Chapter 5
Effect of Nanoparticles on Plant Growth and Physiology and on Soil Microbes

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5.1 Introduction

The use of nanotechnology for potential benefits in agriculture is enormous and has been increasing day by day (Shapira and Youtie 2015; Resham et al. 2015; Nath 2015). Novel applications of nanotechnology have been developed in biotechnology and agriculture (Siddiqui et al. 2015; Singh et al. 2016, 2019; Shweta et al. 2017, 2018; Arif et al. 2018; Vishwakarma et al. 2018) to manage food productivity (Kumari et al. 2014). Nanoparticles (NPs) are very tiny particles, defined as the 10^{-9} part of 1 m (1 m^{-9}) (Huang et al. 2015). NP efficiency relies on their surface area, size, composition, shape, and above all the effective concentration at which they work efficiently (Khodakovskaya et al. 2012; Ranjan et al. 2014;

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Dasgupta et al. 2016; Jain et al. 2016; Maddineni et al. 2015). Nanotechnology provides a very large variety of techniques and devices to formulate NPs, detect biotic and abiotic stress in plants, and provide genetic manipulation that allows more precise plant breeding (Perez-de-Luque and Hermosin 2013; Fraceto et al. 2016). Fertilizers are very important in the growth, development, and metabolism of plants (Giraldo et al. 2014), but at most concentrations applied fertilizers are not available to plants because of leaching, runoff, and degradation. Thus, it is very important to control or minimize chemical fertilizer loss. With their unique properties, NPs encapsulate nutrients, which, released as required, control the discharge of chemical fertilizers for plant growth (Derosa et al. 2010; Nair et al. 2010; Shweta et al. 2018). Several studies have shown that particular low doses of NPs enhance plant physiology (Zheng et al. 2005; Klaine et al. 2008). NPs can enter plant cells through the stomata of leaves and roots to transport nutrients, DNA, and chemicals (Galbraith 2007; Torney et al. 2007). Nanomaterials can break down the plasma membrane, inducing pore formation to enter into the plant cells (Wong et al. 2016) and reach the cytosol (Serag et al. 2011). These NPs enhance chlorophyll activity, water uptake, and specific microbial communities in the soil (Fig. 5.1).

With unique physicochemical properties, NPs can enhance the biochemical processes of plants (Giraldo et al. 2014). The application of carbon nanotubes (CNTs) to activate the growth and physiology of different plants has been well documented;

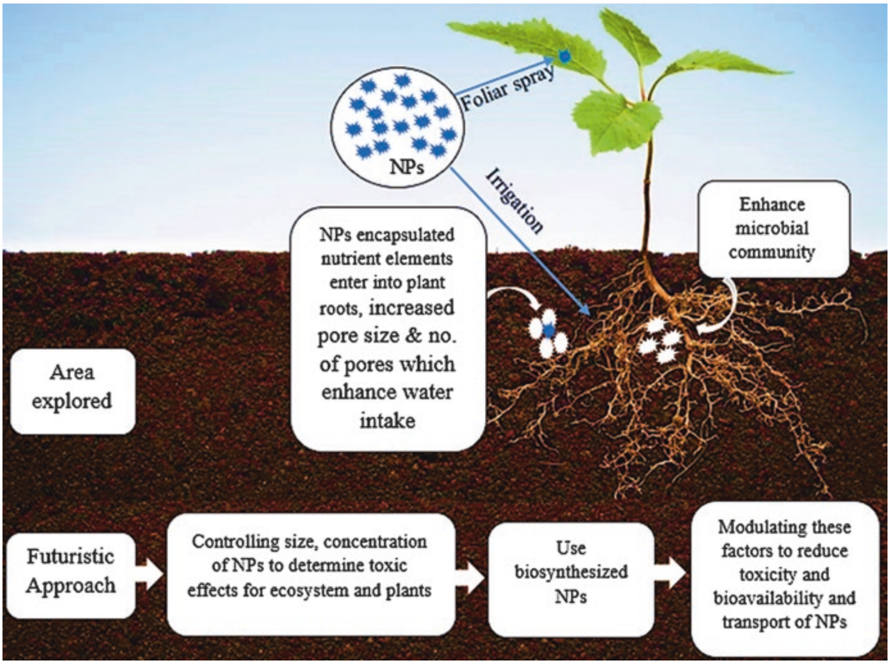

Fig. 5.1 Nanoparticle spray or irrigation and the effects on plant growth and the soil microbial community

