Chapter 4
Influence of Nanoparticles on the Plant Rhizosphere Microbiome

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1 Introduction

Nanotechnology is a multidimensional face of science that has achieved value in agriculture and many more welfare activities including hydraulics industries and others such as cosmetics, electronics, textiles, and food (Wu et al. 2020; Faizan et al. 2020a, b; Alam et al. 2015). Nanotechnology in agriculture has gained recognition in recent years as a result of technological advancements that have enabled the development of a variety of devices, including nanoparticles (NPs) and nanotubes that are ultimately reported to influence the microbiome of the plant rhizosphere. NPs with unique properties are documented to influence the plant's development, cell structure, physiological, and biochemical processes (Faizan et al. 2021a, b). Besides, numerous chemicals, including metallic NPs, aluminum (Al), titanium (Ti), zinc (Zn), copper (Cu), gold (Au), silver (Ag), iron (Fe), and cobalt (Co), are utilized to adorn NPs which can act as an indirect mean of contaminants' release to the environment (Khot et al. 2012). NPs have specific properties in respect to their minute size (less than 100 nm) with at least in one dimension, which consequences in elevated surface area charges, therefore, they are extra reactive over their

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large amount counterparts (Dimkpa et al. 2019; Faraz et al. 2019). Benefits in farming comprise abridged fertilizer loss; improvement of agricultural efficiency (Rai and Ingle 2012); augmented plants quality and yield (Velasco et al. 2020); and the possibility for pest management (Landa 2021), becoming a substitute to chemical insecticides since they are measured comparatively secure for humans' contrast to synthetic insecticides (Salem et al. 2015). Nanofertilizers are used to slowly release nutrients while diminishing pollution (Seghatoleslami and Forutani 2015). These nanoscale fertilizers are a move toward that creates nutrients accessible to plant leaves, thus raising the competence of plant nutrient uptake (Vishekaii et al. 2019). Zinc oxide NPs have been accounted to lessen the oxidative damage in various crops (Dimkpa et al. 2020; Faizan et al. 2018, 2021c). Zinc oxide NPs abridged malondialdehyde (MDA) content and improved catalase (CAT) and superoxide dismutase (SOD) activities in stressed *Leucaena leucocephala* (Zahedi et al. 2020). Similar results were also reported in *Oryza sativa* (Faizan et al. 2021d) and *Beta vulgaris* (Sun et al. 2020). Due to their small dimension, nanofertilizers have an advanced and quicker translocation between plant parts, which augments nutrient efficiency (Smith 2014). In crop growing, plant yield and effectiveness are enhanced by the employment of pesticides. NPs envelop broad diversity of products, some of which previously are accessible in the market (Nuruzzaman et al. 2016). Scientists demonstrated various methodologies for NPs formulation, characterization, their consequence, and their appliance in plant disease management (Al-Samarrai 2012).

Soil microbial communities have a straight effect on soil eminence through procedures like symbiotic relationships with terrestrial plants, nutrient cycling, and decomposition of organic matter (Kennedy and Smith 1995). Therefore, the defense of soil microbial growth and variety is the most important challenge in agriculture. Numerous carbon nanotubes (CNTs) have recently gained considerable interest due to their potential applications in the management of plant growth. Plus, CNTs play a positive role in the enhancement of plant physiological attributes and biochemical indices as well. According to Tripathi and Sarkar (2014), carbon nanodots over control significantly increased the root growth in wheat. Likewise, the gram plant also showed a positive impact after exposure to carbon nano-onions (Sonkar et al. 2012). It is known that the category, dimension, concentration, and functionalization of CNTs be able to conclude their toxicological and physiological property in dissimilar crops (Tiwari et al. 2014). CNTs have potential agricultural appliances because of their impacts on modifiable plant growth, the aptitude to navigate plant cell walls, and as an average for pesticide submission (Jordan et al. 2020). These can be effective in manipulating the metabolism of cells by stimulating enzymatic and metabolic activity and gene expression, in addition to boosting the photosynthetic performance of leaves via an increase in photosynthetic pigment levels (Rahmani et al. 2020).

