

Chapter 2

Role of Nanoparticles in Plants

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Abstract Nanotechnology opens a large scope of novel application in the fields of biotechnology and agricultural industries, because nanoparticles (NPs) have unique physicochemical properties, i.e., high surface area, high reactivity, tunable pore size, and particle morphology. Nanoparticles can serve as “magic bullets”, containing herbicides, nano-pesticide fertilizers, or genes, which target specific cellular organelles in plant to release their content. Despite the plenty of information available on the toxicity of nanoparticles to plant system, few studies have been conducted on mechanisms, by which nanoparticles exert their effect on plant growth and development. Therefore, the present review highlights the key role of nanoparticles in plants. Moreover, nanoscience contributes new ideas leading us to understand the suitable mode of action of nanoparticles in plants. The appropriate elucidation of physiological, biochemical, and molecular mechanism of nanoparticles in plant leads to better plant growth and development.

Keywords Plant nutrition • Plant growth and development • Nanoparticles • Photosynthesis

2.1 Introduction

Nanotechnology, a new emerging and fascinating field of science, permits advanced research in many areas, and nanotechnological discoveries could open up novel applications in the field of biotechnology and agriculture. In the field of electronics, energy, medicine, and life sciences, nanotechnology offers an expanding research, such as reproductive science and technology, conversion of agricultural and food

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wastes to energy and other useful byproducts through enzymatic nanobioprocessing, chemical sensors, cleaning of water, disease prevention, and treatment in plants using various nanocides (Carmen et al. 2003; Nair et al. 2010). Although fertilizers are very important for plant growth and development, most of the applied fertilizers are rendered unavailable to plants due to many factors, such as leaching, degradation by photolysis, hydrolysis, and decomposition. Hence, it is necessary to minimize nutrient losses in fertilization, and to increase the crop yield through the exploitation of new applications with the help of nanotechnology and nanomaterials. Nanofertilizers or nano-encapsulated nutrients might have properties that are effective to crops, released the nutrients on-demand, controlled release of chemicals fertilizers that regulate plant growth and enhanced target activity (DeRosa et al. 2010; Nair et al. 2010). Higher plants, as sessile organisms, have a remarkable ability to develop mechanism to perform better under suitable and unsuitable conditions. Nowadays scientists/researchers want to develop new techniques that could be suitable for plants to boost their native functions. Nanoparticles have unique physicochemical properties and the potential to boost the plant metabolism (Giraldo et al. 2014). According to Galbraith (2007) and Torney et al. (2007) engineered nanoparticles are able to inter into plants cells and leaves, and also can transport DNA and chemicals into plant cells. This area of research offers new possibilities in plant biotechnology to target specific genes manipulation and expression in the specific cells of the plants. The researchers have augmented plants' ability to harvest more light energy by delivering carbon nanotubes into chloroplast, and also carbon nanotubes could serve as artificial antennae that allow chloroplast to capture wavelengths of light which is not in their normal range, such as ultraviolet, green, and near-infrared (Cossins 2014; Giraldo et al. 2014). The engineered carbon nanotubes also boost seed germination, growth, and development of plants (Lahiani et al. 2013; Siddiqui and Al-Whaibi 2014). However, the majority of studies on NPs to date concern toxicity. Comparatively few studies have been conducted on NPs are beneficiary to plants. Research in the field of nanotechnology is required to discover the novel applications to target specific delivery of chemicals, proteins, nucleotides for genetic transformation of crops (Torney et al. 2007; Scrinis and Lyons 2007). Nanotechnology has large potential to provide an opportunity for the researchers of plant science and other fields, to develop new tools for incorporation of nanoparticles into plants that could augment existing functions and add new ones (Cossins 2014). In the present review, we discuss the recent developments in plant science that focuses on the role of nanoparticles (NPs) in plant growth and development and also on plant mechanism.

