Sarangdhar, V., and Nadanathangam, V. (2020). Toxicological effects of TiO2 nanoparticles on plant growth promoting soil bacteria. *Emerg. Contam.* 6, 87–92. doi: 10.1016/j.emcon.2020.01.003

Chavan, S., Sarangdhar, V., and Vigneshwaran, N. (2022). Nanopore-based metagenomic analysis of the impact of nanoparticles on soil microbial communities. *Heliyon* 8:e09693. doi: 10.1016/j.heliyon.2022.e09693

Chobotarov, A., Volkogon, M., Voytenko, L., and Kurdish, I. (2017). Accumulation of phytohormones by soil bacteria Azotobacter vinelandii and *Bacillus subtilis* under the influence of nanomaterials. *J. Microbiol. Biotechnol. Food Sci.* 7, 271–274. doi: 10.15414/jmbfs.2017/18.7.3.271-274

Cui, J., Bai, L., Liu, X., Jie, W., and Cai, B. (2018). Arbuscular mycorrhizal fungal communities in the rhizosphere of a continuous cropping soybean system at the seedling stage. *Braz. J. Microbiol.* 49, 240–247. doi: 10.1016/j.bjm.2017.03.017

Danish, M., Shahid, M., Zeyad, M. T., Bukhari, N. A., Al-Khattaf, F. S., Hatamleh, A. A., et al. (2022). *Bacillus mojavensis*, a metal-tolerant plant growth-promoting bacterium, improves growth, photosynthetic attributes, gas exchange parameters, and Alkalo-polyphenol contents in silver nanoparticle (ag-NP)-treated *Withania somnifera* L. (Ashwagandha). *ACS Omega* 7, 13878–13893. doi: 10.1021/acsomega.2c00262

Davod, T., Reza, Z., Azghandi Ali, V., and Mehrdad, C. (2011). Effects of nanosilver and nitroxin biofertilizer on yield and yield components of potato minitubers. *Int. J. Agric. Biol.* 13, 986–990.

de Andrade, L. A., Santos, C. H. B., Frezarin, E. T., Sales, L. R., and Rigobelo, E. C. (2023). Plant growth-promoting Rhizobacteria for sustainable agricultural production. *Microorganisms* 11:1088. doi: 10.3390/microorganisms11041088

De Gregorio, P. R., Michavila, G., Muller, L. R., De Souza Borges, C., Pomares, M. F., De Sá, E. L. S., et al. (2017). Beneficial rhizobacteria immobilized in nanofibers for potential application as soybean seed bioinoculants. *PLoS One* 12:176930. doi: 10.1371/journal.pone.0176930

Dhawi, F. (2023). The role of plant growth-promoting microorganisms (PGPMs) and their feasibility in hydroponics and vertical farming. *Meta* 13, 1–12. doi: 10.3390/metabo13020247

Dimkpa, C. O., Zeng, J., McLean, J. E., Britt, D. W., Zhan, J., and Anderson, A. J. (2012). Production of indole-3-acetic acid via the indole-3-acetamide pathway in the plant-beneficial bacterium *Pseudomonas chlororaphis* O6 is inhibited by ZnO nanoparticles but enhanced by CuO nanoparticles. *Appl. Environ. Microbiol.* 78, 1404–1410. doi: 10.1128/AEM.07424-11

Elizabath, A. (2019). Application of nanotechnology in agriculture. *Int. J. Pure Appl. Biosci.* 7, 131–139. doi: 10.18782/2320-7051.6493

Eskandari, A., Hashemi, M., Sepaskhani, A., Rostami, M., and Shams, Z. (2023). Application of nano-biofertilizer under abiotic stress on the vegetative growth, greenhouse gas emission, and essential oil production of rosemary (*Rosmarinus officinalis* L.). *J Gene Engg Bio Res* 5, 162–168.

