Chapter 18
Role of Nanomaterials in the Mitigation of Abiotic Stress in Plants

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18.1 Introduction

Nanotechnology is a novel scientific approach that involves the use of materials and equipments capable of manipulating the physical and chemical properties of a substance at molecular levels to develop products and services used in diverse fields ranging from medicine to agriculture (Siddiqi and Husen 2016, 2017). We know that agriculture is the backbone of developing countries, with more than 60% of their population depending on it for their livelihood (Brock et al. 2011). Nanotechnology has the potential to revolutionize the agricultural and food industry by providing novel tools for the molecular management of plant diseases, and by enhancing the ability of plants to absorb nutrients, and withstand the inhospitable environmental conditions (Khan et al. 2016). Thus, it can potentially enhance crop yields and their nutritional values, develop improved systems for monitoring the environmental conditions, and enhance plant resistance/tolerance to environmental stress (Tarafdar et al. 2013).

Nanotechnology promises to provide smart sensors and delivery systems that will help the agricultural industry immensely. In the near future, nanostructured catalysts are likely to be available to increase the efficiency of input utilization, allowing lower doses of agricultural inputs and managing the crop production systems more efficiently (Liu and Lal 2015). Nanotechnology will also protect the environment indirectly through the use of alternative (renewable) energy supplies and filters or catalysts to reduce pollution and clean up the existing pollutants in soil and water (Adeleye et al. 2016; Mohamed 2017). In the agricultural sector, nanotech

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research and development may frame the next level of expansion of genetically modified crops, animal production inputs, chemical pesticides, and precision farming techniques (Prasad et al. 2012). While nanochemical pesticides are already in use, other applications related mainly to the fine-tuning and more precise micromanagement of problem soils, the more efficient and targeted use of inputs in the wake of climate change and global warming, and the new toxin formulations for pest control are yet to come in full swing (Aragay et al. 2012; Kah 2015).

With the emergence of nanotechnology and its wide-spectrum applications in diverse fields, more attention is being paid on the synthesis of nanomaterials (NMs) from metals like Ag, Au, Pb, etc. or metal oxides, e.g., TiO_2, SiO_2, ZnO, etc. There are several physical, chemical, or biological methods through which nanoparticles (NPs) can be synthesized (Husen and Siddiqi 2014; Tulinski and Jurczyk 2017). Fabrication of metallic NPs using plants or their extracts is becoming more popular now. All plants contain a variety of chemical compounds such as enzymes, sugars, proteins, and other phytochemicals like flavanoids, latex, phenolics, terpenoids, alcohols, amines, cofactors, etc., which act as the reducing and stabilizing agents during the synthesis of metal NPs from metal salts with well-defined size and shape without creating any atmospheric pollution (Husen 2017). It is also observed that under certain conditions plants are capable of producing natural mineralized NMs necessary for their growth (Wang et al. 2001). However, designing a material from the atomic level to achieve a tailored response in extreme conditions is a grand challenge in material research. Controlling the radiation-induced defects via interfaces is the key factor in reducing the damage and imparting stability to certain NMs under conditions where bulk materials exhibit void swelling and/or embrittlement (Tulinski and Jurczyk 2017). The recovery of radiation-induced point defects at free surfaces and grain boundaries and stabilization of helium bubbles at interphase boundaries have been reviewed recently, and an approach for processing the bulk nanocomposites containing interfaces that are stable under irradiation has been suggested (Beyerlein et al. 2013). As the understanding of nanotechnology deepens, it will hopefully become a major economic driving force that will benefit consumers as well as farmers with no adverse effect on humans and their environment (Lutz and Steevens 2009). This chapter is focused on strategies adopted for mitigating the harmful effects of abiotic stresses by using the potential NMs to achieve the optimum plant growth and yield.

18.2 NMs to Mitigate the Harmful Effects of Abiotic Stress

NPs, also termed as nanoscale particles (NSPs), are small molecular aggregates having dimensions between 1 and 100 nm. Due to their extremely small size, such particles acquire some peculiar and diverse physicochemical properties in comparison to their standard or bulk form, as described in detail in Chaps. 1, 2, and 3 of this book. Nanostructured metals and composites provide huge interfaces that attract, absorb, and annihilate point and line defects. These interfaces recover and control defects produced in materials subjected to extremes of displacement damage, impurity implantation, stress, and temperature (Tulinski and Jurczyk 2017). Among the abiotic stresses, drought, salinity, flooding, mineral deficiencies, and various pollutants including radiations are considered as the major factors that affect crop growth and productivity (Andy 2016; Husen et al. 2014, 2016). Plants, being the sessile organism in general, have no choice but to face various environmental stresses throughout their life cycle. They, therefore, develop their defense against environmental stresses at various levels by modulating the molecular, biochemical, and physiological pathways (Husen et al. 2017, 2018). There are several studies indicating that NP-mediated effects on plant growth and development are concentration-dependent. NPs are involved in upregulating the activities of antioxidative enzymes like catalase, superoxide dismutase, and peroxidase under oxidative stress (Laware and Raskar 2014; Farhangi-Abriz and Torabian 2018). The following text summarizes the efforts being made to use various NPs for mitigating the harmful effects of abiotic stresses on plant species.

18.2.1 Salinity Stress

Salinity, which is caused normally by accumulation of chloride (Cl^-) and sulfate ($SO4^{2-}$) anions of predominantly sodium (Na^+) cation but sometimes of calcium (Ca^{2+}) and magnesium (Mg^{2+}) cations as well in soils of arid, semiarid, and coastal areas, is a major abiotic stress factor limiting food production. It is estimated that more than 20% of cultivated land worldwide is experiencing salinity stress and the area is increasing day by day. Since the majority of the major crop species belong to the glycophyte category, they are susceptible to salt stress (Munns and Tester 2008). Salinity stress causes negative impact on various biochemical and physiological processes associated with plant growth and yield. Lowering of soil osmotic potential, creation of nutritional imbalance, enhancing specific ionic toxicity (salt stress), and/or the combination(s) of these factors are some of the common implications of salinity stress experienced by plants. Some other vital processes of plant system, like photosynthesis, protein synthesis, and lipid metabolism, are also affected markedly (Qureshi et al. 2013; Yousuf et al. 2016, 2017). Recent studies on the application of multi-walled carbon nanotubes (MWCNTs) in broccoli (Martinez-Ballesta et al. 2016), chitosan NPs in maize (Bruna et al. 2016) and tomato (Hernandez-Hernandez et al. 2018), and silver NPs in wheat (Mohamed et al. 2017; Abou-Zeid and Ismail 2018) have clearly revealed their alleviating effect on salinity stress.

Studies have indicated that NPs of silica (SiO_2) and titanium dioxide (TiO_2) improve growth and yield in plants under stress. This tolerance may be attributed to the absorption of silicon NPs by the root where they develop a fine layer in the cell wall which helps plant to resist various stresses and maintain the yield (Derosa et al. 2010; Latef et al. 2018). Suriyaprabha et al. (2012) have reported that nanoSiO_2 particles are absorbed better and faster than the bulk or micro-SiO_2, Na_2SiO_3, and H_4SiO_4 when applied to maize roots and seeds. Because of their fast absorption, NPs can be immediately utilized by plants to fulfill their growth needs (Suriyaprabha et al. 2012). In tomato (*Lycopersicon esculentum*) and squash (*Cucurbita pepo*) plants grown under salinity stress, seed germination and the antioxidant system have shown improvement when treated with nanoSiO_2 particles (Haghighi and Pourkhaloee 2013).