2.2 Effects of Nanoparticles on Plant Growth and Development

Nanoparticles interact with plants causing many morphological and physiological changes, depending on the properties of NPs. Efficacy of NPs is determined by their chemical composition, size, surface covering, reactivity, and most importantly the dose

at which they are effective (Khodakovskaya et al. 2012). Researchers from their findings suggested both positive and negative effects on plant growth and development, and the impact of engineered nanoparticles (ENPs) on plants depends on the composition, concentration, size, and physical and chemical properties of ENPs as well as plant species (Ma et al. 2010). Efficacy of NPs depends on their concentration and varies from plants to plants (Table 2.1). However, this review covers plausible role NPs in seed germination, roots, plant growth (shoot and root biomass) and photosynthesis.

2.2.1 Silicon Dioxide Nanoparticles

Plant growth and development starts from the germination of seeds followed by root elongation and shoot emergence as the earliest signs of growth and development. Therefore, it is important to understand the course of plant growth and development in relation to NPs. The reported data from various studies suggested that effect of NPs on seed germination was concentrations dependent.

The lower concentrations of nano-SiO₂ improved seed germination of tomato (Fig. 2.1; Siddiqui and Al-Whaibi 2014). According to Suriyaprabha et al. (2012) nano-SiO₂ increased seed germination by providing better nutrients availability to maize seeds, and pH and conductivity to the growing medium. Bao-shan et al. (2004) applied exogenous application of nano-SiO₂ on Changbai larch (*Larix olgensis*) seedlings and found that nano-SiO₂ improved seedling growth and quality, including mean height, root collar diameter, main root length, and the number of lateral roots of seedlings and also induced the synthesis of chlorophyll. Under abiotic stress, nano-SiO₂ augments seed germination. Haghighi et al. (2012), in tomato and Siddiqui et al. (2014) in squash reported that nano-SiO₂ enhanced seed germination and stimulated the antioxidant system under NaCl stress. Shah and Belozerovala (2009) tested silica, palladium, gold and copper NPs in their study and found that all these NPs have a significant influence on lettuce seeds. Exogenous application of nano-SiO₂ and nano-titanium dioxide (nano-TiO₂) improves seed germination of soybean by increasing nitrate reductase (Lu et al. 2002) and also by enhancing seeds ability to absorb and utilize water and nutrients (Zheng et al. 2005). Under salinity stress, nano-SiO₂ improves leaf fresh and dry weight, chlorophyll content and proline accumulation. An increase in the accumulation of proline, free amino acids, content of nutrients, antioxidant enzymes activity due to the nano-SiO₂, thereby improving the tolerance of plants to abiotic stress (Kalthah et al. 2014; Haghighi et al. 2012; Li et al. 2012; Siddiqui et al. 2014). Wang et al. (2014) performed an experiment on rice plant treated with quantum dots (QDs), without QDs and with silica coated with QDs, and found silica coated with QDs promoted markedly rice root growth. Nano-SiO₂ enhances the plant growth and development by increasing gas exchange and chlorophyll fluorescence parameters, such as net photosynthetic rate, transpiration rate, stomatal conductance, PSII potential activity, effective photochemical efficiency, actual photochemical efficiency, electron transport rate and photochemical quench (Siddiqui et al. 2014; Xie et al. 2011).