for example, the root growth of ryegrass, onion, and cucumber was increased by CNTs (Lin and Xing 2007; Canas et al. 2008; Shweta et al. 2017). NPs have some toxic effects on plants and other living organisms, but also increase the growth, physiology, and photosynthesis of plants. This review discusses the impact of nanoparticles on plants and microbial communities.

5.2 Effect of Nanoparticles on Plants

The impact of nanoparticles on plants depends upon the plant species and the NP variety (Table 5.1) (Nair 2016; Servin and White 2016; Singh et al. 2016; Vishwakarma et al. 2018; Tripathi et al. 2017; Rastogi et al. 2019). Minerals such as nitrogen and phosphorus act as growth factors, regulating plant growth and also increasing crop productivity. Phosphorus fertilizer increases the availability of phosphorus in the soil and increases the uptake of phosphorus from the root surfaces. In phosphorus-solubilizing enzymes in which Zn is a cofactor, phosphatase and phytase enzyme activity was increased by 84–108%. ZnO NPs also enhanced root length, root volume, and the chlorophyll and protein content of the leaves in mung bean plants. ZnO NPs also maintained soil health by influencing the soil microbial community (Raliya et al. 2016).

Germination of cucumber seed was enhanced by exposure to various concentrations of ZnO NPs (de la Rosa et al. 2013). ZnO NPs not only were absorbed by *Vigna radiata* and *Cicer arietinum* roots but also improved the length and biomass of the roots and shoots of these species (Mahajan et al. 2011). This NP also enhanced somatic embryogenesis by shoot regeneration, induced the synthesis of proline, and increased tolerance against stress by increasing the activity of different enzymes (Helaly et al. 2014). Gold (Au) NPs enhanced the seed germination of *Brassica juncea*, *Boswellia ovalifoliolata*, and *Gloriosa superba (*Arora et al. 2012; Gopinath et al. 2014). The Au NPs increased the number of leaves, leaf area, and length of the plant and its chlorophyll and carbohydrate content, which increased growth, development, and crop yield (Arora et al. 2012; Gopinath et al. 2014). The Au NPs demonstrated importance in seed germination, in antioxidants, and altered the expression of micro-RNAs that regulate morphological, physiological, and metabolic processes in plants (Kumar et al. 2013).

The effects of CeO_2 were collectively found on seed germination, vegetative parts, the cotyledon, floral parts, and ripening of fruits. The rate of seed germination (97%) was high in a 10 mg/l concentration of CeO_2. No negative effect on germination and no significant effect on production of chlorophyll was seen with any concentration of CeO_2 NPs on tomato plants, although there was a significant difference in the growth of the vegetative parts of the tomato plant; faster growth was found at 10 mg/l CeO_2 NPs. The number of floral buds was slightly higher in the control and the 10 mg/l concentration of CeO_2 NPs, and 67% of buds were converted into the flower. Fruit size, production, and ripening were enhanced by increasing concentrations of CeO_2 NPs; large, heavy fruits were found at 10 mg/l (Wang et al. 2012a).

Table 5.1 Effect of nanoparticles on plant growth/physiology/tolerance against stress