2 Source and Impacts of NPs on Soil Properties

The bound of loam to effort as an alive framework, with the surroundings and ground usage restrictions, has been characterized as soil well-being to maintain crop and respiration system effectiveness, improve water and air quality, and crops. Soils are permeable organizations consisting of multifarious prearranged congregations of mineral and natural elements joint in liquid and gaseous points. The behavior and bioavailability of general pollutants such as pesticides, trace metals, and polycyclic aromatic hydrocarbons are highly influenced by soil behavior and characteristics (Labud et al. 2007; Ranjard et al. 2000). The study of the communications among NPs and soil is complex by the elevated unpredictability in properties, sourced by dissimilarity in the ecological situation and soil masterpiece, and by the huge numeral of forms of available NPs. Each year, 11 million tons of metal oxide and metal NPs are expected to be produced in the world, with soil resources determining the final amount (Sun et al. 2014).

These days, nanotechnology is fast attention from industry gratitude to the appearance of novel functions in dissimilar fields like medical, electronics, and agriculture. This rising attention is foremost to higher manufacture of NPs in the business and spaces us in exceptional novel development where the effect might have on the surroundings and livelihood beings wants to be immediately evaluated. Nanoscience is demonstrated as the branch of science that studies nanometric scale matter, bearing in mind its size and uniqueness. However, nanotechnology examines ways of makeover and controlling these properties (Jeevanandam et al. 2018). The term NPs defines the particles whose dimensions are in the nanometer scale for some authors and for others it contains the shortest definition of NPs, which is probably the most instinctive one, taking into contemplation only their size, which is limited conservatively to about 100 nm in any direction (Strambeanu et al. 2015). This minute size produces a broad range of functions in various scientific fields (Tweney 2006).

Nanoparticles affect the majority of soil belongings but there have been no evaluations of their effect on the density performance of soil and the force of collectives. Therefore, we evaluated the impact of NPs on the large density and the restricted density and tensile strength of summative of calcareous loamy soil. The performance of NPs in the environment has involved significant attention in present years due to the dramatic boost in NPs production and consumer use, which has resulted in rising revelation and discharge to the environment. Some researchers have explained the contradictory phenomenon, specifically, the impact of NPs on the environment in common, and on soil properties in particular. Elliott and Zhang (2001) subjected bimetallic NPs to a test area to reveal the decrease of trichloroethene and other chlorinated aliphatic hydrocarbons. The porosity of the soil was not pretentious by the NPs, and the blockage was shown to be insignificant. Fullerene NPs were found to have a modest effect on soil-microbial societies and microbial processes (Nyberg et al. 2008). Multi-walled carbon nanotubes were shown to decrease enzymes activity in the soil and microbial growth (Chung et al. 2011).

Metal oxide NPs were also examined; Ge et al. (2011) studied the effect of TiO_2 and ZnO on soil microbial societies and established that both NPs abridged microbial growth and diversity. Pradhan et al. (2011) examined the impact of copper oxide and silver NPs on leaf microbial putrefaction presentation that experience to these NPs led to a reduction in leaf rotting rate. Furthermore, the decrease in rotting was attended by transformation in the organization of the microbial societies.

3 Effects of NPs on Rhizospheric Microbiome Functionality

The group of microorganisms and their respective genomes living within the sphere of the plants' root are jointly referred to as rhizospheric microbiome (Rajput et al. 2021). They consist of bacteria and fungi, forming the dominant population, and other groups of organisms such as viruses, archaea, and protists, which are also found in other environments beside soils such as aquatic habitat, plants, animals, and humans (Merten et al. 2020). However, the soil microbial community denotes the highest reservoir of biological diversity in the world, as the rhizospheric unit is reported to contain about 10^{11} microbial cell g^{-1} of the roots, accounting for roughly more than 30,000 prokaryotes species (Berendsen et al. 2012). These microbes are known to have either beneficial, commensal, or pathogenic relationships among themselves as well as with their host plants. They are key players in biogeochemical cycles of nutrients such as nitrogen, phosphorus, potassium, carbon, sulfur, etc., and biochemical reactions such as nutrients uptake, antibiotics production, biomass decomposition, biodegradation, maintenance of soil structure, and stimulating stress tolerance in the plants (Rahman et al. 2021; Khan et al. 2021). Thus, plays an important role in the overall determination of fertility and health of soil. Nevertheless, many external factors ranging from farming practices, physical and chemical properties of soils, biotic and abiotic stress, including the use of NPs adversely affect the microbial diversity in the rhizosphere (Brolsma et al. 2017). Subsequently, favor the selective enrichment of certain microbial communities over the others and their associated functions in the rhizosphere.