Table 2.1 Beneficiary concentration(s) of nanoparticles for plants

Nanoparticle(s)	Beneficiary concentration(s)	Plant	Part of plant/process	Reference(s)
Graphene oxide	400 and 800 mg/L	<i>Vicia faba</i> L.	Germination	Anjum et al. (2014)
CNTs	40 µg/mL	<i>Lycopersicon esculantum</i>	Germination and seedling growth	Morla et al. (2011)
	75 wt% CNTs	<i>Medicago sativa</i> , <i>Triticum aestivum</i>	Root elongation	Miralles et al. (2012)
	75 wt% CNTs Impurities	<i>Medicago sativa</i> , <i>Triticum aestivum</i>	Root elongation	Miralles et al. (2012)
SWCNTs	9, 56, 315, and 1,750 mg/L	<i>Allium cepa</i> , <i>Cucumis sativus</i>	Root elongation	Cañas et al. (2008)
MWCNTs	25–100 µg/mL	<i>Hordeum vulgare</i> L., <i>Glycine max</i> , <i>Zea mays</i>	Germination	Lahiani et al. (2013)
	50 and 200 µg/mL	<i>Lycopersicon esculentum</i> Mill	Plant height and number of flowers	Khodakovskaya et al. (2013)
o-MWCNTs	5 up to 500 µg/mL	<i>Nicotiana tabacum</i>	Growth	Khodakovskaya et al. (2012)
	10–160 µg/mL	<i>Triticum aestivum</i>	Root growth, vegetative biomass	Wang et al. (2012a)
wsCNTs	6.0 µg/mL	<i>Cicer arietinum</i>	Growth rate	Tripathi et al. (2011)
MWCNTs, dMW/CNT	40 µg/mL	<i>Lycopersicon esculentum</i> Mill	Uptake nutrients (K, Ca, Fe, Mn and Zn)	Tiwari et al. (2013)
Pristine MW/CNTs	20 mg/L	<i>Zea Mays</i>	Nutrient transport, biomass	Tiwari et al. (2014)
ZnO NPs	400 mg/kg	<i>Cucumis sativus</i> fruit	Micronutrients (Cu, Mn and Zn)	Zhao et al. (2014)
	1.5 ppm (foliar spray)	<i>Cicer arietinum</i> L	Shoot dry weight	Burman et al. (2013)
	20 ppm (suspension, foliar spray)	<i>Vigna radiata</i>	Biomass	Dhoke et al. (2013)
	1,000 ppm	<i>Arachis hypogaea</i>	Germination	Prasad et al. (2012)
	1,000 ppm	<i>Arachis hypogaea</i>	Stem, root growth and Yield	Prasad et al. (2012)
	500, 1,000, 2,000 and 4,000 ppm	<i>Vigna radiata</i> L. Wilczek	Dry weight	Patra et al. (2013)

(continued)

Table 2.1 (continued)

Nanoparticle(s)	Beneficiary concentration(s)	Plant	Part of plant/process	Reference(s)
GNPs	10 and 80 µg/mL	<i>Arabidopsis thaliana</i>	Germination	Kumar et al. (2013)
	10 and 80 µg/mL	<i>Arabidopsis thaliana</i>	Root length	Kumar et al. (2013)
	10 µg/mL	<i>Arabidopsis thaliana</i>	Shoot and root system (longer), early flowering, yield	Kumar et al. (2013)
AgNPs	10–30 µg/mL	<i>Boswellia ovalifoliolata</i>	Germination and seedling growth	Savithramma et al. (2012)
	60 ppm	<i>Phaseolus vulgaris</i> L., <i>Zea mays</i> L.	Root length	Salama (2012)
	60 ppm	<i>Phaseolus vulgaris</i> L., <i>Zea mays</i> L.	Shoot length	Salama (2012)
	60 ppm	<i>Phaseolus vulgaris</i> L., <i>Zea mays</i> L.	Dry weight of root and shoot	Salama (2012)
	100 µM	<i>Vigna radiata</i>	Antagonize inhibition by 2,4-dichlorophenoxyacetic acid (2,4-D) at 500 µM of plant growth	Karuppanandian et al. (2011)
Sulfur NPs	500, 1,000, 2,000 and 4,000 ppm	<i>Vigna radiata</i>	Dry weight	Patra et al. (2013)
SiO ₂ NPs	15 kg/ha	<i>Zea mays</i> L.	Growth parameters	Yuvakkumar et al. (2011), Suriyaprabha et al. (2012)
TiO ₂ NPs	400 mg/L	<i>Arabidopsis thaliana</i> ,	Root length	Lee et al. (2010)
	60 ppm	<i>Foeniculum vulgare</i>	Germination	Feizi et al. (2013)
	lower than 200 mg/L	<i>Lemna minor</i>	Plant growth	Song et al. (2012)
	1,000 mg/L	<i>Triticum aestivum</i>	Chlorophyll content	Mahmoodzadeh et al. (2013)
	0.25 %	<i>Spinacia oleracea</i>	Hill reaction, non cyclic photophosphorylation, protect chloroplasts from aging	Hong et al. (2005a, b)
	0.05–0.2 g/L	<i>Lycopersicon esculentum</i> Mill	Net photosynthetic rate, conductance to H ₂ O, and transpiration rate, Regulation of photosystem II (PSII)	Qi et al. (2013)