Nanoparticles	Plant	Impact on plant parts/process	References
Al_2O_3	*Lemna minor*	Increased root length, photosynthetic activity, biomass accumulation	Juhel et al. (2011)
TiO_2	*Triticum aestivum*	Increased root length	Larue et al. (2012)
CeO_2, ZnO	*Zea mays*	Reduced yield	Zhao et al. (2012)
CuO	*Brassica napus*	Increased plant growth	Rahmani et al. (2016)
$FeCl_3$	*Lepidium sativum* *Sinapis alba* *Sorghum saccharatum*	Seed germination, seedling length, biomass	Libralato et al. (2016)
Ag NO_3	Lentil seed	Seed germination/elongation of root and shoot	Hojjat and Hojjat (2016)
Fe_2O_3	Soybean	Increased root length, regulated the enzyme	Alidoust and Isoda (2013)
Cu, Zn	Wheat seedling	Increased RWC and stabilized photosynthetic pigments	Taran et al. (2017)
$Ca_3(PO_4)_2$	Rice	Increased growth, micro-fertilizer and promoter of growth	Upadhyaya et al. (2017)
Fe_3O_4, TiO_2	Soya bean	Enhanced plant growth, crop yield, effect on leaf carbon and phosphorus	Burke David et al. (2015)
CeO_2	Soya bean	Stimulated plant growth, rubisco carboxylase activity, relative water content	Cao et al. (2017)
ZnO	Chickpea	Effect on root, accumulation of biomass in seedlings, lowered ROS, promoted antioxidant activity	Burmana et al. (2013)
Ag	Wheat	Increased shoot fresh and dry weight, enhanced salt tolerance ability of crop	Mohamed et al. (2017)
SiO_2	*Zea mays* L., *Phaseolus vulgaris* L., *Hyssopus officinalis* L., *Nigella sativa* L., *Amaranthus retroflexus* L., *Taraxacum officinale* F. H. Wigg	Seed germination, root and shoot length, fresh weight (except *Hyssopus officinalis* L.) and dry weight, photosynthetic pigments, total protein and total amino acids (except *Hyssopus officinalis* L.) significantly increased at 400 mg l^{-1}; these parameters were decreased in weeds, and total carbohydrates decreased in all plants except *A. retroflexus*	Sharifi-Rad et al. (2016)

(continued)

Table 5.1 (continued)

Nanoparticles	Plant	Impact on plant parts/process	References
Ag	Wheat (*Triticum astivium* var. UP2338), cowpea (*Vigna sinensis* var. Pusa Komal), brassica (*Brassica juncea* var. Pusa jai Kisan), oat	Wheat was unaffected by Ag NPs, but overall growth of cowpea and *Brassica* plants was influenced	Pallavi et al. (2016)
TiO_2	*Arabidopsis thaliana* (L.) Heynh, corn, cabbage, lettuce, oat, *Brassica napus* L. Cucumber, fennel, onion, tomato Parsley (*Petroselinum crispum* Mill.), red clover, soybean, spinach, wheat	Enhanced germination, root elongation and seedling growth	Szymanska et al. (2016), Andersen et al. (2016), Mahmoodzadeh et al. (2013), Servin et al. (2012), Feizi et al. (2013, 2012), Haghighi and Teixeira da Silva (2014), Dehkourdi and Mosavi (2013), Gogos et al. (2016), Rezaei et al. (2015), Zheng et al. (2005), Mahmoodzadeh and Aghili (2014).
TiO_2	Chickpea (*Cicer arietinum* L.), tomato, wheat, Flax (*Linum usitatissium* L.)	Enhanced tolerance against cold in chickpea, heat in tomato, drought in wheat and flax	Mohammadi et al. (2013, 2014), Qi et al. (2013), Jaberzadeh et al. (2013), Aghdam et al. (2016)
TiO_2	Tomato, oilseed rape, *Arabidopsis*, spinach, basil (*Ocimum basilicum* L.)	Increased chlorophyll contents of tomato and oil seed rape, promoted activity of rubisco and net photosynthesis in *Arabidopsis*, spinach, tomato, and basil (*Ocimum basilicum* L.)	Raliya et al. (2015a), Li et al. (2015), Ze et al. (2011), Lei et al. (2008), Kiapour et al. (2015)
TiO_2	Barley, corn, mung bean, snail clover, tomato, wheat	Enhanced crop yield and biomass	Moaveni and Kheiri (2011), Morteza et al. (2013), Raliya et al. (2015b), Rafique et al. (2015)

