Chapter 4
Exploring Nanotechnology to Reduce Stress: Mechanism of Nanomaterial-Mediated Alleviation

Sidra tul Muntha, Mohammad Faizan, Saba Mehreen, and Shareen

Abstract Global food production does not meet the demand of ever increasing population which is expected to reach around 9 billion by the first half of twenty-first century. Plants being sessile organisms are under detrimental effects of environment as well as plant diseases. Abiotic stresses including drought, heat, flooding, salinity and frost are major factors, adversely affect plant growth that may minimize the productivity to 70%. These stresses lead to morphological, physiological, biochemical and molecular changes in plants resulting crop loss. Due to unavailability of adequate arable land and severe environmental issues, there is an immediate need of novel avenues of research to meet global food supply. Progress in plant sciences and genetics has revealed new technologies to develop stress tolerant plants and investigate the better ways to grow plants under detrimental conditions. Nanotechnology comprises nanoparticles (NP) gained high impulse to mitigate the limitations related to abiotic stresses resulting high plant growth. Nanoparticles are metal or metal oxide molecules synthesize by physiochemical or biological approaches, with small size of 1–100 nm dimensions. Nanoparticles due to their exclusive properties of small size, high reaction potential, increased surface area, tensile pore width and divergent morphology opens new doors in agriculture research. Hence, the current chapter will focus on the role of nanoparticles against plant environmental challenges and how can nanoparticles be used in growth improvement of plants under stressed conditions.

S. t. Muntha (✉)
Laboratory of Germplasm Innovation and Molecular Breeding, College of Agriculture and Biotechnology, Zhejiang University, Hangzhou, China

M. Faizan
Collaborative Innovation Center of Sustainable Forestry in Southern China, College of Forest Science, Nanjing University, Nanjing, China

S. Mehreen
Department of Chemistry, Quaid-i-Azam University, Islamabad, Pakistan

Shareen
Department of Agricultural Microbiology, Faculty of Agriculture, Aligarh Munslim University, Aligarh, India

M. Faizan et al. (eds.), *Sustainable Agriculture Reviews 53*, Sustainable Agriculture Reviews 53, https://doi.org/10.1007/978-3-030-86876-5_4

Keywords Abiotic stress · Nanotechnology · Nanoparticles

4.1 Introduction

4.1.1 Cascade of Signaling Behind Plant-NPs Interaction and Stress Tolerance

Plants have a complex system for defense against environmental stresses, yet the mechanism of perception of stimulus to the transduction and activation of responsive units against stimulant before stress prompted destruction is decisive to cellular machinery. As per available information about plant-NPs interaction against abiotic stresses, it is obvious that synthesis of ROS is vital phenomenon in plant cell against environmental stimuli (Khan et al. 2017). Although the mechanism of action of plants by the application of NPs is not well understood, however the omic approaches help to conceive the signaling pathways in plant cells.

Signaling molecules predominantly activate a defense mechanism which triggers molecular network to encounter a particular challenge. Calcium ions (Ca^{2+}) being secondary messenger molecules act as vital components in signal transduction. Upon receiving a stress signal Ca^{2+} start transport from stores to cytosol via Ca2+ gated channels and ultimately increase the cytoplasmic level of secondary messenger, which is identified my calcium binding proteins (CaBPs) that start a cascade of reaction downstream to alter the gene expression of plant against that particular stress (Khan et al. 2014a, b; Tuteja and Mahajan 2007). It has been evident that nitric oxide (NO) promotes the cytosolic Ca2+ in cell upon the onset of environmental stress and pathogen attack (Khan et al. 2012a, b; Lamotte et al. 2006) and inevitably Ca2+ promote the NO synthesis (Del Rio et al. 2004; Corpas et al. 2004).

Proteomic studies on *Oryza sativa* roots have declared the role of Ag NPs-responsive proteins in oxidative stress pathway, second messenger (Ca2+) regulation, signal transduction and expression and post transcription changes, cellular growth and programmed cell death (Mirzajani et al. 2014). The study is a prove of previous work by Goyer (1995) who anticipated the Ag-NPs role in cellular metabolism by binding Ca2+ gated channels and Ca/Na pumps (Goyer 1995). It has been further observed that C60 nano-crystals prompted the functional regulation of Ca2+/calmodulin- dependent protein kinase II (CaMKII) (Miao et al. 2014). Further studies on Arabidopsis thaliana investigated the overexpressed Ca2+ dependent protein (CML45) and CaMPK23 caused by the activity of cadmium sulfide QDs (Marmiroli et al. 2015). These overexpressed proteins play a pivotal role in stress resistance in various plants (Delk et al. 2005; Xu et al. 2011; Boudsocq and Sheen 2013) however Ca2+ in the proteins can be switched with NPs (Cheung 1980).