The prevalence of NPs in the rhizospheric region has been attributed from many sources; including natural mineralization by plants in response to different environmental stress, use of industrial coated NPs-based products such as fertilizers and pesticides in the soils, human activities, sewage or industrial waste products deposited in the soils (Ovais et al. 2018). The use of industrial coated NP products is commonly used in sustainable agricultural practices as a viable technology with a positive impact on soil microbial community, plant growth, yield, and yield quality (Prasad et al. 2017). The efficiency of their application large rests on their sizes, shapes, surface area, composition, and more importantly, the level at which they optimally exert their effects (Khodakovskaya et al. 2012; Zhai et al. 2016; Rastogi et al. 2017). Therefore, depending on their concentrations in the rhizospheric region, the unprecedented utilization and release of NPs may lead to a huge repercussion to the soil microbiomes (Khanna et al. 2021). Nanoparticles can potentially affect microbial functionality and plants in both positive and negative ways (Fig. 4.1). Few studies investigated the positive effects of NP products on microbiome functionality (Shah and Belozerova 2009; Shah et al. 2014). For example, Asadishad et al. (2017) studies revealed that exposing the soil to a fixed size citrate-coated nAu (50 nm) generally increased soil enzymatic activities within 30 days of exposure; the abundance of bacterial groups (Actinobacteria and Proteobacteria) was also considerably increased. Suggesting that exposing the nAu to soils may enhance the enzymatic activities along with microbial communities, thereby affecting the nutrient cycling in the soil.

Contrarily, although the current environmental concentrations of NPs are still under the threshold level of toxicity in most soils, some even argue the idea that NPs (like nZnO and nAg) are not toxic (Mu et al. 2011; Zhou et al. 2015). These, in addition to the limited available literature on the environmental impacts and antimicrobial properties, demanded a thorough investigation in better understanding the physicochemical as well as biotic impacts of NPs in the soils (Kiss et al. 2021). Several reports have revealed negative impacts of NPs on exposure to microbial functionality. For instance, the study conducted by Shen et al. (2015) on neutral soils treated with 1 mg ZnO-NPs and the ecotoxicology impacts on soil microorganism observed a decrease in respiration, ammonification, dehydrogenase (DH), and fluorescence diacetate hydrolase (FDAH) activity within the first to the third month of the study, the proposed mechanisms being the direct contact of Zn-NPs with biologic targets. Similarly, results from Ma et al. (2013) also described the toxic