Clement et al. (2013) determined the effect of TiO_2 NPs on algae, rotifers, and plants. High concentrations of TiO_2 NPs have antimicrobial activity and also promoted the growth of roots. The collective effect of SiO_2 NPs on germination of seeds, elongation of roots and shoots, and water content of *Zea mays* L. was determined. SiO_2 NP uptake by plants from a hydroponic environment and increased growth of seed and elongation of roots was high as compared to control. Seed germination was increased at 400 mg/l but decreased at 2000 and 4000 mg/l concentrations of SiO_2 NPs. SiO_2 NPs increased root length but decreased shoot length of plants at concentrations from 0 to 4000 mg/l. SiO_2 NPs showed a negative correlation between NP concentration and relative water content (RWC) in plants. The RWC was decreased as the concentration of SiO_2 increased from 0 to 4000 mg/l. It was observed that SiO_2 NPs had a significant effect on photosynthetic pigments (chlorophyll *a*, *b*, and carotenoids), which increased at 400–4000 mg/l NP concentration in *Z. mays*. High photosynthetic content was found at 400 mg/l SiO_2 NPs (Rad et al. 2014).

5.2.1 Effects of NPs on Photosynthesis

Photosynthesis is the key mechanism that transforms light energy into chemical energy. Rubisco is an enzyme used in carbon fixation during light reactions. SiO_2 NP increased the photosynthesis rate by increasing the activity of carbonic anhydrase and the formation of photosynthetic pigments (Xie et al. 2012; Siddiqui and Al-Whaibi 2014). Carbon anhydrase acts as a supplier for CO_2 to the rubisco enzyme, which enhances photosynthesis (Siddiqui et al. 2012). TiO_2 has photocatalytic properties that not only increase the efficiency of light absorbance but also increase the conversion of light energy into chemical energy. TiO_2 also improved fixation of CO_2, prevented the plant from aging, and ultimately enhanced the photosynthesis process (Hong et al. 2005; Yang et al. 2006).

TiO_2 NPs increased CO_2 fixation by increasing the activity of rubisco and ultimately improving plant growth. TiO_2 NPs enhanced the net rate of photosynthesis, water conduction, and plant transpiration (Ma et al. 2008; Qi et al. 2013). ZnO NPs showed a positive effect on the growth of cotton (*Gossypium hirsutum* L.). The growth (130.6%) and biomass (131%) of cotton were significantly enhanced by ZnO NPs.

ZnO NPs increased the level of chlorophyll *a*, *b*, and carotenoids (141.6%, 134.7%, 138.6%, respectively) and increased soluble protein (179.4%) but reduced malondialdehyde (MDA) level in plant leaves. Various enzymatic activities of catalase, superoxide dismutase (264.2%), and peroxidase (182.8%) were also increased and improved the growth of cotton plants (Venkatachalam et al. 2016).

5.3 Effect of Nanoparticles on the Soil Microbial Community

Soil microbes have a significant role in soil health, plant growth, productivity, and biological and chemical reactions within soil and plants (Table 5.2) (Falkowski et al. 2008; Schimel and Schaeffer 2012; Philippot et al. 2013; Vacheron et al. 2013; Singh et al. 2019). NPs enter into the soil through several ways including human

Table 5.2 Effect of nanoparticles on the soil microbial community

Nanoparticles	Impact on soil microbial community/processes	References
Fe_3O_4, TiO_2	Changed the soil microbial community, influenced the colonies of nitrifying bacteria associated with roots	Burke David et al. (2015)
CuO	Influenced the composition and activity of the bacterial community, decreased the oxidative potential of the soil	Schlich and Hund-Rinke (2015)
ZnO	Ammonification, dehydrogenase, and hydrolase activity	Shen et al. (2015)
TiO_2	Influenced carbon mineralization, pH of soil, organic matter; identified soil type and moisture	Simonin et al. (2015)
CeO_2, Fe_3O_4, SnO	No effect on microbial biomass C and N	VittoriAntisari et al. (2013)
Ag	Different impact on ion release shape and function of the natural soil microbes	Zhai et al. (2016)
TiO_2, ZnO	Altered soil microbes, enhanced the degradation of organic pollutants	Ge et al. (2012)
Ag	Influenced soil microbial diversity and functional bacterial diversity	Pallavi et al. (2016)
Ag	Increased biomass of *Aspergillus niger and Penicillium chrysogenum* Enhanced soil extract and inhibited antifungal activity of Ag	Pietrzak and Gutarowska (2015)
Ag	Affected functional diversity of soil microbial community and associated ecosystem processes	Zhai et al. (2016)
CuO, Fe_3O_4	Increased toxicity toward microbial community	Frenk et al. (2013)
SiO_2, Pd, Au, Cu	Increased number of microbial colonies in soil, enhanced metabolic rate of soil community	Shah and Belozerova 2009