NPs have been reported to involve in increased nitrate reductase activity that is key enzyme in nitric oxide (NO) biosynthesis to regulate plant immune system (Carpenter et al. 2012; Shahrokh et al. 2014; Chandra et al. 2015). On the other hand

NO interacts NP-induced toxicity mechanism and antioxidant genes to increase their transcript level and decrease ROS and lipid degradation (Chen et al. 2015). NPs are involved in upregulated expression of genes related to stress responsive and cell growth and development (Almutairi 2016; Khodakovskaya et al. 2011a, b, 2012).

The studies on NPs-plant interaction have exhibited the increased generation of ROS that play not only signaling molecules in plant but also increase phytotoxicity (Oukarroum et al. 2012; Qi et al. 2013; Ma et al. 2010; Van Hoecke et al. 2008; Simon et al. 2013; Wei and Wang 2013).

The dual action of NPs needs a comprehensive study to evaluate how NPs protect plants against ROS while acting as inducers of oxidative stress at the same time. Genomics and proteomics approaches aid to existing knowledge by investigating the role of NPs in plants under environmental stress. A proteomic study using Ag NPs and AgNO3 in *Eruca sativa* demonstrated the altered level of proteins involved in redox regulation and metabolism of sulfur as a result of physiochemical nature of NPs (Vannini et al. 2013). A differential expression of genes realted to abiotic stress has been observed in Arabidopsis thaliana by the application of Ag NPs and Ag+ covered with polyvinylpyrrolidone (PVP) (Kaveh et al. 2013). The study concluded that the Ag NPs induced stress is partially due to Ag+ toxicity and partially it is the consequence of nanoparticle-specific effects.

Expression of miRNA in response to NPs paves another way to understand the mechanism of action of NPs against environment in plants. Increased expression of miRNA in Tobacco plant on application of optimum concentration of TiO2 and Al2O3 was demonstrated against metal stress however increased level of NPs negatively affected the growth and development of plant (Frazier et al. 2014; Burklew et al. 2012). AHA2 (gene involved in stomatal opening) in Arabidopsis is upregulated by the treatment of zero valent NP, which cause tolerance to drought stress (Kim et al. 2015). Moreover studies conducted on the application of TiO2 and MWCNTs on Arabidopsis showed the downregulated gene expression involved in development and phosphate deficiency (García-Sanchez et al. 2015).

4.2 Nanoparticles and Abiotic Stress Resistance

4.2.1 Salinity Stress

Salinity, due to the deposition of anions (chloride and sulfate) or cations (primarily sodium but occasionally of calcium and magnesium) in arid to coastal areas soil, is one of the major abiotic stresses limiting food production. Over 20% of agricultural land is affected by salinity and the limit is ever increasing. Salinity is detrimental as it causes reduction in growth and development by influencing physiological, biochemical and molecular pathways in plants. It not only shifts the osmotic stress but also ionic imbalance in plants due to high accumulation of salts. Due to Osmotic stress plants' nutrients and water uptake is decreased while ionic stress engenders decreased proportion of K+/Na+ (Khan et al. 2012) and over production of ROS that affects molecular mechanisms in plants leading to electrolytes splits and damages metabolic pathways such as protein and lipid metabolism, and photosynthesis in cytol (Sharma et al. 2012; Ismail et al. 2014; Khan et al. 2010).

Current advancement in nanotechnology highlighted that the NP of Silica (SiO2) the second most abundant natural element and titanium dioxide (TiO2) contributed much to enhance vegetative growth and overall crop production under salinity. The tolerance is attributed to silicon NP that might better absorbed by maize roots than its micro or bulk counterparts Suriyaprabha et al. (2012) and form a thin layer in cell wall to enhance resistance against stress to maintain yield (Latef et al. 2018; Derosa et al. 2010).

The stressed tomato and squash plants exhibited better seed germination, the anti-oxidative enzyme activities, photosynthetic rate and leaf water absorption rate when treated with Si NP (Haghighi and Pourkhaloee 2013).