The effect of AgNPs application was concentration-dependent, with the optimum at 50 ppm, for growth amelioration in *Brassica juncea* under salinity stress (Sharma et al. 2012b). Similarly, silicon NPs and silicon fertilizer exhibited promising effects on physiological and morphological traits of basil (*Ocimum basilicum*) under salinity stress, as was evident from significant increase in growth and development indices, chlorophyll content (chl-a) and proline level (Kalteh et al. 2014). This could be due to tolerance induction in plants, thereby mitigating the effect of salinity stress (Haghighi et al. 2012). Application of SiO_2NPs has shown potential increase in chlorophyll content, fresh weight and dry weight of leaves, proline accumulation, and antioxidant enzymes' activity in some other plants also grown under salinity stress (Almutairi 2016; Mahmoud et al. 2017). Application of silicon NPs revealed significant increase in seed germination percentage and seedling growth of lentil (*Lens culinaris*) genotypes, which had suffered a significant reduction in these parameters due to salinity stress (Sabaghnia and Janmohammadi 2014). Salinity stress reduced the crop growth and yield due to Na^+ ion toxicity in tomato plants, but the use of SiO_2NPs reduced the ionic toxicity leading to enhanced crop growth and yield (Savvasd et al. 2009). Some similar results were obtained in maize also (Gao et al. 2006). These NPs apparently reduce Na^+ ion concentration, perhaps by reducing Na^+ ion absorption by plant tissues.

Treatment of squash seeds with NaCl reduced the seed germination percentage and the vigor, length, and biomass of roots and shoots (Siddiqui et al. 2014). Application of nanoSiO_2 improved these growth parameters by reducing the levels of malondialdehyde (MDA), hydrogen peroxide (H_2O_2), and electrolyte leakage. In addition, it reduced chlorophyll degradation and enhanced the net photosynthetic rate (P_n), stomatal conductance (g_s), transpiration rate, and water-use efficiency. The increase in plant germination and growth characteristics through application of nanoSiO_2 might reflect an enhanced K/Na ratio (Alsaeedi et al. 2018) and a reduction in oxidative damage due to expression of antioxidant enzymes (Torabian et al. 2016; Farhangi-Abriz and Torabian 2018). Askary et al. (2017) reported that Fe_2O_3NPs caused increases in foliar fresh and dry weights and in the phosphorus, potassium, iron, zinc, and calcium contents of peppermint (*Mentha piperita*) under salinity stress, but had no effect on sodium content. Lipid peroxidation and proline contents decreased significantly. The maximum activities of antioxidant enzymes (catalase, superoxide dismutase, and guaiacol peroxidase) were observed in plants treated with 150 mM of NaCl, but application of Fe_2O_3NPs suppressed these activities. Further, seedlings of cv. California wonder sweet pepper (*Capsicum annuum*) plants were irrigated with saline water with an EC (electrical conductivity) of 5.47 dS m^{-1} and silicon in regular (25%) as well as nanosilicon (25%) forms. All aspects of plant growth and yield were improved under all silicon treatments compared to non-treated plants. Treatment with 1 mL L^{-1} of nanosilicon recorded the maximal and significant success in mitigating the negative effects of salinity. Thus, nanosilicon was more effective and efficient in mitigating the salt-stress impact on sweet pepper plants (Tantawy et al. 2015).

Haghighi and Pessarakli (2013) studied the influence of silicon and nanosilicon on salinity tolerance of cherry tomatoes (*Lycopersicon esculentum*) at early growth stage and reported that salinity caused deleterious effects on plant-growth parameters. Conversely, electrolyte leakage increased by increasing the salinity levels. High salinity levels diminished the sub-stomatal CO_2 content, photosynthetic rate, mesophyll conductance, and water-use efficiency. Si application alleviated the effect of salinity stress on chlorophyll concentration, photosynthetic rate, leaf water content, and, ultimately, on fresh weight of the plant. In short, application of Si was beneficial in improving the salt tolerance of tomato plants; the effect of Si and nanoSi was not significantly different. Torabian et al. (2016) have reported increase in growth, net CO_2 assimilation rate, sub-stomatal CO_2 concentration, chlorophyll content, Fv/Fm and Zn contents, and a decreased Na content in the leaves of sunflower (*Helianthus annuus*) under the influence of nanoZnO. Exposure of wheat plants to CuO/ZnONPs improved the growth of both root and shoot, and this was attributed to lower solubility of CuONPs. It has been suggested that due to alkaline soil, Cu and Fe may precipitate as hydroxides and therefore may not be available for absorption by plants. However, chelated Cu and FeNPs may be an answer to this problem (Fathi et al. 2017). The above discussion shows that the NMs of differrent compounds are capable of mitigating the ill-effects of salinity stress and enhancing the growth of several plant species.

18.2.2 Drought Stress

Climate change and global warming have paved the way for several problems, the global water crisis being the most prominent among them. The ever-increasing scarcity of agricultural water is affecting the agricultural production adversely (FAO 2012) and destroying the green belts in the arid and semiarid regions worldwide (Aref et al. 2013, 2016). Therefore, identification of tolerant plant material or augmentation of drought tolerance in plants is always a prime concern related to sustainable agriculture and crop production. Efforts have been made to mitigate the harmful effects of limited water supply or drought stress on crop plants by using NMs. Use of nanosensors in global positioning systems yielding satellite images of fields might enable farmers to detect the impact of stress in plants at an early stage (Khot et al. 2012). In addition, due to their porous properties and the capillary suction they exert, nanozeolites can be used for enhanced water retention in soils (Boroghani et al. 2011). Improving water-retention capacity of soils could result in increased crop production in areas prone to drought (Gururaj and Krishna 2016).

Application of different fractions of silica NPs improved the tolerance of hawthorn (*Crataegus* sp.) toward drought stress (Ashkavand et al. 2015). Silicon NPs seem to be involved in maintaining the critical physiological and biochemical attributes in order to induce drought tolerance in hawthorn seedlings, but the exact mechanism is yet to be understood. Sedghi et al. (2013) demonstrated that nanozinc oxide can increase seed germination in soybean subjected to water stress by facilitating the rapid use of seed reservoirs for seedling growth. Absorption of microelement iron in plants under drought stress may also have a pivotal role in drought tolerance. Foliar application of iron NPs exhibited drought stress-mitigating effects on yield components and oil percentage of Goldasht spring safflower cultivars (Davar et al. 2014). *Martinez-Fernandez* et al. *(*2015*) reported that meghemite (*Fe_2O_3*)* counteracted drought stress with no effect on proline, total amino acids, and mobilization of trace elements in sunflower (*Helianthus annuus*). Further, foliar application of 0.02% TiO_2NPs improved various agronomic traits such as plant height, ear weight, ear number, seed number, 1000-seed weight, final yield, biomass, harvest index, and the gluten and starch contents of wheat under drought stress (Jaberzadeh et al. 2013).

In the case of dragonhead (*Dracocephalum moldavica*) grown under water-deficit condition, plants treated with 10 ppm TiO_2NPs had more proline and much less H_2O_2 and malondialdehyde contents, as compared to untreated plants (Mohammadi et al. 2014). It was concluded that water-deficit stress-induced damages such as oxidative stress and membrane damage can be ameliorated by foliar application of TiO_2NPs at appropriate concentrations. Similarly, AgNPs application reduced the negative effects of drought stress induced by polyethylene glycol on germination rate, germination percentage, and the length as well as fresh and dry weights of roots in lentil (*Lens culinaris*) (Hojjat 2016). The drought impact was alleviated by foliar application of fullerenol NPs in sugarbeet (*Beta vulgaris*) (Borisev et al. 2016) and TiO_2NPs in linseed (*Linum usitatissimum*) (Aghdam et al. 2016). Multi-walled carbon nanotubes (MWCNTs) and sodium nitroprusside (SN) NPs could improve tolerance of barley against drought and salinity by boosting seed water absorption and increasing seedling water content (Karami and Sepehri 2017). Recently, a group of Iranian scientists has revealed the beneficial effects of nanographine oxide at low concentrations and its phytotoxicity at higher concentrations on callus cells of *Plantago major* (a medicinal plant) grown under the polyethylene glycol-induced drought (Ghorbanpoura et al. 2018). In soybean, The use of composite micronutrient NPs (Dimkpa et al. 2017) and cerium oxide (CeO_2) NPs could enhance crop performance of soybean under drought stress (Cao et al. 2018). In vitro application of iron NPs along with salicylic acid proved to be a useful method for enhancing adaptation of strawberry plants to drought before their transplantation in the field (Mozafari et al. 2018).