activity, sewage, and industrial waste. NPs of silica, palladium, gold, and copper have beneficial effects on soil microbes and seed germination of lettuce (Shah and Belozerova 2009). Biological and physicochemical properties determined their health and increased soil productivity. Biosolids have been used as organic fertilizers for decades; silver and titanium NPs were detected above the threshold level and adversely affected soil microbiota (Kim et al. 2010; Rottman et al. 2012; Wang et al. 2012a, b). Zinc oxide and copper NPs did not show harmful effects on soil microbes although silver and titanium NPs showed an adverse effect on the microbial biomass richness (Cardoso et al. 2013; Shah et al. 2014).

Asadishad et al. (2017) investigated the efficacy of gold nanoparticles coated with citrate (50 nm) and polyvinylpyrrolidone (PVP) (5, 50, and 100 nm) on soil enzymatic activity and soil microbes. They noted that a low concentration of Au NPs (0.1 mg/kg) reduced the size of PVP. Au NPs stimulate soil enzymatic activity; the Au NP size and soil enzymatic activity showed no correlation at a high dose (100 mg/kg). Citrate-coated Au NPs significantly increased soil enzymatic activity as compared to PVP-coated Au NPs at 50 nm size of both particles. Biomass of the important soil bacteria Actinobacteria and Proteobacteria was increased by the addition of citrate-coated Au NPs.

5.4 Impact of Carbon Nanotubes on Plants

Carbon nanotubes are allotropic forms of carbon nanoparticles, open or closed nano-structure cylindrical tubes that are single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotube (MWCNTs). These layers are composed of rolled sheets of graphene. These nanotubes vary from 100 nm to some centimeters in length; the outer diameter of SWCNTs varies from 0.8 to 2 nm and that of MWCNTs from 5 to 20 nm (De Volder et al. 2013). CNTs were shown to act as growth regulators for plants (Khot et al. 2012). It was also noted that different sizes and composition of CNTs affect different plant growth parameters (Table 5.3). The stress-related gene of the tomato seed was regulated by MWCNTs that enhance seed germination and growth (Khodakovskaya et al. 2009).

CNTs are involved in major cellular processes of plants such as up- or downregulation of gene expression. MWCNTs induced the expression of a gene that codes for water channels and increased the water intake ability of root cells. CNTs are very small in diameter, so they can easily pass through the pores of the cell wall and also can increase the cell-wall pores. CNTs induced pores in the cell wall that enhanced water uptake, which regulates the activity of starch hydrolase enzymes and increases seed germination (Santos et al. 2013; Vithanage et al. 2017). These CNTs also act as a slow-release fertilizer that promotes plant growth (Wu 2013).

MWCNTs are also frequently used in hydroponic culture; CNTs (2000 mg/l) increase the root length of ryegrass (Lin and Xing 2007). Canas et al. (2008) showed that CNTs enhanced the physiology of six crops: cucumber, carrot, onion, tomato, cabbage, and lettuce. Plants were treated with uncoated (0, 104, 315, or 1750 mg/l) or coated (0, 160, 900, or 5000 mg/l) CNTs for 48 h. The uncoated CNTs significantly boosted root length of onion and cucumber more than the coated CNTs, with an inverse proportion between time and root elongation in these hydroponic crops. More effective results were seen on the first day as compared to the second day. It was hypothesized that CNTs may have an obligatory effect on the root length of plants by obstructing the relationship between roots and microbes, altering vital biological and chemical reactions. CNTs not only were absorbed by the plant but accumulated in the epidermal tissue of wheat roots (Wild and Jones 2009). Citrate-coated CNTs enhanced the growth and physiology of plants by increasing water uptake capability and also the uptake of nutrients and minerals, which directly affected the photosynthesis of the plants. CNTs increased plant length and also increased the number of leaves, which enhanced plant photosynthetic activity (Tripathi et al. 2011).