Na+ ion toxicity led a reduced yield in maize; however SiO2NPs alleviated the plant response under salinity stress by reducing Na+ ion concentration in cell wall through lower absorption of the ions (Gao et al. 2006a, b). Similar studies were conducted in tomato plants that lead to better plant growth (Savvasd et al. 2009). A remarkable elevation in germination and seedling growth was observed in *Lens culinaris* under salinity stress by application of Si NP (Sabaghnia and Janmohammadi 2014). A promising effect of Si nano fertilizer was highlighted by Kalteh et al. (2014) in *Ocimum basilicum*, where increased chlorophyll content, proline level and other physiological traits were recorded under salinity stress. Under high concentration of salt Squash (Cucurbita pepo) showed a lethal reduction in roots and shoots growth, vigor length and yield of plant (Siddiqui et al. 2014). Use of SiO2 NP ameliorated the traits by decreasing the electrolyte leakage and level of hydrogen peroxide (H2O2), malondialdehyde (MDA) and chlorophyll degradation.

Fe2 NPs proved to be auspicious addition in Nano biotechnology. The application revealed that it positively affected foliar fresh and dry weights and mineral contents of peppermint (Mentha piperita) however it didn't show any effect on sodium content. Maximum activities of anti- oxidant enzymes were recorded under salinity stress but masked by the application of Fe_2O_3 NP (Askary et al. 2017). Torabian et al. (2016) have described high level of chlorophyll content, photosynthesis rate, CO2 concentration, osmotic regulation and reduced Na content in *Helianthus annuus* by the use of nanoZnO under salt stress.

Contemporary studies on the significance of chitosan NPs (maize and tomato), multi-walled carbon nanotubes (broccoli) and silver NPs (wheat) have demonstrated their mitigating effect on salinity (Bruna et al. 2016; Hernandez-Hernandez et al. 2018; Martinez-Ballesta et al. 2016; Abou-Zeid and Ismail 2018; Mohamed et al. 2017).

4.2.2 Drought Stress

Water is the vital component for life on the planet and its deficiency leads to severe conditions (Drought stress) in living organisms including plants. Drought is most commonly occurring environmental stress which affects almost 45% of global agriculture area (Dos Reis et al. 2016). Water scarcity in plants leads to decrease in water potential and turgor of cell, which increase the level of molecules in the cytol and extracellular surfaces. Later, decreased cell size elicits the retarded growth and reproduction failure in plants. Ultimately cell starts to accumulate abscisic acid (ABA) and proline (Osmotic regulator), which leads to excessive production of ROS, glutathione and ascorbate (radical scavengers) which exasperates the severity (Hussain et al. 2019; Ahmad et al. 2017). Drought not only affects cell water potential but it also influences the stomatal closure, gaseous and ionic exchange, photosynthesis and transpiration rate (Schulze et al. 2019).

During the past decade tremendous efforts have been made to counter the water induced stress in plants using NP. The nanoparticles of TiO (Rutile) exhibited intense effect by exogenous application in spinach plant. The morphological, biochemical and physiological changes occurred in plant resulted in high rubisco activase activity, chlorophyll synthesis and promoted photosynthesis which leads to increase in dry weight of plant (Gao et al. 2008). Foliar application of TiO2 NP might cause an increase photosynthesis rate which augmented the overall seed yield in cow pea (Vigna unguiculata L.) (Owolade et al. 2008). As the effect of TiO2 NP varies among the species and with different applied environments, 0.02% of foliar spray of TiO2 NP enhanced the vigor of wheat plants by improving yield traits such as plant height, ear number and weight, 1000-kernal weight and seeds/plant, harvest index, and starch and gluten content of plant under water scarcity (Jaberzadeh et al. 2013). Dragonhead (Dracocephalum moldavica) plants treated with TiO2 NP (10 ppm) exhibited more proline level with less H2O2 and MAD content as compared to control plant under water deficit state (Mohammadi et al. 2014a, b). It was established that drought-prompted mutilations in plants like membrane damage and oxidative stress can be mitigated by optimal concentrations of TiO2 NPs. Silica NPs protects cell wall during water deficit conditions by reducing cell wall permeability of leaves resulting low lipid peroxidation (Zhu et al. 2004). SiO2 has proved to increase proline content with addition of escalated CAT and POD activities in plants under stress vs. controlled plants of tomato (Siddiqui and Al-Whaibi 2014), faba bean (Qados and Moftah 2015; Qados 2015) and alfalfa (Cakmak et al. 1996). Reative water content (RWC), water use proficiency and turgor pressure in leaf cells are the physio-chemical processes effected by Silica NPs that directly influence xylum transport plant. At different level of water deficiencies the response of Silica NPs varies in Hawthorns (Crataegus sp.). Enhanced tolerance was observed in plant against drought at different concentrations of NPs by positively effecting physio-biochemical processes (chlorophyll, carotenoid, carbohydrateand proline contents, and increased photosynthesis rate, MDA, (RWC) and membrane electrolyte leakage (ELI)) within the cell (Ashkavand et al. 2015).Silicon NP posed a positive effect on two sorghum cultivars with relatively different drought vulnerability irrespective of level of stress by maintaining photosynthesis rate and improved root growth (Hattori et al. 2005).