Ferrusquía-Jiménez, N. I., González-Arias, B., Rosales, A., Esquivel, K., Escamilla-Silva, E. M., Ortega-Torres, A. E., et al. (2022). Elicitation of *Bacillus cereus*-Amazcala (B.C-a) with SiO2 nanoparticles improves its role as a plant growth-promoting bacteria (PGPB) in chili pepper plants. *Plants* 11:445. doi: 10.3390/plants11243445

Fetsiukh, A., Conrad, J., Bergquist, J., and Timmusk, S. (2021). Silica particles trigger the exopolysaccharide production of harsh environment isolates of growth-promoting rhizobacteria and increase their ability to enhance wheat biomass in drought-stressed soils. *Int. J. Mol. Sci.* 22:201. doi: 10.3390/ijms22126201

FAO (2021). Progress towards sustainable agriculture – drivers of change. Rome: FAO.

Guardiola-Márquez, C. E., López-Mena, E. R., Segura-Jiménez, M. E., Gutierrez-Marmolejo, I., Flores-Matzumiya, M. A., Mora-Godínez, S., et al. (2023). Development and evaluation of zinc and iron nanoparticles functionalized with plant growth-promoting rhizobacteria (PGPR) and microalgae for their application as bio-nanofertilizers. *Plants* 12, 3657–3680. doi: 10.3390/plants12203657

Haris, Z., and Ahmad, I. (2017). Impact of metal oxide nanoparticles on beneficial soil microorganisms and their secondary metabolites. *Int. J. Life-Sci. Sci. Res.* 3:10. doi: 10.21276/ijlssr.2017.3.3.10

Hasan, B. K., and Saad, T. M. (2019). Effect of nano biological and mineral fertilizers on growth and yield of wheat (*Triticum aestivum* L.). *Indian J. Ecol.* 46, 97–101.

Hasan, A., Tabassum, B., Hashim, M., and Khan, N. (2024). Role of plant growth promoting rhizobacteria (PGPR) as a plant growth enhancer for sustainable agriculture: a review. *Bacteria* 3, 59–75. doi: 10.3390/bacteria3020005

Hosseinpour, A., Haliloglu, K., Cinisli, K. T., Ozkan, G., Ozturk, H. I., Pour-Aboughadareh, A., et al. (2020). Application of zinc oxide nanoparticles and plant growth promoting bacteria reduces genetic impairment under salt stress in tomato (*Solanum lycopersicum* l. 'linda'). *Agriculture* 10, 1–16. doi: 10.3390/agriculture10110521

Hosseinpour, A., Ilhan, E., Özkan, G., Öztürk, H. İ., Haliloglu, K., and Cinisli, K. T. (2022). Plant growth-promoting bacteria (PGPBs) and copper (II) oxide (CuO) nanoparticle ameliorates DNA damage and DNA methylation in wheat (*Triticum aestivum* L.) exposed to NaCl stress. *J. Plant Biochem. Biotechnol.* 31, 751–764. doi: 10.1007/s13562-021-00713-w

Isfahani, F. M., Tahmourespour, A., Hoodaji, M., Ataabadi, M., and Mohammadi, A. (2019). Influence of exopolysaccharide-producing bacteria and SiO2 nanoparticles on proline content and antioxidant enzyme activities of tomato seedlings (*Solanum lycopersicum* L.) under salinity stress. *Pol. J. Environ. Stud.* 28, 153–163. doi: 10.15244/pjoes/81206

Jalal, A., Oliveira, C. E. d. S., Bastos, A. d. C., Fernandes, G. C., de Lima, B. H., Furlani Junior, E., et al. (2023). Nanozinc and plant growth-promoting bacteria improve biochemical and metabolic attributes of maize in tropical Cerrado. *Front. Plant Sci.* 13:1046642. doi: 10.3389/fpls.2022.1046642

Jeyanthi, V., and Kanimozhi, S. (2018). Plant growth promoting rhizobacteria (PGPR)-prospective and mechanisms: a review. *J. Pure Appl. Microbiol.* 12, 733–749. doi: 10.22207/JPAM.12.2.34

Jha, S., Singh, R., Pandey, A., Tripathi, S. K., Bhardwaj, M., Mishra, R. K., et al. (2018). Bacterial toxicological assay of calcium oxide nanoparticles against some plant growth promoting rhizobacteria. *SJ Impact Factor* 6:887.