MWCNTs regulated the gene expression of the aquaporin gene (*NtPIPI*), and of two water channel genes (*CycB* and *NtLRX*), which increased cell permeability for water absorption and also helped in formation of the cell wall and regulation of mitosis (Khodakovskaya et al. 2012). MWCNTs also had a significant effect on root

Table 5.3 Effect of carbon nanoparticles and nanotubes on plant growth processes

Plant name	CNPs/CNT	Impact on plant parts, growth/process	References
Lycopersicon esculentum	CNTs	Seed germination and growth	Anjum et al. (2014)
Medicago sativa, Triticum aestivum	CNTs	Root elongation	Miralles et al. (2012)
Allium cepa, Cucumis sativus	SWCNTs	Root elongation	Canas et al. 2008
Hordeum vulgare L., *Glycine max, Zea mays*	MWCNTs	Growth (leaf, root and shoot)/germination	Lahiani et al. (2013)
Wheat	MWCNTs	Root growth and yield	Wang et al. (2012a)
Lycopersicon esculentum	MWCNTs	Increased uptake of water and nutrients	Tiwari et al. (2013)
Zea mays	MWCNTs	Increased nutrient transport and yield	Tiwari et al. (2014)
Mustard plant *(Brassica juncea)*	MWCNTs	Increased seed germination, root elongation	Mondal et al. (2011)
Tomato	MWCNTs	Increased plant growth (flower and fruit) and yield	Khodakovskaya et al. (2013), Alimohammadi et al. (2011)
Wheat, maize, peanut, garlic	CNTs	Increase in root and shoot length	Rao and Srivastava (2014)
Red spinach, lettuce, rice, cucumber, chili, lady finger (okra), soybean	CNTs	Increased growth, root and shoot length	Begum et al. (2014)
Corn	CNTs	Increased growth, root and shoot length, biomass	De La Torre-Roche et al. (2013)
Hyoscyamus niger	SWCNTs	Enhanced plant performance, antioxidant activity, and biosynthesis of protein	Hatami et al. 2017
Zucchini	SWCNTs, MWCNTs	No significant change in seed germination	Stampoulis et al. (2009)
Solanum lycopersicum	CNPs	Seed coat permeability	Ratnikova et al. 2015
Buckypaper	CNTs (SWCNTs, MWCNTs)	Increased permeability (pore size)	Shen et al. (2017)
Broccoli	CNTs	Positive effect on growth, enhanced CO_2 assimilation	Martinez-Ballesta et al. (2016)
Arabidopsis thaliana	MWCNTs	Effect on efficiency of photosynthesis and physiological mechanism	Voleti (2015)

length of wheat seedlings, and on germination and growth of soya bean, corn, and barley (Wang et al. 2012a, b; Lahiani et al. 2013). The root length of wheat seedlings increased 32% with MWCNTs at 40–160 μg/l for 3 to 7 days (Wang et al. 2012a, b). CNTs impacted early plant growth by germination of seed, expression of genes, cell culturing, and physiological processes such as photosynthesis and antioxidant activities (Canas et al. 2008).

SWCNTs enhanced photosynthetic activity threefold as compared to normal photosynthesis, and increased the rate of electron transport because SWCNTs combine with the chloroplast and enable the leaf to enhance the rate of electron transport by a photo-absorption mechanism (Giraldo et al. 2014). The germination ability of seed might be enhanced by increasing concentrations of MWCNTs. The highest seed germination rate was noted at 60 μg/ml CNTs; increasing CNT concentrations increased plant growth and also enhanced the yield of cotton per plant. The highest yield of cotton was found at 100 μg/ml CNTs (Sawant 2016): there was a linear correlation between seed germination and CNT concentration. It was observed that the length of plants (62 ± 5.58cm), boll' number/ plant (5.8 ± 0.64) and size of boll (3.41 ± 0.27cm) and yield of cotton (3.4 ± 0.37/hectare) was found highest at 120 μg/ml, 80 μg/ml, 60 μg/ml, 100 μg/ml of CNTs respectively (Sawant 2016).