ZnO and CuO NPs act as fertilizers as these are source of Zn and Cu to plants. At different doses the NPs react on different parts of roots as Zn NPs causes increased lateral roots whereas Cu NPs induce proliferated and elongated root hair close to root tip in *Triticum aestivum* seedlings under drought (Yang et al. 2017). The short root length may reduce access to water. CuO possibly change the water supply thus shrink the cell wall in Arabidopsis and mustard thus increase lignification. The altered water transport may also be the reason of Cu-pectin association in cell wall (Nair and Chung 2017). The continuous drought stress elevates proline and anthrocynin in cell. The high level of ROS during the stress which leads to increased ABA may cause differential gene expression for drought tolerance (Dimkpa et al. 2012). Silver nanoparticles (AgNPs) are one of the most abundant NPs in use to mitigate abiotic as well as biotic stresses. AgNPs provided an inhibitory role against microorganisms (Beyene et al. 2017). In water deficit lentil plants, application AgNPs resulted in high germination rate and high growth and production parameters (Hojjat and Ganjali 2016).

Sodium nitroprusside (SN) along with Multi walled carbon nanotubes (MWCNTs) provide tolerance in *Hordeum vulgare* against water and salt stress by not only improving water absorption capacity of seed as well as seedling water concentration (Karami and Sepehri 2017). Increased antioxidants and high germination rate was recorded in *Hordeum vulgare*, *Glycine max* and *Zea mays* using MWCNTs (Lahiani et al. 2013; Liu et al. 2016). High root and shoot growth in *Triticum aestivum* suggested the drought tolerance though MWCNTs (Srivastava and Rao 2014).cerium oxide (CeO2) provided another source of NP to enhance crop production under water defict condition in Glycine max (Cao et al. 2018). In addition the *in vitro* use of iron (FeO2) NPs alongside salicylic acid manifested to be an effective tool against water deficiency in strawberry at pre transplantation to soil (Mozafari et al. 2018).

A comprehensive knowledge of metabolic and molecular mechanisms of plant through NPs to ameliorate abiotic stress will pave a way to develop stress resistant crops (Singh et al. 2017). Syntheses of dehydrins in susceptible plants, by application of NPs cause mitigation of drought stress (Lopez et al. 2003). Production of compatible molecules like proline, betaine, etc., is initiated by dehydrins which in turn maintains cell integrity and water deficiency (Paleg et al. 1984). Once it is known that at which stage of metabolic pathways NPs counter abiotic stresses, the massive increase in their use will be possible.

4.2.3 Temperature Stress

Temperature is vital factor which determines plant growth, development and crop yield. It is characterized by the ideal point beyond that plant growth is effected badly, though the optimum temperature varies between species and genera. Temperature stress includes high temperature stress (above the threshold temperature) and low temperature or chilling stress (very low than ideal) for a certain time span to cause a permanent damage to plant (Wahid 2007).

4.2.3.1 Heat Stress

Thermal stress implies the increase in temperature beyond the optimum level for a longer time span that causes permanent loss to development and vegetative growth (Wahid 2007). The stress negatively affects growth and yield of crop globally. High temperature elevates the synthesis of ROS and cause oxidative imbalance which leads to breakdown of organic molecules (proteins), degradation of lipids and escape of ions in cell membrane (Karuppanapandian et al. 2011; Moller et al. 2007; Savicka and Skute 2010;) that may affect chlorophyll content ultimately photosynthesis (Prasad et al. 2011).