Joudeh, N., and Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *J. Nanobiotechnol.* 20:262. doi: 10.1186/s12951-022-01477-8

Jumaah, A., Al-Fahdawi, J., and Allawi, M. M. (2019). Impact of biofertilizers and nano potassium on growth and yield of eggplant (*Solanum melongena* L.). *Plant Arch.* 19, 1809–1815.

Karunakaran, G., Suriyaprabha, R., Manivasakan, P., Rajendran, V., and Kannan, N. (2014). Influence of nano and bulk SiO2 and Al2O3 particles on PGPR and soil nutrient contents. *Curr. Nanosci.* 10, 604–612. doi: 10.2174/15734137113096660126

Khan, N., and Bano, A. (2016). Role of plant growth promoting rhizobacteria and ag-nano particle in the bioremediation of heavy metals and maize growth under municipal wastewater irrigation. *Int. J. Phytoremediation* 18, 211–221. doi: 10.1080/15226514.2015.1064352

Khati, P., Parul, Bhatt, P., Nisha, Kumar, R., and Sharma, A. (2018). Effect of nanozeolite and plant growth promoting rhizobacteria on maize. *Biotech* 8:1142. doi: 10.1007/s13205-018-1142-1

Kukreti, B., Sharma, A., Chaudhary, P., Agri, U., and Maithani, D. (2020). Influence of nanosilicon dioxide along with bioinoculants on Zea mays and its rhizospheric soil. *Biotech* 10:345. doi: 10.1007/s13205-020-02329-8

Kumar, P., Chib, P., Chandel, V., and Mehta, H. (2023). Nano-biofertilizers and biological amendments in productivity enhancement and nutrient use efficiency of fruit crops. *Food Sci. Rep.* 4, 36–45.

Kumar, R., Kumar, R., and Prakash, O. (2019). The impact of chemical fertilizers on our environment and ecosystem. *Chief Ed* 35, 1173–1189.

Kumar, P., Pahal, V., Gupta, A., Vadhan, R., Chandra, H., and Dubey, R. C. (2020). Effect of silver nanoparticles and *Bacillus cereus* LPR2 on the growth of *Zea mays*. *Sci. Rep.* 10:20409. doi: 10.1038/s41598-020-77460-w

Kumar, M., Poonam, Ahmad, S., and Singh, R. P. (2022). Plant growth promoting microbes: diverse roles for sustainable and ecofriendly agriculture. *Energy Nexus* 7:100133. doi: 10.1016/j.nexus.2022.100133

Kumari, A., Gupta, A. K., Sharma, S., Jadon, V. S., Sharma, V., Chun, S. C., et al. (2024). Nanoparticles as a tool for alleviating plant stress: mechanisms, implications, and challenges. *Plants* 13:528. doi: 10.3390/plants13111528

Kumari, S., Sharma, A., Chaudhary, P., and Khati, P. (2020). Management of plant vigor and soil health using two agriusable nanocompounds and plant growth promotory rhizobacteria in fenugreek. *3 Biotech* 10:461. doi: 10.1007/s13205-020-02448-2

Lewis, R. W., Unrine, J., Bertsch, P. M., and McNear, D. H. (2017). Silver engineered nanomaterials and ions elicit species-specific O2 consumption responses in plant growth promoting rhizobacteria. *Biointerphases* 12:5605. doi: 10.1116/1.4995605

Lucy, M., Reed, E., and Glick, B. R. (2004). Applications of free living plant growth-promoting rhizobacteria. *Antonie Van Leeuwenhoek* 86, 1–25. doi: 10.1023/B:ANTO.0000024903.10757.6e

Ma, Y., Dias, M. C., and Freitas, H. (2020). Drought and salinity stress responses and microbe-induced tolerance in plants. *Front. Plant Sci.* 11, 1–18. doi: 10.3389/fpls.2020.591911

Marambe, B., and Silva, P. (2012). Handbook of sustainability management. London: World Scientific.