A complete understanding of the mechanism of ameliorating action of NPs at cellular and metabolic levels will likely help scientists to develop resistant crop cultivars and manage them well for better yield not only in regions of limited water availability but also under other abiotic stresses (Singh et al. 2017). Some studies have confirmed the synthesis of new proteins and enzymes called dehydrins whose enhanced accumulation is related to acquisition of drought tolerance (Lopez et al. 2003). These enzymes, among others, lead to the synthesis of compatible solutes like proline, betaine, polyamines, etc., which protect cells from excessive loss of water and maintain the membranes and cell integrity (Paleg et al. 1984). It would be interesting to know at which point(s) of metabolic pathways the NPs interact with abiotic stresses for enahncing the stress tolerance of plants. It is, however, clear that NPs can be used to enhance crop yield under limited water-supply conditions.

18.2.3 Flooding Stress

Heavy rainfall can cause flooding of fields, if proper drainage is not available. Overflow of water in rivers and rise of groundwater table also cause flooding, which may destroy the standing crops. In addition, excessive irrigation also results in flooding or temporary waterlogging. All these situations may cause either partial anaerobiosis (hypoxia) or complete anaerobic condition (anoxia) in the soil, driving out air from the soil (Ricard et al. 1994; Vartapetian et al. 2014). Flooding causes not only the deficiency of O_2 whose diffusion rate is 10^4-fold slower in water than in air (Armstrong and Drew 2002) but also produces toxic compounds, which retard plant growth and often kill the plants. Hypoxia and anoxia result in energy-deficit conditions, inhibition of respiration, and upregulation of ethylene and abscisic acid synthesis-related genes as strategies for adaptation to waterlogging (Komatsu et al. 2009). Other adaptive strategies include the formation of nodal roots at the air-water interphase and the development of aerenchymatous cells in the root cortex in order to facilitate diffusion of oxygen (Yamauchi et al. 2013). It is, therefore, imperative to know whether NPs enhance the flooding tolerance or mitigate the ill-effects of flooding in plants (Bailey-Serres and Colmer 2014). A study of saffron (*Crocus sativus*), a medicinal and aromatic plant species (Rezvani et al. 2012), revealed a reduction in the number of roots, root length, root biomass, and leaf biomass caused by a 10-day flooding stress, whereas soaking the saffron corms with 40 or 80 ppm concentration of nanosilver mitigated the ill-effects of flooding stress, as indicated by increased production of roots. The effect of Al_2O_3NPs of 30–60 nm was studied on soybean plant under flooding condition with the result that the root length increased while mitochondrial proteins related to glycolysis were suppressed (Mustafa and Komatsu 2016). Also, Al_2O_3NPs of varying size and shape modulated the scavenging activity of cells by regulating the ascorbate/glutathione pathway (Mustafa et al. 2015a). In addition, some other physiological and biochemical strategies include (i) shifting of carbohydrate metabolism toward fermentation (Banti et al. 2013) and (ii) downregulation of alcohol dehydrogenase enzyme in tolerant species (Mustafa et al. 2015b). The apparent paucity of information on NPs-plants interaction warrants further well-planned investigations. However, based on the available information, it can be postulated that NMs play a vital role in alleviating the harmful effects of flooding stress through modulating the metabolism and gene expression.

18.2.4 Mineral Nutrient Stress

Application of fertilizers is a common practice in agriculture to increase the crop productivity. Efforts have been made to identify NMs that may not only increase the crop production and yield but also minimize the nutrient loss of fertilizers, causing nutrient deficiency, and augment their effective availability to plants (Liu and Lal 2015). Development of nanofertilizers (NFs) or nano-encapsulated nutrients that may ensure constant availability and smooth release of nutrients could be an effective tool toward sustainable agriculture. The NFs can be classified under four categories: macronutrient NFs, micronutrient NFs, nutrient-loaded NFs, and plant growth-enhancing NMs (Liu and Lal 2015). Application of NFs could be a potential approach to address issues of soil toxicity and associated stress problems on one hand and enhance the nutrient-use efficiency, on the other. Xiumei et al. (2005) demonstrated that application of nano$CaCO_3$ coordinated with humic acid and organic manures could improve growth and development of peanut plants significantly, and the contents of soluble sugar and protein also increased notably in the stems and leaves accompanied by enhanced absorbability of nutrient elements (calcium, nitrogen, phosphorus, and potassium). The effect of synthesized zinc NPs, characterized for size, shape, surface structure, crystalline nature, and elemental proportion, was studied in pearl millet (*Pennisetum americanum* L.) cv. HHB 67 (Tarafdar et al. 2014). Results indicated that synthesized NPs of 15–25 nm brought significant improvement in root and shoot growth, chlorophyll content, total soluble leaf protein, plant dry biomass, and enzyme activities of acid phosphatase, alkaline phosphatase, phytase, and dehydrogenase in 6-week-old plants. Moreover, grain yield was improved by 37.7% due to application of zinc NF.

Silicon NPs have distinctive physicochemical characteristics and are able to enter into plants, influence the plant metabolism, and improve plant growth and yield under unfavorable environmental conditions. The effect of nanosilicon foliar application on safflower growth under organic and inorganic fertilizer regimes was also investigated (Janmohammadi et al. 2016). Safflower plants were treated with SiO_2 suspension at leaf development, branching, and capitulum emergence stages. The findings suggested that application of organic fertilizers with foliar spray of SiO_2NPs can improve safflower production. Further, the response of two Iranian rice cultivars to nitrogen and nanopotassium fertilizer was studied by Lemraski et al. (2017) who found that NPs consumption by rice cultivars resulted in improved yields. In brief, the use of NFs with a view to reducing nutrient deficiencies in the soil may be quite effective and enhance the growth and yield of different crops.

18.2.5 Temperature Stress

Since the industrial revolution, the atmospheric CO_2 concentration is consistently increasing, giving rise to “global warming.” Adverse effects of rising temperatures on crop production have been predicted (Asseng et al. 2015; Kumar 2016), and efforts are being made world over to arrest the rise of temperature to make agriculture sustainable. Both high temperature (heat stress) and low temperature (cold stress or chilling/freezing stress) become injurious to plants on crossing the threshold level.

18.2.5.1 Heat Stress

High temperature stress or heat stress is the rise in temperature beyond a critical threshold for a period of time sufficient to cause irreversible damage to plant growth, development, and yield (Wahid 2007). Heat stress accelerates overproduction of ROS and creates oxidative stress, which causes disintegration of membrane lipids, leakage of electrolytes, and denaturation of biomolecules (Savicka and Skute 2010; Karuppanapandian et al. 2011; Aref et al. 2016) and decreases the chlorophyll content and photosynthesis rate (Prasad et al. 2011). Iqbal et al. (2017) conducted experiments to investigate the effect of AgNPs on the regulation of growth of wheat under heat stress. Plant extract of *Moringa oleifera* was used for AgNPs synthesis followed by its characterization through UV-Vis spectroscopy, X-ray diffractrometry (XRD), scanning electron microscopy (SEM), and atomic force microscopy (AFM). Different concentrations of AgNPs were applied to wheat plants at three-leaf stage under heat stress of 35–40 °C for 3 h day^{-1} for 3 days. Exposure of heat stress alone reduced several plant-growth parameters including dry biomass, whereas application of AgNPs at 50 and 75 mg L^{-1} protected wheat plants against heat stress and improved their growth significantly. Application of low concentration of selenium (Se) NPs also increased chlorophyll content, hydration level, and growth of tomato and sorghum plants because of their antioxidative properties (Haghighi et al. 2014; Djanaguiraman et al. 2018). Heat shock proteins (HSPs), the molecular chaperons, are synthesized in response to heat stress (Schulze et al. 2005). HSPs and compatible solutes help other proteins in maintaining their stability under heat stress (Paleg et al. 1981; Wahid et al. 2007) and play an important role in thermotolerance. Khodakovkazya et al. (2011), using genetic, photothermal, and photoacoustic methods, demonstrated that MWCNTs upregulated the expression of various stress-related genes including *HSP90* (Table 18.1). These findings are also supported by Zhao et al. (2012) who observed that cerium oxide NPs (CeO_2) caused stress response in corn plants resulting in overproduction of H_2O_2 and upregulation of *HSP70*. Qi et al. (2013) found that TiO_2NPs alleviated heat stress through the regulation of stomatal opening. These interesting findings, inter alia, are encouraging especially for those working on aspects related to global warming versus agricultural productivity and food security.