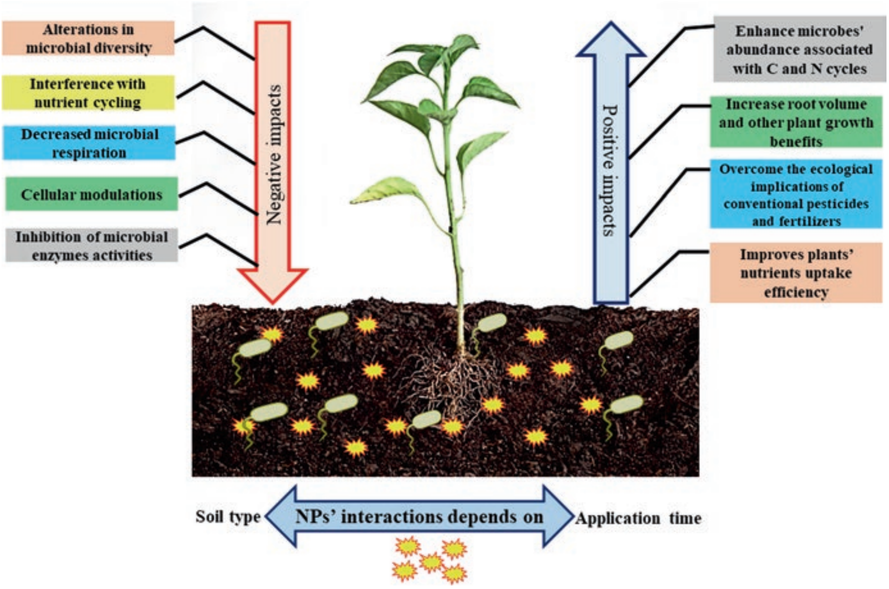

Fig. 4.1 Schematic representation of NPs' interaction with soil microbiome and associated impacts on its functions and plants

nature of ZnO-NPs to the different bacterial systems, leading to the dissociation of ZnO-NPs to zinc ions (Zn+), and generative of reactive oxygen species (ROS), as a result of direct interplay with the biologic target. These were both influenced by environmental conditions (Li et al. 2011). The utilization of nanoscale zero-valent iron (nZVI) has also been reported to have antimicrobial properties (Cullen et al. 2011; Saccà et al. 2014; Fajardo et al. 2019). For instance, Semerád and Cajthaml (2016) reported from their studies a pronounced change in autochthonous bacteria species often exposed to nZVI, which was observed to vary among soil types (2.4 and 2.2) with the phylogenetic changes appear to be more abundant than at the functional level. Hence, suggesting maintenance of the overall functions of soil ecosystem on exposure to nZVI. Generally, living tissues of microorganisms such as cell mitochondria and the cell nucleus often exposed to these nanoparticles can be taken up spontaneously, and subsequently results in the alteration of the cell membrane, mutation of DNA, structural damage to mitochondria, and ultimately, death of the cells (Geiser et al. 2005; Porter et al. 2007; Li et al. 2011).

4 Interactions of Nanoenabled Agrochemicals with Soil Microbiome

Agrochemicals play a crucial part in the economic productivity of agricultural products. When used conventionally, however, they are reported to be degraded or expelled by environmental variables such as wind, sunlight, rain, etc. (Gill and Garg 2014). Also, a considerable fraction of agrochemicals do not reach their intended species, thereby they are applied on a regular basis. Thus, recurrent agrochemical applications not only raise the expense, but also have adverse effects on plants, the environment, and the health of those exposed through the food chain (Vurro et al. 2019). In this context, several techniques have been emerged to resolve this issue and nanotechnology is also one of them. Because of the unique properties of nanomaterials, combining nanotechnology with agro-biotechnology is becoming more frequent in the agricultural sector (Srivastava and Singh 2021). At low concentrations, NMs are reported as potential agents to improve edible plants' yield and quality. Nanomaterials can encapsulate nutrients, coat them with a thin protective nanoscale polymeric coating, or distribute them as nano-emulsions or nanoparticles (Iavicoli et al. 2017). Thus, nano-enabled agrochemicals can either deliver one or more nutrients to plants, hence promoting growth, or they can improve the effectiveness of conventional fertilizers. Also, due to the greater surface area, nano-coatings on fertilizers can hold the substance more firmly on the plant. Thus, nano-enabled agrochemicals are reported to boost the plant-uptake efficiency of nutrients and reduce the adverse impacts of conventional fertilizer applications (Ur Rahim et al. 2021). In recent years, the nanopesticides and nanofertilizers got a great deal of attention due to their numerous advantages over the conventional ones. The basic principle and working of these agrochemicals are discussed in the forthcoming paragraphs.