(continued)

Table 2.1 (continued)

Nanoparticle(s)	Beneficiary concentration(s)	Plant	Part of plant/process	Reference(s)
Nano-anatase TiO ₂	0.25 % (foliar spray)	<i>Spinacia oleracea</i>	Rubisco activase (rca) mRNA expressions,	Ma et al. (2008)
	0.25 % (foliar spray)	<i>Spinacia oleracea</i>	Oxygen evolution, Rubisco carboxylation, Rubisco Activase, rate of photosynthetic carbon reaction	Gao et al. (2006), Zheng et al. (2007), Gao et al. (2008), Ma et al. (2008)
	0.25 %	<i>Spinacia oleracea</i>	Several enzymes activities induction	Yang et al. (2006)
Aluminum oxide NPs	400–4,000 mg/L	<i>Arabidopsis thaliana</i> ,	Root length	Lee et al. (2010)
Alumina NPs	10 mg/L	<i>Lemna minor</i>	Root length	Juhel et al. (2011)
nZVI (nanoscale Zero- Valent Iron particles) Iron oxide NPs	0.3 g/L	<i>Lemna minor</i>	Biomass accumulation	Juhel et al. (2011)
	0.5 g/L	<i>Arabidopsis thaliana</i>	Root elongation	Kim et al. (2014)
Iron oxide NPs	0.5–0.75 g/L	<i>Glycine max</i>	Yield and quality	Sheykhabglou et al. (2010)
	50 ppm (foliar spray)	<i>Vigna radiata</i>	Biomass	Dhoke et al. (2013)
	50 ppm (foliar spray)	<i>Vigna radiata</i>	Biomass	Dhoke et al. (2013)
ZnFeCu-oxide NPs (suspension)				
CeO ₂ NPs	250 ppm	<i>Arabidopsis thaliana</i>	Biomass	Ma et al. (2013)
CO ₃ O ₄ NPs	5 g/L	<i>Raphanus sativus</i> L.	Root elongation	Wu et al. (2012)
CuO NPs	500 mg/kg (sand culture)	<i>Triticum aestivum</i>	Biomass	Dimkpa et al. (2012)
Hydroxyapatite suspension	100–2,000 mg/L	<i>Lactuca sativa</i>	Root length	Wang et al. (2012b)

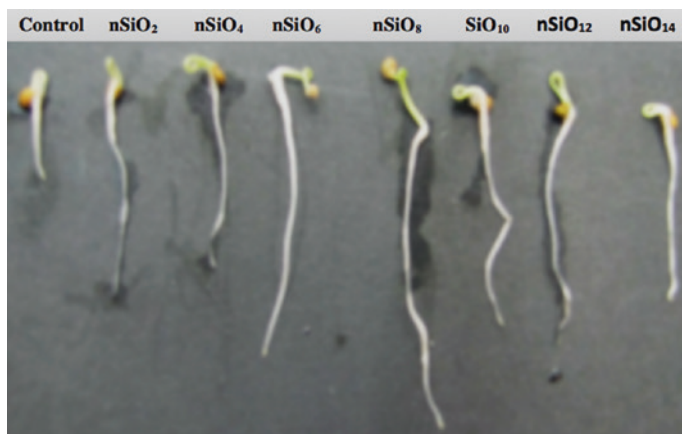


Fig. 2.1 Effect of nSiO_2 on seedlings growth of tomato. 1 SiO_0 (control), 2 SiO_2 , 3 SiO_4 , 4 SiO_6 , 5 SiO_8 and 6 SiO_{10} , 7 SiO_{12} , 8 SiO_{14} [the concentration (in g L^{-1} for nSiO_2 is indicated as a subscript)]. (Siddiqui and Al-Whaibi 2014). Copyright © 2014 King Saud University