18.2.5.2 Cold Stress

The frequent and unusual occurrence of low temperature is also a cause of concern to farmers. Cold stress (0–15 °C) is caused by the temperature cool enough to produce injury without forming ice crystals in plant tissues, while freezing stress

Table 18.1 Alleviating effects of frequently used nanomaterials on abiotic stresses in plants

Nanomaterial	Abiotic stress	Plant species	Effects	References
Ag	Post-harvest	Orchid (*Dendrobium* sp.), Peruvian lily (*Alstroemeria* sp.)	Suppressed the abscission of flowers and flower buds	Wagstaff et al. (2005) and Uthaichay et al. (2007)
		Chrysanthemums (*Chrysanthemum morifolium*)	Increased survival and succulence of cut flowers, decreased fresh weight loss, reduced stem bacterial colonies	Kazemipour et al. (2013)
	Flooding	Saffron (*Crocus sativus*)	Blocked ethylene signaling, promoted root growth	Rezvani et al. (2012)
		Soybean (*Glycine max*)	Reduced generation of cytotoxic by-products of glycolysis, increased the abundance of stress-related proteins, enhanced seedling growth	Mustafa et al. (2015b)
	Dark	Horse-shoe pelargonium (*Pelargonium zonale*)	Increased antioxidative enzyme activities, leaf chl and carotenoid content, reduced lipid peroxidation, increased petal longevity,decreased petal abscission	Hatami and Ghorbanpour (2013, 2014)
	Cold	Arabidopsis (*Arabidopsis thaliana*)	Activated and enriched antioxidant genes (*MeCu/ZnSOD* and *MeAPX2*), 35% of similar genes were regulated by both AgNPs and cold stress	Kohan-Baghkheirati and Geisler-Lee (2015)
	Drought	Lentil (*Lens culinaris*)	Reduced negative effects on germination rate and germination percentage, root length, root fresh and dry weights	Hojjat (2016)
	Heat	Wheat (*Triticum aestivum*)	Protected plants against heat stress and improved plant growth significantly	Iqbal et al. (2017)
		Wheat (*Triticum aestivum*)	Alleviated the harmful effects of salinity stress	Mohamed et al. (2017) and Abou-Zeid and Ismail (2018)
Al_2O_3	Flooding	Soybean (*Glycine max*)	Regulated energy metabolism and cell death, improved growth	Mustafa et al. (2015a)
			Increased root length, suppressed mitochondrial proteins related to glycolysis	Mustafa and Komatsu (2016)

Anatase-TiO_2	UV-B radiation	Spinach (*Spinacia oleracea*)	Decreased reactive oxygen species (ROS) and MDA content, increased activities of antioxidative enzymes, improved the rate of oxygen evolution	Lei et al. (2007, 2008)
Au^{3+}	Au^{3+}	Cowpea (*Vigna unguiculata*)	Increased generation of Au-nanoparticles and decreased phenolic-induced reduction of toxic Au^{3+} to form non-/less toxic AuNPs	Shabnam et al. (2014)
$CaCO_3$	Mineral nutrient	Peanut (*Arachis hypogaea*)	Improved the growth and development of peanut significantly, also increased the contents of soluble sugar and protein notably in the stems and leaves	Xiumei et al. (2005)
Carboxyl-CdSe/ZnS quantum dots	Pb and Cu	*Chlorella kesslerii* (cell-walled strain), *Chlamydomonas reinhardtii* (walled and wall-less strain)	Decreased intracellular Cu and Pb contents in walled strains, increased Cu and Pb in wall-less strains	Worms et al. (2012)
Cd-telluride quantum	UV-B radiation	Wheat (*Triticum aestivum*)	Programmed cell death and DNA laddering, inhibited root and shoot growth	Chen et al. (2011)
CeO_2	UV-B radiation	Green alga (*Chlorella vulgaris*)	Facilitated efficient absorption of UV radiation without scattering the useful visible light, limited oxidative stress damage	Sicard et al. (2011)
	Heat	Maize (*Zea mays*)	Enhanced production of H_2O_2 and upregulation of *HSP70*	Zhao et al. (2012)
	Drought	Soybean (*Glycine max*)	Enhanced growth, development, and yield resulting in the overall better performance of crop	Cao et al. (2018)
Chitosan	Salinity	Maize (*Zea mays*)	Alleviated the harmful effects of salinity stress	Bruna et al. (2016)
		Tomato (*Lycopersicon esculentum*)	Alleviated the harmful effects of salinity stress	Hernandez-Hernandez et al. (2018)
Cu	Post-harvest	Parsley (*Petroselinum crispum*)	Prevented weight loss, reduced lipid peroxidation, and maintained higher ascorbic acid concentration	Ouzounidou and Gaitis (2011)
CuO	UV radiation	Waterweed (*Elodea nuttallii*)	Increased Cu accumulation, reduced chlorophyll content and photosynthetic capacity, enhanced peroxidase activity	Regier et al. (2015)
	Salinity	Wheat (*Triticum aestivum*)	Improved the growth of both root and shoot	Fathi et al. (2017)

(continued)

Table 18.1 (continued)

Nanomaterial	Abiotic stress	Plant species	Effects	References
Fe	Drought	Safflower (*Carthamus tinctorius*)	Reduced impact of drought and improved yield due to foliar application	Davar et al. (2014)
		Strawberry (*Fragaria ananassa*)	Enahanced acclimation and ressitance of plants to drought before their transplantation in the field	Mozafari et al. (2018)
Fullerenol	Drought	Sugar beet (*Beta vulgaris*)	Injurious effects of drought dissapeared by foliar application of fullerenol NPs	Borisev et al. (2016)
Maghemite (y-Fe_2O_3)	Drought	Sunflower (*Helianthus annuus*)	Counteracted drought stress with no effect on proline, total amino acids, and mobilization of trace elements	Martinez-Fernandez et al. (2015)
	Salinity	Peppermint (*Mentha piperita*)	Increased leaf fresh and dry weights, phosphorus, potassium, iron, zinc, and calcium contents	Askary et al. (2017)
MWCNTs (multi-walled carbon nanotubes)	Heat	Tomato (*Lycopersicon esculentum*)	Upregulated the expression of various stress-related genes including *HSP90*	Khodakovskaya et al. (2011)
	Salinity	Cabbage (*Brassica oleracea*)	Alleviated the harmful effects of salinity stress	Martinez-Ballesta et al. (2016)
	Drought and salinity	Barley (*Hordeum vulgare*)	Improved drought and salinity tolerance by boosting seed water absorption and increasing seedling water content	Karami and Sepehri (2017)
Na_2SeO_4	Heat and cold	Tomato (*Lycopersicon esculentum*)	Improved plant growth, chlorophyll, and leaf-relative water contents	Haghighi et al. (2014)
Na_2SiO_3	Cr (VI)	Pea (*Pisum sativum*)	Protected pea seedlings against Cr(VI) phytotoxicity, reduced uptake of Cr(VI) and oxidative stress, upregulated antioxidative defense systems, and enhanced accumulation of nutrient elements leading to improved growth	Tripathi et al. (2015)
Nanopotassium	Mineral nutrient	Rice (*Oryza sativa*)	Enhanced total tillers and fertile tillers per hill	Lemraski et al. (2017)
Se	Heat	Tomato (*Lycopersicon esculentum*)	Increased chlorophyll content, hydration of plants, and growth	Haghighi et al. (2014) and Djanaguiraman et al. (2018)
SiO_2	Salinity	Tomato (*Lycopersicon esculentum*)	Enhanced seed germination potential, root length, and dry weight	Haghighi et al. (2012)