Matyszczuk, K., and Krzepiłko, A. (2022). Model study for interaction of sublethal doses of zinc oxide nanoparticles with environmentally beneficial Bacteria Bacillus thuringiensis and *Bacillus megaterium*. *Int. J. Mol. Sci.* 23:820. doi: 10.3390/ijms231911820

Mayurakshee, M., Shilpa, R., Halavath, S., Kumar, D., and Gokul, S. R. (2023). Recent approaches in agriculture. Vol. 2. Delhi: Elite Publishing House.

Merinero, M., Alcudia, A., Begines, B., Martínez, G., Martín-Valero, M. J., Pérez-Romero, J. A., et al. (2022). Assessing the biofortification of wheat plants by combining a plant growth-promoting rhizobacterium (PGPR) and polymeric Fe-nanoparticles: allies or enemies? *Agronomy* 12, 228–247. doi: 10.3390/agronomy12010228

Mir Mahmoudi, T., Hamze, H., and Golabi Lak, I. (2023). Impact of biofertiliser and zinc nanoparticles on enzymatic, biochemical, and agronomic properties of sugar beet under different irrigation regimes. *Zemdirbyste* 110, 217–224. doi: 10.13080/z-a.2023.110.025

Moradi Pour, M., Saberi Riseh, R., Ranjbar-Karimi, R., Hassanisaadi, M., Rahdar, A., and Baino, F. (2022). Microencapsulation of *Bacillus velezensis* using alginate-gum polymers enriched with TiO2 and SiO2 nanoparticles. *Micromachines* 13:1423. doi: 10.3390/mi13091423

Muhammad, F., Raza, M. A. S., Iqbal, R., Zulfiqar, F., Aslam, M. U., Yong, J. W. H., et al. (2022). Ameliorating drought effects in wheat using an exclusive or co-applied Rhizobacteria and ZnO nanoparticles. *Biology* 11:564. doi: 10.3390/biology11111564

Oves, M., Khan, M. S., Zaidi, A., Ahmed, A. S., and Azam, A. (2014). Production of plant-growth promoting substances by nodule forming symbiotic bacterium Rhizobium sp. OS1 is influenced by CuO, ZnO and Fe2O3 nanoparticles. *IIOABJ* 5, 1–4.

Oyediran, O. K., Olagoke, O. O., and Abiodun, S. (2025). Nano-biofertilizers application as sustainable approach to enhance crop productivity and soil health: a review. *Glob. J. Agric. Res.* 13, 47–71. doi: 10.37745/gjar.2013/vol13n14771

Palmqvist, N. G. M., Bejai, S., Meijer, J., Seisenbaeva, G. A., and Kessler, V. G. (2015). Nano titania aided clustering and adhesion of beneficial bacteria to plant roots to enhance crop growth and stress management. *Sci. Rep.* 5, 1–12. doi: 10.1038/srep10146

Panichikkal, J., Prathap, G., Nair, R. A., and Krishnankutty, R. E. (2021). Evaluation of plant probiotic performance of Pseudomonas sp. encapsulated in alginate supplemented with salicylic acid and zinc oxide nanoparticles. *Int. J. Biol. Macromol.* 166, 138–143. doi: 10.1016/j.ijbiomac.2020.10.110

Panichikkal, J., Thomas, R., John, J. C., and Radhakrishnan, E. K. (2019). Biogenic gold nanoparticle supplementation to plant beneficial *Pseudomonas monteilii* was found to enhance its plant probiotic effect. *Curr. Microbiol.* 76, 503–509. doi: 10.1007/s00284-019-01649-0