2.2.2 Zinc Oxide Nanoparticles

In many studies, increasing evidence suggests that zinc oxide nanoparticles (ZnONPs) increase plant growth and development. Prasad et al. (2012) in peanut; Sedghi et al. (2013) in soybean; Ramesh et al. (2014) in wheat and Raskar and Laware (2014) in onion reported that lower concentration of ZnONPs exhibited beneficial effect on seed germination. However, higher dose of ZnONPs impaired seed germination. The effect of NPs on germination depends on concentrations of NPs and varies from plants to plants. de la Rosa et al. (2013) applied different concentrations of ZnONPs on cucumber, alfalfa and tomato, and found that only cucumber seed germination was enhanced. Raliya and Tarafdar (2013) reported that ZnONPs induced a significant improvement in *Cyamopsis tetragonoloba* plant biomass, shoot and root growth, root area, chlorophyll and protein synthesis, rhizospheric microbial population, acid phosphatase, alkaline phosphatase and phytase activity in cluster bean rhizosphere. It is evident from the correlative light and scanning microscope, and inductive coupled plasma/atomic emission spectroscopy that seedling roots of *Vigna radiata* and *Cicer arietinum* absorbed ZnONPs and promoted the root and shoot length, and root and shoot biomass (Mahajan et al. 2011). Nano ZnO supplemented with MS media promoted somatic embryogenesis, shooting, regeneration of plantlets, and also induced proline synthesis, activity of superoxide dismutase, catalase, and peroxidase thereby improving tolerance to biotic stress (Helaly et al. 2014).

2.2.3 Carbon Nanotubes

Among the NPs, carbon nanotubes (CNTs) have acquired an important position due to their unique mechanical, electrical, thermal and chemical properties. The available data reveal that studies on CNTs have mainly focused on animals and humans (Ke et al. 2011; Tiwari et al. 2014). Comparatively, there has been scant information available on CNTs and their relation with plants cells and plant metabolism. Due to the unique properties of CNTs, they have the ability to penetrate the cell wall and membrane of cells and also provide a suitable delivery system of chemicals to cells. The single-walled-CNTs (SWCNTs) act as nanotransporters for delivery of DNA and dye molecules into plants cells (Srinivasan and Saraswathi 2010). However, in various studies researchers have reported that multi-walled-CNTs (MWCNTs) have a magic ability to influence the seed germination and plant growth, and work as a delivery system of DNA and chemicals to plants cells. MWCNTs induce the water and essential Ca and Fe nutrients uptake efficiency that could enhance the seed germination and plant growth and development (Villagarcia et al. 2012; Tiwari et al. 2014). MWCNTs added to sterile agar medium stimulated seed germination of three important crops (barley, soybean, corn) due to the ability of MWCNTs to penetrate the seed coats as the nanotube agglomerates were detected inside the seed coats using Raman Spectroscopy and Transmission Electron Microscopy (Lahiani et al. 2013). Also, they reported that MWCNTs regulated genes expression encoding several types of water channel proteins in soybean, corn and barley seeds coat. The maximum germination rate in tomato, hybrid Bt cotton, *Brassica juncea*, *Phaseolus mungo* and rice was observed with MWCNTs (Morla et al. 2011; Nalwade and Neharkar 2013; Mondal et al. 2011; Nair et al. 2010; Gajanan et al. 2010). Also, many researchers confirmed the positive role of CNTs in seed germination and plant growth and development. Khodakovskaya et al. (2012) reported that MWCNTs act as regulators for seed germination and growth, and they demonstrated that MWCNTs have the ability to augment the growth of tobacco cell culture by upregulating the marker genes for cell divisions (*CycB*), cell wall formation (*NtLRXI*) and water transport (aquaporin, *NNtPIPI*). Wang et al. (2012a) reported oxidized-MWCNTs significantly enhanced cell elongation in the root system and promoted dehydrogenase activity. However, some researchers reported that MWCNTs do not exhibit a positive influence on seed germination in many plants even when they received high concentration of MWCNTs (Husen and Siddiqui 2014; Lin and Xing 2007). MWCNTs improve the root and stem growth and peroxidase and dehydrogenase activity may be due to primary uptake and accumulation of MWCNTs by roots followed by the translocation from roots to leaves (Smirnova et al. 2012) that could induce genes expression (Khodakovskaya et al. 2012; Lahiani et al. 2013; Wang et al. 2012a). Tripathi and Sarkar (2014) confirmed the presence of water soluble CNTs inside the wheat plants using Scanning Electron and Fluorescence Microscope, and they reported that CNTs induced the root and shoot growth in light and dark conditions. Also, MWCNTs improve water retention capacity and