			Alleviated the effect of salinity on fresh weight, chlorophyll concentration, photosynthetic rate, and leaf water content	Haghighi and Pessarakli (2013) and Haghighi and Pourkhaloee (2013)
			Upregulated the expression profile of four salt-stress genes (*AREB*, *TAS14*, *NCED3*, and *CRK1*), and downregulated six genes (*RBOH1*, *APX2*, *MAPK2*, *ERF5*, *MAPK3*, and *DDF2*), suppressed the effect of salinity on seed germination rate, root length, and fresh weight	Almutairi (2016)
		Squash (*Cucurbita pepo*)	Improved seed germination and growth characteristics; reduced levels of MDA, H_2O_2, and electrolyte leakage; reduced chlorophyll degradation and oxidative damage; enhanced photosynthetic parameters and antioxidative enzymes	Haghighi and Pourkhaloee (2013) and Siddiqui et al. (2014)
		Basil (*Ocimum basilicum*)	Increased fresh and dry weights, chlorophyll, and proline contents	Kalteh et al. (2014) and
		Lentil (*Lens culinaris*)	Enhanced seed germination and seedling growth	Sabaghnia and Janmohammadi (2014)
		Cucumber (*Cucumis sativus*)	Increased plant germination and growth characteristics	Alsaeedi et al. (2018)
		Soybean (*Glycine max*)	Reduced oxidative damage due to expression of antioxidative enzymes	Farhangi-Abriz and Torabian (2018)
	Cold	Wheatgrass (*Agropyron elongatum*)	Overcame seed dormancy, enhanced seed germination and seedling weight	Azimi et al. (2014)
	Drought	Hawthorn (*Crataegus* sp.)	A significant positive effect on photosynthetic rate, stomatal conductance, and plant biomass, nonsignificant effect on chlorophyll and carotenoid contents	Ashkavand et al. (2015)
	Cr	Pea (*Pisum sativum*)	Alleviated metal-induced toxicity of plants	Tripathi et al. (2015)
	Mineral nutrient	Safflower (*Carthamus tinctorius*)	Improved safflower production	Janmohammadi et al. (2016)
	UV-B radiation	Wheat (*Triticum aestivum*)	Alleviated harmful effects of UV-B radiation in seedlings	Tripathi et al. (2017)

(continued)

Table 18.1 (continued)

Nanomaterial	Abiotic stress	Plant species	Effects	References
TiO_2	Excessive light	Spinach (*Spinacia oleracea*)	Increased activities of antioxidative enzymes, decreased accumulation of reactive oxygen free radicals and the level of MDA, membrane stability and structure of chloroplast remained intact	Hong et al. (2005a, b)
	Heat	Tomato (*Lycopersicon esculentum*)	Enhanced photosynthesis by regulating energy dissipation, caused cooling of leaves through inducing stomatal opening	Qi et al. (2013)
	Drought	*Wheat (Triticum aestivum)*	Increased growth, yield, gluten, and starch content	Jaberzadeh et al. (2013)
		Moldavian dragonhead *(Dracocephalum moldavica)*	More proline and much less H_2O_2 and MDA contents, less oxidative stress and membrane damage	Mohammadi et al. (2014)
		Lin seed (*Linum usitatissimum*)	Enhanced chlorophyll and carotenoid content, improved growth and yield attributes, decreased hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) contents	Aghdam et al. (2015)
	Cold	Chickpea (*Cicer arietinum*)	Enhanced activities of antioxidative enzymes, decreased H_2O_2 content and electrolyte leakage, enhanced accumulation of TiO_2 in sensitive genotype than in tolerant one	Mohammadi et al. (2013a, b)
			Enhanced expression of Rubisco- and chlorophyll-binding protein genes, decreased H_2O_2 content, enhanced activity of phosphoenolpyruvate carboxylase	Hasanpour et al. (2015)
Zn	Mineral nutrient	Pearl millet (*Pennisetum americanum*)	Improved shoot length, root length, root area, chlorophyll content, total soluble leaf protein, plant dry biomass, and enzyme activities significantly	Tarafdar et al. (2014)
ZnO	Drought	*Soybean* (*Glycine max*)	Increased germination percentage and germination rate, decrease in seed residual fresh and dry weights	Sedghi et al. (2013)
	Salinity	Sunflower (*Helianthus annuus*)	Increased growth, net CO_2 assimilation rate, sub-stomatal CO_2 concentration, chlorophyll content, Fv/Fm and Zn content, and decreased Na content in leaves	Torabian et al. (2016)
		Wheat (Triticum aestivum)	Improved the growth of both root and shoot	Fathi et al. (2017)

(<0 °C) results in the formation of ice crystals in plant tissues causing frost-killing of crops (Hasanuzzaman et al. 2013). Loss of fluidity of membranes and leakage of electrolytes are the distinct effects of cold stress. Plants exposed to cold stress show poor germination, retarded growth, and reduced crop yield (Welti et al. 2002; Suzuki et al. 2008). However, susceptibility to cold stress varies among species and cultivars. Plants with higher tolerance levels show less membrane injury than the sensitive species (Amiri et al. 2010; Heidarvand et al. 2011).

With the objective of how to diminish the ill-effects of cold stress on crop plants, Mohammadi et al. (2013a) assessed the effect of TiO_2NPs on changes in membrane damage indices like electrolyte leakage index and malondialdehyde content during cold stress of 4 °C in a sensitive (ILC 533) and a tolerant (Sel 11439) chickpea (*Cicer arietinum*) genotypes. Bioaccumulation of NPs within the vacuole and chloroplast showed that, under thermal treatments, the sensitive genotype had more permeability to NPs compared to the tolerant one, and TiO_2 content was higher during cold stress than at the optimum temperature. Obviously, physiological indices were positively affected by NPs during thermal treatments. TiO_2 treatments not only prevented oxidative damage in chickpea genotypes but also alleviated membrane damage under cold stress. It was suggested for the first time that TiO_2NPs improved the redox status of the genotypes under thermal treatments. Extending their studies, Mohammadi et al. (2013b) confirmed the earlier results and suggested that TiO_2NPs confer an increased tolerance of chickpea plants to cold stress by decreasing the level of injuries and increasing the capacity of defense systems. Further research may likely endorse the usefulness of NPs in general and TiO_2NPs in particular for increasing the crop tolerance against cold stress.