4.1 Nanopesticides

The nanoformulation of conventional pesticides with polymers or metal nanoparticles is an emerging area in the pesticide industry in and of itself. Any pesticide formulation that implies either very small particles of a pesticide active component or other small, designed structures with effective pesticidal characteristics is referred to as a "nanopesticide" (Kookana et al. 2014; Iavicoli et al. 2017). The controlled and progressive release of active ingredient by modification in the outer shell of the nanocapsule delivers a mild dose over a longer time period and prevents excess run-off of undesirable pesticide, which make it a viable approach for agricultural personnel (Gill and Garg 2014; Sharma et al. 2019). Thus, nano-formulations for pesticides provide benefits due to their improved solubility, mobility, and durability.

4.2 Nanofertilizers

Nanofertilizers are NMs that deliver one or more essential nutrients to plants directly. Also, it has been observed that nanofertilizers improve the performance, availability, or usage of traditional fertilizers (Zulfiqar et al. 2019). Over the last few decades, the global pressure for chemical fertilizers to restore nutrient levels in soils that are regularly used for crop production has expanded considerably (Selim 2020). Contrarily, the most critical elements required by plants, such as nitrogen (N), phosphorus (P), and potassium (K), continue to have low nutrient usage efficiency. Thus, deficits in nutrient delivery to and utilization by plants cause farmers and producers to apply excessive amounts, leading to environmental contamination from emissions, leaching, and run-off (Dimkpa et al. 2019). Owing to this reason, numerous researchers have found that nanofertilizers possess the potential to improve nutrient delivery efficiency to plants. Nanofertilizer is classified into three types based on plants' nutritional requirements: (A) macro- and (B) micronanofertilizer, and (C) nanoparticulate fertilizer (Kumari et al. 2019).

Despite the uncountable advantages of nano-enabled agrochemicals, there are still some gaps and controversies regarding their efficacy and fate in microbiome. The soil is a reservoir of microorganisms, in which the plant selects a certain microbiome, which makes a significant contribution to the plant's growth and health (Trivedi et al. 2020). As a result of the selected microbiome, the plant adapts more quickly to stressors whether abiotic or biotic. Therefore, understanding how nanopesticides and nanofertilizers interact with the microbiome is critical for developing smart nanoagrochemicals that combine efficiency with ecocompatibility to protect soil microbial diversity. There are currently two types of nanomaterials that have resulted in commercially accessible nanoenabled agrochemicals: copper nanoparticles as fungicides and colloidal silver to treat fungal pathogens on seeds, tubers, and vegetative plants (He et al. 2019). The impact of nano-CuO was observed on the soil enzymes activities and composition of microbial community. The applications of TiO_2 and CuO NPs were reported to decrease the soil microbial biomass and enzymatic activities (Xu et al. 2015). In a study, the influence of nanosized CuO on five agricultural was recorded. The exposure of CuO-NPs caused significant reductions in the microbial activities of soil which involved the carbon and nitrogen cycles, respiration, nitrification, and denitrification (Zhao et al. 2020). Likewise, in the study of You et al. (2018), ZnO, TiO_2, CeO_2, and Fe_3O_4 NPs on soil enzymatic activities and bacterial communities of saline-alkali and black soils. The findings revealed an impact on soil enzyme activity, changes in the soil bacterial community, and a risk to biological nitrogen fixation. The content of microorganisms in soil was dramatically reduced when Fe_3O_4 NPs were present in high concentration (Cao et al. 2016). Plate counts of *Azotobacter*, P-solubilizing, and K-solubilizing bacteria were altered by zinc oxide and CeO_2 NPs, and enzymatic activity was inhibited (Chai et al. 2015).