Various studies have shown that SWCNTs and MWCNTs positively affect germination and growth of tomato, rice, common gram, and tobacco by increasing their water uptake ability, which improves germination processes (Khodakovskaya et al. 2009; Nair 2016). The toxic levels of Ag, ZnO, and Al_2O_3 induced oxidative stress and produced reactive oxygen and nitrogen species, which reduced plant growth (Zhao et al. 2012; Thwala et al. 2013; Hossain et al. 2015; Xia et al. 2015). Oxidative species reduced rubisco activity and decreased the photo-protective activity of photosystem II (Jiang et al. 2017). The defensive system of plant consists of nonenzymatic antioxidants, which include thiols, glutathione, phenolics, ascorbate and enzymatic CAT, SOD, APX, GR, GPX, and GST (Singh et al. 2015). Oxidative stresses were caused by NPs that decreased photosynthetic rate, ultimately inhibiting plant growth (Da Costa and Sharma 2016; Li et al. 2016).

Chegini et al. (2017) observed that physiological parameters were affected by MWCNTs, drought conditions, and their interactions in *Salvia mirzayanii.* The leaf water content and chlorophyll index showed significant alterations under drought conditions. The various levels of MWCNTs affected electrolyte leakage index and caused a significant difference in phenolic compounds under the interactions of the experimental treatments. Phenolic content was significantly influenced at MWCNT 50 and 200 mg/l, to 25% of field capacity (FC), respectively. The concentration of MWCNTs (50 mg/l) in moderate drought condition changed the physiological traits and antioxidant activity of *S. mirzayanii*.

Barbinta-Patrascu et al. (2017) reported an effect of carbon nanotubes coated with chlorophyll *a* and laden biomimetic membrane. The multilamellar lipid vesicles increased antioxidant (85%) activity and antibacterial activity against *Staphylococcus aureus*, and the highest antioxidant ability was found in hybrid CNTs that originated through the multilamellar lipid vesicles (TP3). They were widely dispersed and increased the reaction sites for removal of ROS by increasing their surface area. The TP3 sample showed the highest antibacterial activity resulting from good dispersion because a large surface area was provided to destroy bacterial contamination. The SWCNTs react directly with bacterial cells and physically break down their cell membrane by puncture, causing the death of the bacterial cells (*S. aureus*) (Bai et al. 2011; Smith and Rodrigues 2015).

5.4.1 Effect of CNTs on Photosynthesis Mechanism

Sunlight is the most available source of energy, which is conserved in many ways in an ecosystem. One of the most efficient methods for the conservation of sunlight is photosynthesis. For this purpose, the higher green plants, algae, and bacteria contain special pigments that use water and CO_2 to form organic molecules. These photosynthetic organisms contain the photo-elements chlorophyll *a*, *b*, *d*, and *f*, and a series of electron carrier redox reactions (Blankenship et al. 2011). The thylakoid membrane of plastids acts as a photo-current producer in the presence of potassium ferrocyanide. The cell surface (1 cm^2) produced maximum electric power, 24 mW, at 625 nm of red light. The thylakoid membrane immobilized with MWCNTs acts as an anode with MWCNTs as a cathode, which produced the maximum current density, 38 mA/cm^2. The maximum electric power produced at this current density is 5.3 mW/cm^2 (Calkins et al. 2013). The effect of CNTs on chlorophyll *f* and *d* was more than that on chlorophyll *a* and *b*: it enhanced the absorption ability of far-red and infrared light (700–750 nm) and also enhanced the ability of photo-convertors (Voloshin et al. 2015). The CNTs were synthetic NPs that penetrate into the biological matrix and have multifunctional properties such as water uptake and conduction for electricity in biological systems. MWCNTs were most electro-conductive in BY-2 tobacco cells as compared to balsam fir wood at high temperature (Di Giacomo et al. 2013; Leslie et al. 2014).