Photosynthesis, a vital process, is prone to cold stress. Plants exposed to cold stress have less chlorophyll content, reduced CO_2 assimilation, and degradation of Rubisco enzyme (Yordanova and Popova 2007; Liu et al. 2012). Positive effects of NMs on photosynthesis enhance carboxylation of Rubisco (Gao et al. 2006), light absorption capacity of chloroplast (Ze et al. 2011), electron transport rate, and inhibition of ROS generation in chloroplast (Giraldo et al. 2014). Application of nano-TiO_2 enhances the expression level of Rubisco- and chlorophyll-binding protein genes (Hasanpour et al. 2015) and activities of catalase, superoxide dismutase, and ascorbate peroxidase (Mohammadi et al. 2014), maintains the stability of chlorophyll and carotenoid contents, and increases plant tolerance to cold stress (Table 18.1). Exposure of plants to chilling stress causes upregulation of *MeCu/ZnSOD* and *MeAPX2* genes and enhances the activities of monodehydroascorbate reductase, dehydroascorbate reductase, and glutathione reductase that improves ROS scavenging, leading to suppressed oxidative stress parameters such as lipid peroxidation, chlorophyll degradation, and H_2O_2 synthesis that ultimately causes stress resistance (Xu et al. 2014). On the other hand, application of NMs alone or along with a short-term chilling stress treatment has been shown to improve growth and the physiological and biochemical attributes of cold-stressed plants (Azimi et al. 2014; Haghighi et al. 2014; Kohan-Baghkheirati and Geisler-Lee 2015, Table 18.1). More work is certainly required to arrive at a concrete conclusion regarding the role of NPs in enhancing cold tolerance of different agricultural and horticultural crops.

18.2.6 Ultraviolet (UV) Radiation Stress

Exposure of plants to ultraviolet-B (UV-B, 280–315 nm), photosynthetically inactive and non-ionizing radiation, leads to accumulation of enhanced level of ROS in cells (Mackerness et al. 2001), which damages DNA, chloroplast structure, and several cellular processes including photosynthesis (Chen et al. 2011; Wang et al. 2012; Hideg et al. 2013). DNA damage results from the formation of dimer of pyrimidine bases leading to the loss of biological activity. RNA, proteins, ABA, and IAA also absorb UV radiation and, consequently, lose their biological activity. Besides activating their enzymatic and nonenzymatic antioxidant defense system, plants tend to adapt to the stressful situation by accumulating phenolic compounds such as flavonoids and flavones that absorb harmful UV radiations (Shen et al. 2010a, b). The use of NMs protects photosynthetic systems from UV-B stress (Table 18.1) by enhancing chl content and Rubisco activity and suppressing oxidative stress (Sicard et al. 2011). It is interesting to note that nanoanatase TiO_2 with a photocatalyzed characteristic under light could cause an oxidation-reduction reaction. Hong et al. (2005a, b) observed that nanoTiO_2 could promote photosynthesis and greatly improve spinach growth. However, the mechanism of the action of nanoTiO_2 in promoting conversion from light energy to electron energy and from electron energy to active chemical energy remains largely unclear. Along these findings, Lei et al. (2007, 2008) reported that during the photosynthesis, electron transfer, photoreduction activity of photosystem II, oxygen evolution, and photophosphorylation of chloroplast in the nanoanatase TiO_2-treated spinach were greatly increased under both visible and ultraviolet light illumination. Likewise, the energy-enriched electron from nanoanatase TiO_2 could enter chloroplast under ultraviolet light, got transferred to photosynthetic electron transport chain, and made NADP+ be reduced to NADPH and coupled to photophosphorylation, making electron energy be transformed to ATP. Moreover, nanoanatase h+, which photogenerated electron holes, captured an electron from water, which accelerated water photolysis and O_2 evolution. However, designing a material from the atomic level to achieve a tailored response in extreme conditions is a grand challenge in material research. NMs for the control of radiation-induced defects via interfaces are the key factors in reducing damage and providing stability in camparison to bulk materials, which display void swelling or embrittlement (Beyerlein et al. 2013; Tulinski and Jurczyk 2017).

The mechanisms by which nanoanatase promotes antioxidant stress in spinach chloroplasts under UV-B radiation are not fully understood (Lei et al. 2008). However, these authors showed that nanoanatase treatment could significantly decrease the accumulation of superoxide radicals (O· −2), hydrogen peroxide (H_2O_2), and malondialdehyde (MDA) contents; increase activities of catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), and guaiacol peroxidase (GPX); and elevate the oxygen evolution rate in spinach chloroplasts under UV-B radiation, thus mitigating the oxidative stress caused by UV-B radiation. Lately, silicon NPs have also been found to alleviate effectively the harmful effects of UV-B radiation in wheat seedlings (Tripathi et al. 2017). Such studies are opening new vistas in research that may prove revolutionary in terms of food production in the future under conditions of abiotic stress.

18.2.7 Irradiance Stress

Enhancing radiation-use efficiency is a prime consideration for realizing the maximum yield of crops. However, when the energy absorbed by the photosystems exceeds the energy that can be used in the photochemistry, it causes photodamage (photooxidation, i.e., bleaching of chl) to the plants (Havaux et al. 2000). Moreover, plants develop mechanisms to avoid photodamage by losing excess light energy as heat due to induced acidification of thylakoid lumen resulting from the formation of a proton-motive force that involves xanthophyll cycle. This leads to the enzymatic conversion of carotene violaxanthin into zeaxanthin which loses the energy as heat (Taiz and Zeiger 2010). Toward this end, the effects of nanoTiO_2 (rutile) on the aging of spinach chloroplast under light were studied (Hong et al. 2005a), and the results showed that when the chloroplasts were illuminated for relatively short periods with 500 μmol cm^{-2} min^{-1} light intensity, oxygen evolution rate rapidly increased; when the chloroplasts were treated for longer periods with similar light intensity, the rate gradually decreased. When spinach was treated with 0.25% nano-TiO_2, the rate of oxygen evolution in chloroplasts with different illumination times (1, 5, 10, 20, 30, and 40 min) was higher than that of the control. It suggested that nanoTiO_2 treatment could protect chloroplasts from aging due to longtime illumination. The results also indicated that nanoTiO_2 treatment could significantly increase the activities of SOD, CAT, and POD, decrease accumulation of reactive oxygen free radicals and the level of MDA, and maintain the stability of membrane structure of chloroplasts under light. Hong et al. (2005b) extended their studies on the effects of nanoTiO_2 (rutile) on the photochemical reaction of chloroplasts of spinach and demonstrated that when spinach was treated with 0.25% nanoTiO_2, the Hill reaction such as the reduction rate of Fe-cytochrome and the rate of oxygen evolution of chloroplasts was accelerated, and noncyclic photophosphorylation (nc-PSP) activity of chloroplasts was higher than cyclic photophosphorylation (c-PSP) activity; the chloroplast coupling was improved, and activities of Mg^{2+}-ATPase and chloroplast coupling factor I (CF_1)-ATPase on thylakoid membranes were activated. These findings suggest that the promotion of photosynthesis by nanoTiO_2 might be related to activation of photochemical reaction of the chloroplasts. On the whole, very little information is available on the effects of NPs on photosynthesis, the sole source of chemical energy for living organisms on the Earth, under long-term illumination with a range of high and low levels of irradiance for different agricultural crops. This is a productive area of basic research which might prove beneficial in enhancing crop yields, especially under low-light stress conditions often resulting from mutual shading of plants (Li et al. 2014).

18.2.8 Post-harvest Stress

The long-distance commercial shipping and handling of horticultural commodities are subjected to various post-harvest stresses. Dark stress, among them, is known to suppress chl content, photosynthesis, and antioxidant enzymes' acitivities, to increase ethylene production and ROS generation and induce membrane damage (Prochazkova and Wilhelmova 2007). These changes in the cellular system result in senescence and abscission that affect the shelf life and commercial value of plants and plant products. Post-harvest stress in horticultural products is attributed to increased water loss, respiration, oxidative stress, and lipid peroxidation, which affect the weight and nutritional value of the commodities concerned (Ouzounidou and Gaitis 2011). Although several approaches have been adopted to counteract these stresses, recent involvement of NMs in modulating the physiological and biochemical processes of plants has gained special attention of experts. Application of AgNPs suppresses abscission of flowers and flower buds, as observed in *Alstroemeria* and *Dendrobium* species (Wagstaff et al. 2005; Uthaichay et al. 2007); AgNPs are more promising in alleviating dark stress than the routine Ag salts. Treatment with CuNPs and AgNPs also improved shelf life of parsley leaves and longevity of cut flowers of chrysanthemum, respectively (Ouzounidou and Gaitis 2011; Kazemipour et al. 2013). Alleviating effect of AgNPs has also been reported with respect to alleviation of the dark stress-induced oxidative stress, and the consequent increase in the longevity of petals due to AgNP treatment has been reported in *Pelargonium zonale* (Hatami and Ghorbanpour 2013, 2014). These authors also observed decreased petal abscission in geranium cultivars treated with AgNPs and thidiazuron during storage in the dark (Table 18.1).