biomass, flowering and fruit yield and increase medicinal properties of plants (Khodakovskaya et al. 2013; Husen and Siddiqi 2014). However, inhibitory effect of MWCNTS on plants growth has been reported by many researchers (Tiwari et al. 2014; Ikhtiar et al. 2013; Begum and Fugetsu 2012; Begum et al. 2014). Thus, the effect of NPs on plants varies from plant to plant, their growth stages, and the nature of nanoparticles.

2.2.4 Gold Nanoparticles

Few studies have been done on the interaction of gold nanoparticle (AuNPs) with plants. Some researchers found AuNPs induce toxicity in plants by inhibiting aquaporin function, a group of proteins that help in the transportation of wide range of molecules including water (Shah and Belozerovala 2009). However, Barrena et al. (2009) in lettuce and cucumber, Arora et al. (2012) in *Brassica juncea*; Savithramma et al. (2012) in *Boswellia ovalifoliolata* and Gopinath et al. (2014) in *Gloriosa superba* reported that AuNPs improve seed germination. AuNPs improve the number of leaves, leaf area, plant height, chlorophyll content, and sugar content that lead to the better crop yield (Arora et al. 2012; Gopinath et al. 2014). Christou et al. (1988) introduced neomycin phosphotransferase II gene into soybean genome through DNA-coated gold particles. The positive effect of AuNPs therefore needs further study to explore the physiological and molecular mechanism. Kumar et al. (2013) reported AuNPs have a significant role on seed germination and antioxidant system in *Arabidopsis thaliana* and altered levels of microRNAs expression that regulates various morphological, physiological, and metabolic processes in plants.

2.2.5 Silver Nanoparticles

According to available data a large number of studies on silver nanoparticles (AgNPs) have been documented on microbial and animal cells; however, only a few studies were done on plants (Krishnaraj et al. 2012; Monica and Cremonini 2009). As we know, NPs have both positive and negative effects on plant growth and development. Recently, Krishnaraj et al. (2012) studied the effect of biologically synthesized AgNPs on hydroponically grown *Bacopa monnieri* growth metabolism, and found that biosynthesized AgNPs showed a significant effect on seed germination and induced the synthesis of protein and carbohydrate and decreased the total phenol contents and catalase and peroxidase activities. Also, biologically synthesized AgNPs enhanced seed germination and seedling growth of trees *Boswellia ovalifoliolata* (Savithramma et al. 2012). AgNPs increased plants growth profile (shoot and root length, leaf area) and biochemical attributes (chlorophyll, carbohydrate and protein contents, antioxidant enzymes) of