5 Impacts of NPs on Plant-Microbiome Interaction

The plant-microbiome is a complex network of genetic, biochemical, physical, and metabolic interactions. In a natural environment, plants are constantly exposed to diverse microbiota and interact with each other with substantial useful effects to the host plants in nutrients uptake, growth promotion, increased productivity, enhanced biological and chemical reactions, resistance to pathogens, and stress tolerance (Philippot et al. 2013; Busby et al. 2016; Singh et al. 2019; Trivedi et al. 2020). The abundance of microbes in the rhizosphere region is primarily owing to the richness in microbial substrates derived from plant photosynthates and other secondary metabolites like flavonoids, which play a crucial role in maintaining communications among soil microbiomes. Plants may interfere in the manipulation of gene expression of the soil community by secreting quorum sensing compounds (Merten et al. 2020). In analog, it is also claimed that plant microbiome extends the potential function of the host, as the microbiome possesses the ability to impact the expression of plant traits and subsequently improve the physiological state of the plants (Mendes et al. 2013). Therefore, it can be inferred that the plant-microbiome relationship cannot be underestimated, the fact that it represents an interweaving mutualistic association among the components (Rahman et al. 2021). The collective genome of the rhizosphere microbiome is referred to as the plant's second genome. The beneficial impacts of bacterial strains and other consortia of microorganisms on their host are considered cultivar and species (associated to diets, environment, etc.) specific, which in turn limits their applications (Cullen et al. 2020; Rai-Kalal and Jajoo 2021). Hence, understanding the functional aspects of the interplay between microbiomes and their host is crucial for their potent use in agriculture (Ortiz et al.

2015; Singh et al. 2016). The balance of microorganisms in the soil is thus an important aspect of plant physiological development. However, these balances can be impaired by several human activities such as the development of antibiotics, heavy metals exploitation, release of plant protection products (PPP), and high levels of nanoparticles in the soils (Rodriguez et al. 2019).

A large number of NPs-based products are being commercially produced and disposed to the soils as a sink in large quantities. These particles often exposed to the soils can directly result in NPs-microbial or indirectly NPs-plants interactions and revealed the consequences on either the plants or microbial community (Guan et al. 2020). The behavior of these particles and their persistence rests on their chemical nature and soil characteristics. More importantly, NPs-based products like nAg and nZnO possess antimicrobial properties, their presence and persistence in soils can result in the alteration of soil microbiome, thereby distorting key microbial processes like N-fixation, nutrients mineralization, phytoremediation, and plant growth-promoting activities (Thijs et al. 2016; Khan 2020). Several studies on the effects of plant-microbiome interactions and the effects have been reported in the literature as presented in Table 4.1.

6 Future Prospective

It is evident from the current state of knowledge that the use of nanotechnology-derived processes and materials can bring substantial enhancements and improvement in the agriculture and allied sectors. Unfortunately, much R&D has been done in a haphazard and random manner, with little regard for the potential for negative repercussions and impacts. Another issue to be concerned about is the increased nutrition provided by nano-fertilizers, which may encourage intrinsic plant defense and systemic resistance pathways. Thus, if nanotechnology-based approaches are effectively developed and implemented, they will play an important role in achieving and maintaining global food security and safety.

7 Conclusions

Nanotechnology offers enormous potential to improve pesticide delivery and usage by crops. According to key findings on plant exposure to nanoparticles, ENMs can be deleterious at higher doses, while the lower dose applications of NMs under specified conditions will have favorable effects such as improved nutrient delivery, antibacterial and disease suppression, and insecticidal and herbicidal applications. Also, when compared to conventional formulations, one very major advancement connected with NMs is that they can dramatically minimize the number of metals/agrichemicals released into the environment. So, in a nutshell, future research

Table 4.1 Impacts of nanoparticles on plants-microbiome interactions

Nanoparticles (NPs) and concentrations applied	Plants and microbes	Soil microbes	Impacts on plant-microbiome interactions	References
SiO_2 @ 5 mg per plant	Pakchoi (*Brassica chinensis* L.)	Bacteria (*Rhodobacteria* and *Paenibacillus*) and fungus (*Chaetomium*)	Increased number of some bacterial and fungal genera that involved in carbon and nitrogen cycles. Thus, suggesting an alteration in the soil metabolites profiles.	Tian et al. (2020)
CuO @ 50 mg kg^{-1}	Wheat (*Triticum aestivum* L.)	Bacteria (*Caulobacteracaea, Chitinophaga, Paenibaccilus, Peredibacter,* and *Pseudomonas*)	Increased nitrate concentration in the rhizosphere correlated with the gene abundance related to N-fixation and a decrease of gene denitrification abundance. However, the effects on microbial diversity were not clearly explained in the studies.	Guan et al. (2020)