18.2.9 Pollutant Stress

Rapid industrialization and urbanization in the recent past have significantly contributed to the man-made pollution of air, land, and water. Air pollutants include O_3, SO_2, NO, NO_2, NH_3, CFCs, peroxyacylnitrate (PAN), and volatile organic compounds (VOC) apart from high concentration of CO_2 (Iqbal et al. 2000), whereas heavy metals such as As, Cd, Cr, Hg, Pb, etc., in addition to Na, Cl, SO_4, CO_3, $HCO_{3,}$ and NO_3 ions, are the major land and water pollutants (Umar et al. 2005). Industrial solid waste products and effluents mostly consisting of the abovementioned toxic heavy metals and other chemical ions contaminate the food chain also. Detoxification or remediation of harmful pollutants using synthetic clay nanomineral is quite common (Prasad et al. 2014). The water to be filtered is percolated through a column of hydrotalcite (synthetic clay mineral), which can also be coupled with leaching through porous pots or filter candles (Gilman 2006). Zinc oxide NPs can be used to remove arsenic, using a point-of-source purification device. Nanoscale zero-valent iron is the most widely used NM that could be deployed to remediate pollutants in soil or groundwater (Chibuike and Obiora 2014). Metal toxicity often suppresses enzyme activities, disrupts uptake of essential elements causing deficiency symptoms (Capuana 2011), and generates ROS leading to oxidative stress coupled with denaturation of cell structure, biomembrane, and macromolecules (Rascio and Navari-Izzo 2011; Sharma et al. 2012a). However, plants evolve a diverse range of defense systems such as biophysical barriers serving as the first line of defense against metal stress. Further they accumulate metal chelates, organic acids, and polyphosphates, which restrict the uptake and promote endogenous sequestration of metals and the activation of antioxidant defense system to scavenge ROS. The timely and target-oriented activation of these defense systems is crucial to counter the ill-effects of metal stress.

Engineered NMs are highly effective in alleviating the metal-induced toxicity of plants (Gunjan et al. 2014; Siddiqi and Husen 2017). As NPs are smaller in size with large surface area, they easily penetrate into the contamination zone and show strong affinity to metals. Availability of Cu and Pb may be reduced due to metal binding to quantum dots (QDs) with the cell wall acting as an additional barrier (Worms et al. 2012). In case the metals pass the biophysical barriers and enter the cell, plants build up resistance to counteract their harmful effects by accumulating biomolecules and nutrients and activating their defense systems. The role of nano-TiO_2, among several NPs, has been most extensively studied. TiO_2NPs restricted Cd uptake in pea seedlings, whereas SiNPs protected them against Cr phytotoxicity (Tripathi et al. 2015). Exposure of cowpea seeds to gold (Au) ion stress provides reduction of Au^{3+} to non-/less toxic AuNPs by phenolics released by the seed coat of germinating seeds (Shabnam et al. 2014, Table 18.1). Other NMs that could be used in remediation include nanoscale zeolites, metal oxides, carbon nanotubes and fibers, and various noble metals (mainly as bimetallic NPs). Titanium dioxide nanoparticle filters can be used to remove organic particles and pesticides, for example, dichlorodiphenyltrichloroethane (DDT), endosulfan, malathion, and chlorpyrifos from water. A variety of nanoparticle filters have been used in remediation of waste sites in the developed countries (Karn et al. 2009).

Thus, NMs are useful in getting the environment and ecosystems freed from the clutches of pollutant stress and protecting plants from the ill-effects of other abiotic stresses. The mode and mechanism of NPs action within the cell to make the cellular machinery more effective and render them less toxic to plants facing abiotic stresses is depicted in Fig. 18.1.

18.2.10 Stress Caused by NMs and Their Impact on Ecosystems

With the rapid advancement in nanotechnology, release of nanoscale materials into the environment is inevitable. This may negatively influence the functioning of the ecosystems. Many manufactured NPs contain heavy metals, which can cause soil and water contamination (Sect. 18.2.9). Proteomic techniques have contributed substantially in understanding the molecular mechanisms of plant responses against

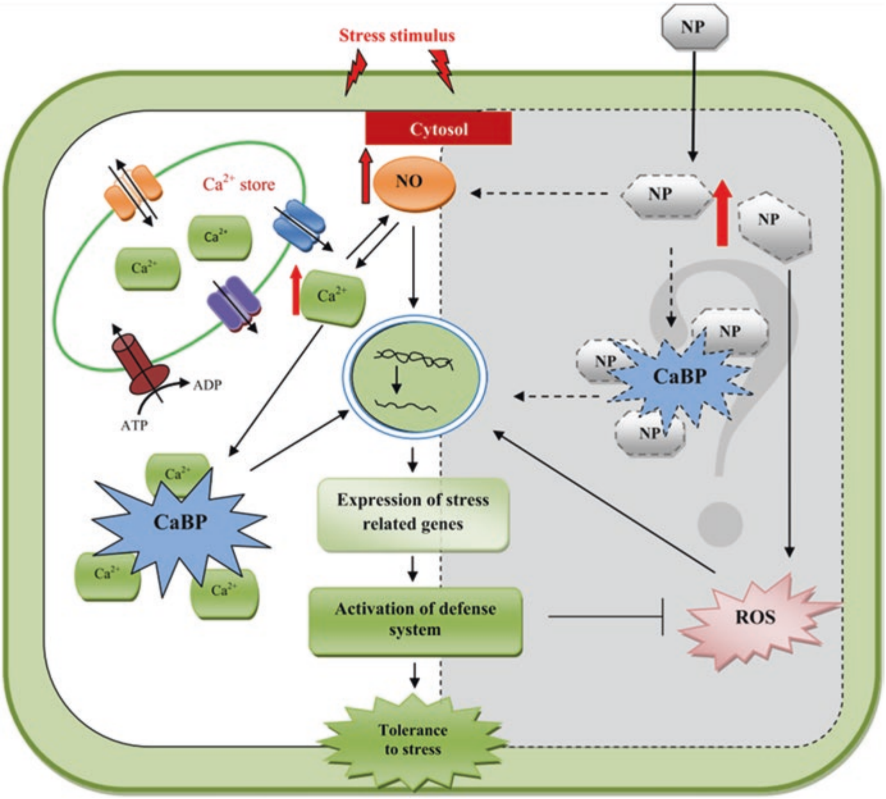

Fig. 18.1 Depiction of the role of NPs in cellular defense against abiotic stress. Gray half of the diagram at right-hand side shows the possible mechanism of NPs action. Red arrows indicate increase, whereas solid arrows and dashed arrows show established pathway and possible pathway, respectively. Perception of stress stimulus elevates the cytosolic Ca^{2+} concentration ($[Ca^{2+}]_{cyt}$), which is sensed by Ca^{2+}-binding protein (CaBP). Binding of Ca^{2+} activates CaBP that directly binds to the promoters of specific genes and induces or represses their expression, causing plant tolerance to the stress. The NPs cause overexpression of CaBPs and bind to CaBPs that trigger downstream signaling and finally the expression of stress-related genes and activation of plant's defense system. Similar to $[Ca^{2+}]_{cyt}$, NPs also induce nitric oxide (NO) synthesis that acts as stress-signaling molecule and induces expression of stress-related genes that activate the defense system and ultimately generate tolerance to stress. Optimum concentration of NPs also maintains reactive oxygen species (ROS), via regulating antioxidant defense system, at the level sufficient enough for stress signaling leading to activation of plant's defense system and development of tolerance to stress. (Source: Khan et al. 2016 with slight modification)