Brassica juncea, common bean and corn (Salama 2012; Sharma et al. 2012). However, Gruyer et al. (2013) reported AgNPs have both positive and negative effect on root elongation depending on the plants species. They reported that root length was increased in barley, but was inhibited in lettuce. Also, Yin et al. (2012) studied the effects of AgNPs on germination of eleven wetland plants species (*Lolium multiflorum*, *Panicum virgatum*, *Carex lurida*, *C. scoparia*, *C. vulpinoidea*, *C. crinita*, *Eupatorium fistulosum*, *Phytolaca americana*, *Scirpus cyperinus*, *Lobelia cardinalis*, *Juncus effusus*) and found AgNPs enhanced the germination rate of one species (*E. fistulosum*). AgNP induces root growth by blocking ethylene signaling in *Crocus sativus* (Rezvani et al. 2012). The impact of AgNPs on morphology and physiology of plants depends on the size and shape of NPs. Syu et al. (2014) studied the effect of 3 different morphologies of AgNPs on physiological and molecular response of *Arabidopsis* and suggested that decahedral AgNPs showed the highest degree of root growth promotion (RGP); however, the spherical AgNPs had no effect on RGP and triggered the highest levels of anthocyanin accumulation in *Arabidopsis* seedlings. The decahedral and spherical AgNPs gave the lowest and highest values for Cu/Zn superoxide dismutase, respectively. The three different size and shape of AgNPs regulated protein accumulations such as, cell-division-cycle kinase 2, protochlorophyllide oxidoreductase, and fructose-1,6 biphosphate aldolase and also induced genes expression involved in cellular events; for example AgNPs induced the gene expression of indoleacetic acid protein 8 (IAA8), 9-cis-epoxycarotenoid dioxygenase (NCED3), and dehydration-responsive RD22. Also, AgNPs activated the aminocyclopropane-1-carboxylic acid (ACC)-derived inhibition of root elongation in *Arabidopsis* seedlings, as well as reduced the expression of ACC synthase 7 and ACC oxidase 2, suggesting that AgNPs acted as inhibitors of ethylene perception and could interfere with ethylene biosynthesis.

2.2.6 Titanium Dioxide Nanoparticles

Similar to AgNPs, a number of researches have focused on the impact of titanium dioxide nanoparticles (TiO₂NPs) on bacteria, algae, plankton, fish, mice, and rats, but research focusing on the realization of the effects of TiO₂NPs on plant remains incomplete. TiO₂NPs enhanced seed germination and promoted radicle and plumule growth of canola seedlings (Mahmoodzadeh et al. 2013). Jaberzadeh et al. (2013) reported that TiO₂NPs augmented wheat plant growth and yielded components under water deficit stress condition. TiO₂NPs regulates enzymes activity involved in nitrogen metabolism such as nitrate reductase, glutamate dehydrogenase, glutamine synthase, and glutamic-pyruvic transaminase that helps the plants to absorb nitrate and also favors the conversion of inorganic nitrogen to organic nitrogen in the form of protein and chlorophyll, that could increase the fresh weight and dry weight of plant (Yang et al. 2006; Mishra et al. 2014). TiO₂NPs acts as a photocatalyst and induces an oxidation-reduction reaction (Crabtree 1998).

TiO₂NPs noticeably promotes aged seeds' vigor and chlorophyll formation and stimulates Ribulose 1, 5-bisphosphate carboxylase (Rubisco) activity and increases photosynthesis, thereby increasing plant growth and development (Yang et al. 2006). TiO₂NPs increases light absorbance, hasten the transport and conversion of the light energy, protect chloroplasts from aging, and prolong the photosynthetic time of the chloroplasts (Yang et al. 2006). It may be due to TiO₂NPs protects the chloroplast from excessive light by augmenting the activity of antioxidant enzymes, such as catalase, peroxidase, superoxide dismutase (Hong et al. 2005a).