Pavlicevic, M., Abdelraheem, W., Zuverza-Mena, N., O'Keefe, T., Mukhtar, S., Ridge, G., et al. (2022). Engineered nanoparticles, natural nanoclay and biochar, as carriers of plant-growth promoting bacteria. *Nano* 12, 4474–4500. doi: 10.3390/nano12244474

Perez, J. J., Francois, N. J., Maroniche, G. A., Borrajo, M. P., Pereyra, M. A., and Creus, C. M. (2018). A novel, green, low-cost chitosan-starch hydrogel as potential delivery system for plant growth-promoting bacteria. *Carbohydr. Polym.* 202, 409–417. doi: 10.1016/j.carbpol.2018.07.084

Perveen, Z., and Mushtaq, A. (2019). Environment friendly nanofertilizers for sustainable crop management: a review. *IJCBS* 15, 87–93.

Pour, M. M., Riseh, R. S., and Skorik, Y. A. (2022). Sodium alginate–gelatin nanoformulations for encapsulation of Bacillus velezensis and their use for biological control of pistachio gummosis. *Materials* 15:114. doi: 10.3390/ma15062114

Pour, M. M., Saberi-Riseh, R., Mohammadinejad, R., and Hosseini, A. (2019). Nano-encapsulation of plant growth-promoting rhizobacteria and their metabolites using alginate-silica nanoparticles and carbon nanotube improves UCB1 pistachio micropropagation. *J. Microbiol. Biotechnol.* 29, 1096–1103. doi: 10.4014/jmb.1903.03022

Rai, P. K., Rai, A., Sharma, N. K., Singh, T., and Kumar, Y. (2023b). Limitations of biofertilizers and their revitalization through nanotechnology. *J. Clean. Prod.* 418:138194. doi: 10.1016/j.jclepro.2023.138194

Rai, A., Rai, P. K., and Singh, S. (2018). Characterization of phosphate solubilizing fluorescent pseudomonads from the rhizosphere of *Aloe vera* (L.). *Arch. Agron. Soil Sci.* 64, 1032–1040. doi: 10.1080/03650340.2017.1407869

Rai, A., Sharma, N. K., Singh, V. K., Dwivedi, B. S., Singh, J. S., and Rai, P. K. (2023a). Study of phosphate solubilizing fluorescent Pseudomonas recovered from rhizosphere and endorhizosphere of *Aloe barbadensis* (L.). *Geomicrobiol J.* 40, 347–359. doi: 10.1080/01490451.2023.2171165

Rane, M., Bawskar, M., Rathod, D., Nagaonkar, D., and Rai, M. (2015). Influence of calcium phosphate nanoparticles, Piriformospora indica and Glomus mosseae on growth of *Zea mays*. *Adv. Nat. Sci. Nanosci. Nanotechnol.* 6, 1–9. doi: 10.1088/2043-6262/6/4/045014

Safari, M., Motamedi, E., Kari Dolatabad, H., and Modarres Sanavy, S. A. M. (2020). Nano-carriers effects on the viability and efficiency of Pseudomonas strains as phosphate solubilizing bacteria. *Heliyon* 6:e05076. doi: 10.1016/j.heliyon.2020.e05076

Sepehrzadegan, Z., and Alizadeh, O. (2021). Investigation of the growth bacteria and nano iron on the chlorophyll and some nutrients triticale. *Rev. Agrogeoambiental.* 13:1572. doi: 10.18406/2316-1817v13n120211572

Seyed Sharifi, R., and Narimani, H. (2023). Effect of nano silicon and plant growth-promoting rhizobacteria on biomass, nodulation and some physiological traits of grasspea (*Lathyrus sativus* L.). *Iran. J. Field Crops Res.* 20, 435–449. doi: 10.22067/jcesc.2022.75528.1149

Shafiq, T., Yasmin, H., Shah, Z. A., Nosheen, A., Ahmad, P., Kaushik, P., et al. (2022). Titanium oxide and zinc oxide nanoparticles in combination with cadmium tolerant *Bacillus pumilus* ameliorates the cadmium toxicity in maize. *Antioxidants* 11:156. doi: 10.3390/antiox11112156

Sharma, A., and Chaudhary, P. (2019). Response of nanogypsum on the performance of plant growth promotory bacteria recovered from nanocompound infested agriculture field. *Environ Ecol* 37, 363–372.