various stresses by providing a link between gene expression and cell metabolism (Hossain et al. 2015). Because TiO_2 generates reactive oxygen species (ROS) when exposed to ultraviolet radiation (UV-R), nanoparticulate TiO_2 has been used in antibacterial coatings and wastewater disinfection and has been investigated as an anticancer agent (Charpentier et al. 2012). In vivo tests of TiO_2 toxicity with aquatic organisms have typically shown low toxicity, though results across studies have been variable. No work has demonstrated that photoactivity causes environmental toxicity of TiO_2 under natural levels of UV-R. Relatively low levels of ultraviolet light, consistent with those found in nature, can induce toxicity of TiO_2NPs to marine phytoplankton, the most important primary producers on the Earth. No effect of TiO_2 on phytoplankton was found in treatments where UV light was blocked. Under low-intensity UV-R, ROS in seawater increased with increasing nanoTiO_2 concentration. These increases may lead to increased oxidative stress in seawater contaminated by TiO_2, and cause decreased resiliency of marine ecosystems (Miller et al. 2012). Further, the solar UV radiation impacts on toxicity of ZnONPs through photocatalytic ROS generation and photo-induced dissolution. Toxicity of ZnONPs to *Daphnia magna* was examined by Ma et al. (2014) who found enhanced ZnONPs toxicity under simulated solar UV radiation, being parallel to those of photocatalytic ROS generation and increased particle dissolution. These findings demonstrate the importance of considering the environmental solar UV radiation when assessing ZnO and other NPs' toxicity and risk in the aquatic systems.

A comprehensive study of the uptake and toxic effects of CuONPs and Cu^{2+} ions, alone and in combination with UV radiation, was undertaken using the aquatic macrophyte, *Elodea nuttallii,* as the test plant (Regier et al. 2015). Its growth was inhibited when treated with $CuSO_4$ or CuONPs with a lower amount of accumulated copper in $CuSO_4$-treated plants than in those treated with CuONPs. The difference has been attributed to the solubility of Cu^{2+} in CuO nanoparticle medium. Surprisingly, the relation between accumulated Cu and dissolved Cu^{2+} was higher in plants exposed to 256 $\mu g\ L^{-1}$ Cu^{2+} than those exposed to 10 $mg\ L^{-1}$ CuONPs containing nearly 2 $mg\ L^{-1}$ dissolved Cu, as the formation of large agglomerates prevents the dissolution of Cu. Interestingly, Cu accumulation was enhanced under UV radiation in shoots of *Pisum sativum* after 4 h, but there was no direct evidence of enhanced solubility of Cu^{2+} in CuO nanoparticle suspension (Agrawal and Mishra 2009). Rai et al. (1995) observed an altered membrane permeability due to lipid peroxidation in cell membranes of UV-exposed cells of cyanobacteria. In plants, under UV radiation, photosynthetic capacity is strongly reduced. When higher quantities of Cu accumulate in plants, the response of oxidative stress-related enzymes (peroxidase and superoxide dismutase) is also high. Therefore, phototoxicity must be considered while evaluating the environmental impacts of NMs, as many of them are photoactive.

The cells in higher plants act against the toxic effects of NPs, and in doing so, certain metals are absorbed, and certain others are precipitated. Phytotoxicity of commercial CuO (<50 nm) and ZnNPs (<100 nm) against sand-grown wheat (*T. aestivum*) has been investigated (Watson et al. 2014). Oxidative stress in the nanoparticle-treated plants was reflected by an increase in lipid peroxidation and oxidized glutathione and higher peroxidase and catalase activities in roots. Also, CuONPs have been shown to induce DNA damage in plants (Atha et al. 2012). Growth inhibition in radish (*Raphanus sativus*), perennial ryegrass (*Lolium perenne*), and annual ryegrass (*Lolium rigidum*) under laboratory conditions has been reported. Germination of radish seeds in the presence of CuONPs induces substantial accumulation of mutagenic DNA lesions. Radish and similar other plants produce oxygen-derived species (O· −2, H_2O_2,·OH) during germination (Schopfer et al. 2001). H_2O_2 enhances seed germination but, in the presence of peroxidase or transition metal ions, such as iron or copper, produces an excess of ·OH via the Fenton reaction (Sharma et al. 2012a). It is therefore suggested that copper ions produced from CuONPs may catalyze the formation of ·OH which probably inhibited radish root growth to the extent of 79%, which is much more than the effect of Cu^{2+} ions alone.

Morales-Diaz et al. (2017) studied the application of nanoelements in plant nutrition and its impact on ecosystems and consumers. As discussed earlier, nanofertilizers are more effective and efficient than traditional fertilizers due to their impact on crop nutritional quality and stress tolerance in plants. However, there are virtually no studies on the potential environmental impact of NMs when used in agriculture. Such studies are highly desirable because NPs or NMs can be transferred to ecosystems by various pathways where they can cause toxicity to organisms, affecting the biodiversity in ecosystems and also causing risks to human health.

18.3 Conclusion

NPs, being small in size and having large surface area, penetrate into plant cells easily, and their absorption and targeted delivery to the sites and substances are also facilitated in relatively shorter period of time, as compared to their standard or bulk chemical forms. Several have been used for mitigating the harmful effects of various abiotic stresses on fruits, flowers, and vegetables. Some of the frequently used NMs like TiO_2, SiO_2, AgNPs, etc. have been found to have a multitude of beneficial effects, compared to their bulk chemical forms, on the expression of morphological, physiological, and biochemical attributes and enhance crop yields under a variety of abiotic stresses. Their application could have a positive impact on seed germination, plant growth, quality and quantity of yield, chlorophyll and caretonoid contents, photosynthesis rate, expression of Rubisco- and chlorophyll-binding protein genes, stomatal opening, WUE, ability to dissipate excess light energy in the form of heat, etc., thus causing less oxidative damage and enhancing tolerance to abiotic stresses in a range of crops including cereals, pulses, oil seeds, vegetables, and various ornamental, medicinal, and fruit plants.

On the contrary, NMs may generate ROS and cause several toxic effects on plants. However, the enhanced ROS level brought about by NMs could be associated with the amplification of a stress signal that perhaps activates defense systems of plants more effeciently. Information available on the mode and mechanism of action of NMs is still insufficient and inconsistent. It seems, however, that induction of an array of signaling molecules triggers gene expression leading to de novo synthesis of new proteins and enzymes, thus enhancing the tolerance of plants to abiotic stresses, resulting in optimum growth and yield of crop plants (Fig. 18.1). It may be concluded that NMs alleviate the abiotic stress-caused damage through activating the defense system in plants.

So far, there have not been enough studies at field level to allow commercialization of the large-scale use of NMs for enhancing food production. It is essential to understand plant-NP interaction and optimization of NP size and concentration before their practical applications can be taken to farmers' fields. Moreover, their possible negative impact on natural environment and crops should also be assessed and minimized. The prospective research on NM-plant interaction must address especially the effect of hormones in combination with various NPs, seed priming with penetrable (NPs of inorganic salt) and non-penetrable solutes (NPs of polyethylene glycol of higher molecular wt.) and hormones, DNA photolyase, a unique class of flavoenzymes that use blue light to catalyze repair of UV-induced damage to plant DNA, and the effect of soil acidity on the efficiency of NMs. While nanochemical pesticides are already in use, other applications that include mainly the fine-tuning and more precise micromanagement of problem soils, the more efficient and targeted use of inputs in the wake of climate change and global warming, and new toxin formulations for pest control are yet to come in full swing. Also, it would be interesting to know at which point(s) of metabolic pathways the NPs interact with abiotic stresses for enhancing the stress tolerance of plants.

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