It was investigated whether CNTs had a positive effect on photosystem I of cyanobacteria by enhancing the ability of conversion of light into current. The MWCNTs were non-encroaching because a carboxylate pyrene derivative formed the fixed covalent structure of photosystem I (PS I). The PS I was ascribed as the transporter of photo-current to the electrode (MWCNTs) (Ciornii et al. 2017). MWCNTs have a combined effect on thylakoid, the multi-protein complexes PS I and II, and photo-electrochemical properties. SWCNTs enhanced immobilization of the reaction center of the bacterium *Rhodobacter (Rb.) sphaeroides* (sp.) and also enhanced the photo-electrochemical activity (Ham et al. 2010; Calkins et al. 2013). MWCNTs significantly enhanced direct transfer of electron in the thylakoid of spinach and of the cyanobacterium *Nostoc* sp. (Sekar et al. 2014). CNTs enhanced the expression of *Arabidopsis* aquaporin in tobacco plant and enhanced photosynthetic activity by production of the photo-electric current. It was observed that CNTs activate gene and protein expression of aquaporin in tobacco cells (Khodakovskaya et al. 2012).

5.5 Effect of CNTs on Soil Microbial Community

The soil contains different microorganisms that form the biota of the soil as the main source of nutrients which are significant in plant growth (Table 5.4). Microorganisms have a key role in recycling of nutrients by decomposition of organic matter (Simonet and Valcarcel 2009; Dinesh et al. 2012). Some microorganisms associate with plant roots; the soil microbial community normally consists of gram-positive bacteria, gram-negative bacteria, and fungi (Luongo and Zhang 2010; Santos et al. 2013). The major challenge in the agriculture sector is the conservation of biodiversity and protection of the biomass of these soil microbes. CNTs can change a microbial community by increasing or decreasing the toxins present in organic compounds (Dinesh et al. 2012). Limited literature is available on the impact of CNTs on soil microbial communities. It has been also reported that CNTs had no significant effect on soil microbes. So, there is a need to thoroughly explore CNT impacts on soil microbes.

Mukherjee et al. (2016) reported that low and high concentrations of CNTs have no adverse effect on soil microbiota. High (10–10,000 mg/kg) and low (10–1,000 mg/ml) concentrations of CNTs were used to investigate effects on soil microbial community and enzymatic activity, but it was found that CNTs had no visible effect on soil microbes and enzymatic activity, although these high and low CNT concentrations reduced selected species of bacteria. These specific concentrations increased the amount of polycyclic aromatic hydrocarbon (PAH)-degrading bacteria. Similarly, when red clover was treated with MWCNTs, the activity of symbiotic microorganisms as nitrogen fixers was slightly increased at 3000 mg/kg MWCNTs (Moll et al. 2016).

Table 5.4 Effect of carbon nanoparticles (CNP) and carbon nanotubes (CT) on the soil microbial community

CNPs/ CNT	Impact on soil microbial community/processes	References
MWCNTs	Enhanced activity of anaerobic ammonium oxidation bacteria, high carbohydrate and protein	Wang et al. (2013)
SWCNTs	Strong antimicrobial activity	Kang et al. (2007)
SWCNTs	Effect on both gram-positive and gram-negative bacteria	Jin et al. (2014)
MWCNTs	Effect on soil enzyme activity, soil microbial biomass	Chung et al. (2015)
MWCNTs	Conditionally affect soil microbial community	Kerfahi et al. (2015)
CNTs	Effects on composition of soil microbes	Khodakovskaya et al. (2013)
CNTs	Affect growth of gram-negative bacteria	Cordeiro et al. (2014)
SWCNTs	Effects on antimicrobial activity of surface bacteria	Jackson et al. (2013)
CNTs	Toxic effect on microbes	Petersen et al. (2014)

5.6 Future Possibilities

Nanoparticles have great potential to promote plant growth and development by increasing nutrient uptake, improving water uptake efficiency, and enhancing photosynthetic activity. However, there is a need to improve NP use in agriculture by developing target-specific NPs to enhance plant growth, physiological parameters, and the soil microbial community. There is an urgent need to utilize NPs having great potential to enhance photosynthesis mechanism because minimal attention is being given to this area of research. Biosynthesized NPs should be used: by controlling their size and concentration we can determine the mechanism of toxicity in plants. Modulating these factors, we can reduce transportation, toxicity, and bioavailability to the ecosystem. There is further need to explore the function of NPs beneath plant roots.

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