Shukla, S. K., Kumar, R., Mishra, R. K., Pandey, A., Pathak, A., Zaidi, M., et al. (2015). Prediction and validation of gold nanoparticles (GNPs) on plant growth promoting rhizobacteria (PGPR): a step toward development of nano-biofertilizers. *Nanotechnol. Rev.* 4, 439–448. doi: 10.1515/ntrev-2015-0036

Singh, J. S. (2013). Plant growth promoting Rhizobacteria potential microbes for sustainable agriculture. *Resonance* 18, 275–281.

Snigdha, S., Kalarikkal, N., Thomas, S., and Radhakrishnan, E. K. (2021). Laponite Ò clay/poly(ethylene oxide) gel beads for delivery of plant growth-promoting rhizobacteria. *Bull. Mater. Sci.* 44, 1–7. doi: 10.1007/s12034-021-02383-9S

Sorial, M. E., Soliman, A. A., and Selim, D. A.-F. H. (2022). Physiological responses of *Phaseolus vulgaris* to some nano bio-stimulants under salt stress conditions. *Ann. Agric. Sci., Moshtohor.* 60, 809–820.

Timmusk, S., Seisenbaeva, G., and Behers, L. (2018). Titania (TiO2) nanoparticles enhance the performance of growth-promoting rhizobacteria. *Sci. Rep.* 8:1. doi: 10.1038/s41598-017-18939-x

Tiranov, A. B., Tiranova, L. V., Grigoriev, A. V., Sevostyanova, N. N., and Yakovleva, V. A. (2021). Influence of Azotovite and Phosphatovite on the productivity of oats and the fertility of sod-Podzolic soil in the conditions of the Novgorod region. *IOP Conf. Series Earth Environ. Sci.* 852:105. doi: 10.1088/1755-1315/852/1/012105

Verma, K. K., Joshi, A., Song, X. P., Singh, S., Kumari, A., Arora, J., et al. (2024). Synergistic interactions of nanoparticles and plant growth promoting rhizobacteria enhancing soil-plant systems: a multigenerational perspective. *Front. Plant Sci.* 15, 1–14. doi: 10.3389/fpls.2024.1376214

Verma, N., Omar, R. A., Gupta, G. S., and Gahoi, P. (2021). Rhizobacteria and acylated homoserine lactone-based nanobiofertilizer to improve growth and pathogen defense in Cicer arietinum and *Triticum aestivum* plants. *ACS Agric. Sci. Technol.* 1, 240–252. doi: 10.1021/acsagscitech.1c00039

Yadav, A., and Yadav, K. (2024). Challenges and opportunities in biofertilizer commercialization. *SVOA Microbiol.* 5, 1–14. doi: 10.58624/SVOAMB.2024.05.037

Yasmeen, T., Arif, M. S., Shahzad, S. M., Riaz, M., Tufail, M. A., Mubarik, M. S., et al. (2022). Abandoned agriculture soil can be recultivated by promoting biological phosphorus fertility when amended with nano-rock phosphate and suitable bacterial inoculant. *Ecotoxicol. Environ. Saf.* 234:113385. doi: 10.1016/j.ecoenv.2022.113385

Zahedi, H. (2014). Evaluation of nano biofertilizer efficiency on agronomic traits of spring wheat at different sowing date. *Biol. Forum Int. J.* 6, 349–356.