(continued)

Table 4.1 (continued)

Nanoparticles (NPs) and concentrations applied	Plants and microbes	Soil microbes	Impacts on plant-microbiome interactions	References
Ag and TiO_2 @ 100 mg L^{-1}	Early growth of wheat (*Triticum aestivum* L.,) and flax (*Linumusitatissimum*)	Bacteria (*Bacillus* and *Pseudomonas*)	TiO_2 enhanced germination and seedling growth of what, whereas both the NPs increased chlorophyll contents of flax. The bacterial community was not significantly altered; however, the total contents were observed to increase except in positively charged TiO. Hence, suggesting variability of the plants and bacterial communities in response to NPs at varying degree	Gorczyca et al. (2018)
TiO_2 (Conc. Not not specified)	Wheat (*Triticum aestivum* L.)	Fungus (*Arbuscular mycorrhiza*) and prokaryotic	NPs altered the structure of prokaryotic community but the fungal structure remains unaltered. Both the wheat growth and arbuscular mycorrhizal colonization were not negatively affected by different TiO2 concentrations	Moll et al. (2017)

(continued)

Table 4.1 (continued)

Nanoparticles (NPs) and concentrations applied	Plants and microbes	Soil microbes	Impacts on plant-microbiome interactions	References
Fe_3O_4 @ 2000 mg L^{-1}	Common bean (*Phaseolus vulgaris*)	Fungus *(Rhizobium inoculum; Leguminorum CF1 strain*)	Improved symbiotic performance such as nitrogenase activity, nodule leghemoglobin, iron contents, active nodules per plant, nodules dry weight, along with increased root and shoot nitrogen content of the 35-day-old harvested plant. Hence, suggesting a strong relationship between rhizobium and common bean plant due to improved nodulation and N-fixation following application of Fe3O4 NPs	De Souza-Torres et al. (2021)

(continued)

Table 4.1 (continued)

Nanoparticles (NPs) and concentrations applied	Plants and microbes	Soil microbes	Impacts on plant-microbiome interactions	References
ZnO @ 250–1000 mg Zn kg^{-1}	Bean (*Phaseolus vulgaris*)	Bacteria (*Pseudomonad*)	Only NPs at 1000 mg concentrations significantly inhibit shoot growth. Also correlated with root growth inhibition, solubility of Fe, Mn and shoot accumulation of Zn, Fe, and Mn after 7 days. Root ferric reductase activity also often diminished after exposure to NPs. Concluding that soil bacteria could reduce plant accumulation of metals under toxic levels of NPs, thereby negatively affecting uptake of essential elements	Dimkpa et al. (2015)
Hydroxyapatite (nHA) (Conc. not specified)	Soybean (*Glycine max*)	Different general of bacterial and fungal sp. was studied	Treatments with nHA revealed nearly similar results in growth, biomass, total plant phosphorus, and yield. The soil and rhizosphere community also revealed similar results in the nHA and HA, with the minor shifts in the former. Hence, extrapolating that application of nHA may not be considered a viable alternative to traditional Pi fertilizers	McKnight et al. (2020)

(continued)

Table 4.1 (continued)

Nanoparticles (NPs) and concentrations applied	Plants and microbes	Soil microbes	Impacts on plant-microbiome interactions	References
Cu, Ni, and Zn @ 100, 1000, and 10,000 mg kg^{-1}	Radish (*Raphanus sativus*)	Bacteria (*Azotobacter* sp.)	Contamination of the soil with NPs observed to cause deterioration of the biological properties like abundance of bacteria (*Azotobacter* sp.), activity of catalase dehydrogenases, seed germination rate, and the length of radish roots. The Cu ranked first and Zn second, then Zn in order of highest ecotoxicity of the studied pollutants exposed under the same concentration. Their degree of negative impacts on biological activities.	Kolesnikov et al. (2021)

should focus on the possibility of generating different types of nutrient-augmented nanomaterials with a safer and more effective profile.

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