2.3 Role of Nanoparticles in Photosynthesis

We know that photosynthesis is a key process for plants on earth that changes light energy to chemical energy. Plants convert only 2–4 % of the available energy in radiation into new plant growth (Kirschbaum 2011). Nowadays, scientists are trying to improve this low efficiency of vascular plants by manipulating techniques and gene manipulations. For speed-up of plant photosynthesis and turbocharged crops, scientists are working with Rubisco, an important enzyme for photosynthesis process to catalyze the incorporation of carbon dioxide into biological compounds. Recently, Lin et al. (2014) developed new tobacco plants by replacing the Rubisco gene for carbon-fixing in tobacco plant, with two genes of cyanobacterium *Synechococcus elongates*; these new engineered plants have more photosynthetic efficiency than native plants. Also, in the field of nanobiotechnology, researchers want to develop bionic plants that could have better photosynthesis efficiency and biochemical sensing. Giraldo et al. (2014) reported that embedded SWCNTs in the isolated chloroplast augmented three times higher photosynthetic activity than that of controls, and enhanced maximum electron transport rates, and SWCNTs enabled the plants to sense nitric oxide, a signaling molecule. They suggested that nanobionics approach to engineered plants would enable new and advanced functional properties in photosynthetic organelles. Also, they said that still extensive research would be needed to see the impact CNTs on the ultimate products of photosynthesis such as sugars and glucose. Also, Noji et al. (2011) reported that a nano mesoporous silica compound (SBA) bound with photosystem II (PSII) and induced stable activity of a photosynthetic oxygen-evolving reaction, indicating the light-driven electron transport from water to the quinone molecules, and they suggested that PSII-SBA conjugate might have properties to develop for photosensors and artificial photosynthetic system. SiO₂NPs improves photosynthetic rate by improving activity of carbonic anhydrase and synthesis of photosynthetic pigments (Siddiqui et al. 2014; Xie et al. 2012). Carbonic anhydrase supplies CO₂ to the Rubisco, which may improve photosynthesis (Siddiqui et al. 2012).

Nano-anatase TiO₂ have a photocatalyzed characteristic and improves the light absorbance and the transformation from light energy to electrical and chemical energy, and also induces carbon dioxide assimilation. TiO₂NPs protect chloroplast from aging for long time illumination (Hong et al. 2005a, b; Yang et al. 2006).

Nano-anatase TiO₂ enhances the photosynthetic carbon assimilation by activating Rubisco (complex of Rubisco and Rubisco activase) that could promote Rubisco carboxylation, thereby increasing growth of plants (Gao et al. 2006). Ma et al. (2008) studied the impact of nano-anatase on molecular mechanism of carbon reaction and suggested nano-anatase-induced marker gene for Rubisco activase (*rca*) mRNA and enhanced protein levels and activities of Rubisco activase resulted in the improvement of the Rubisco carboxylation and the high rate of photosynthetic carbon reaction. The exogenous application of TiO₂NPs improves net photosynthetic rate, conductance to water, and transpiration rate in plants (Qi et al. 2013). According to Lei et al. (2007) nano-anatase promoted strongly whole chain electron transport, photoreduction activity of photosystem II, O₂-evolving and photophosphorylation activity of chlorophyll under both visible and ultraviolet light.

According to Govorov and Carmeli (2007), metal nanoparticles can induce the efficiency of chemical energy production in photosynthetic systems. The chlorophyll in photosynthetic reaction center binds to the AuNPs and Ag nanocrystals, thereby forming a novel hybrid system that may produce ten times more excited electrons due to plasmon resonance and fast electron-hole separation. The enhancement mechanisms may help in the design of artificial light-harvesting systems.

2.4 Conclusion and Future Prospects

No doubt, nanotechnology is an evolutionary science and has introduced many novel applications in the field of electronics, energy, medicine, and life science. However, due to their unique properties, a number of researches have been done on the toxicological effect of NPs on plants, yet research focusing on the realization of the beneficial effects of NPs on plant remains incomplete. Few studies have shown positive effect of NPs on plant growth and development (Table 2.1). It is evident from compiled information that effect of NPs varies from plant to plant and depends on their mode of application, size, and concentrations. This chapter reveals that the research on NPs, essentiality for plants, is in the beginning; more rigorous works are needed to understand physiological, biochemical, and molecular mechanisms of plants in relation to NPs. Also, more studies are needed to explore the mode of action of NPs, their interaction with biomolecules, and their impact on the regulation of gene expressions in plants.

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