Selenium (Se) nanoparticles provide an alleviated response of high temperature when used in low concentration by modulation of hydration potential and chlorophyll content (Haghighi et al. 2014). High level of Se is associated with oxidative stress while the low concentration is considered to be responsible for antioxidative response (Hasanuzzaman et al. 2014; Hartikainen et al. 2000). Heat shock proteins (molecular chaperones) are produced by plant during high temperature stress which along with other proteins cause stress tolerance by retaining their stability under challenging condition (Wahid et al. 2007). It has been reported that MWCNTs are involved in up regulation of gene expression associated with stress tolerance including HSP 90 (Khodakovskaya et al. 2011a, b). Furthermore a study in susceptible corn plant confirmed the role of heat shock proteins by application of cerium oxide (CeO2) NPs that lead to the higher synthesis of H2O2 and high expression of HSP70 (Zhao et al. 2012). TiO2 NPs also play role in heat stress by enhanced photosynthesis by regulation of stomata opening in plant leaves (Qi et al. 2013).

4.2.3.2 Cold Stress

When plants are exposed to the temperature very lower than their optimum temperature, the cell and tissues are damaged due to physiological and morphological changes, the phenomenon is known as Cold stress (Hasanuzzaman et al. 2013). Electrolytes imbalance and degradation in cell membrane are the adversities related to cold stress which eventually leads to decreased germination, reduced growth and crop production (Welti et al. 2002; Suzuki et al. 2008). Nevertheless, sensitivity to the stress may differs inter species and inter genera with tolerant plants showing least membrane damage than the susceptible (Maali Amiri et al. 2010; Heidarvand et al. 2011). Despite plants vulnerability to stress, NP like TiO2NPs possesses the potential to mitigate the chilling effect by reducing membrane degeneration and maintain electrolyte imbalance (Mohammadi et al. 2013). However its accumulation ratio is more in sensitive (thinner membrane layer and wide stomata) to tolerant genotype (Giacomo et al. 2010). Photosynthesis is essential process of plant that is affected by the chilling stress. Plants subjected to cold result in photosystem damage by decreasing in chlorophyll content, transpiration rate, deterioration in photosystem enzymes (Liu et al. 2012; Yordanova and Popova 2007).

Ameliorations of NPs on photosystem have been inferred by elevated synthesis of Rubisco (photosystem enzymes) (Gao et al. 2006a, b), chlorophyll capacity to absorb light, (Ze et al. 2011), rate of electron movement and and suppressed ROS synthesis in chloroplast (Giraldo et al. 2014). TiO2 NPs manifested the increased expression level in genes associated with Rubisco and chlorophyll binding proteins (Hasanpour et al. 2015), improved activities of antioxidant enzyme such as CAT, APX and SOD (Mohammadi et al. 2014a, b), finally increase resistance against chilling stress.

When plants are subjected to cold stress the transcript level of antioxidant genes like MeAPX2 and MeCu/ ZnSOD is up regulated, dehydroascorbate reductase, monodehydroascorbate reductase and glutathione reductase activities are elevated. As a result ROS scavenging which leads to repressed oxidative stress factors (lipid peroxidation, pigment degradation and H2O2 production) ultimately develop tolerance (Xu et al. 2014). While the application of NPs on Chiling stress have been reported with enhanced growth and physiochemical processes in plants under cold (Azimi et al. 2014; Hawrylak-Nowak et al. 2010; Kohan-Baghkheirati and Geisler-Lee 2015; Haghighi et al. 2014).

4.2.4 Heavy Metals Stress

Metal with high molecular weight and toxic at very low concentrations are termed as heavy metals. Metal stress has become one of the alarming environmental issues plants are facing worldwide that cause toxicity and serious crop loss (Chibuike and Obiora 2014; Rahimi et al. 2012). Heavy metal causes reduction in plant growth by disruption of important plant activities like reduced up take of vital elements, repressed enzyme activities which results into deprivation of important element (Capuana 2011). Plant Growth medium augmented with metals accelerates ROS synthesis, resulting in to oxidative stress in plant cell by disruption of cell structure including organic molecules and plasma membrane (Sharma et al. 2012; Rascio and Navari-Izzo 2011).

To combat heavy metal stress plant evolve a special defense mechanism by producing metal chelate, polyphosphates and organic acids which restrain the uptake of metal ions regulation of anti-oxidative pathways (CAT, POD and SOD)and ultimately ROS scavenging. Although plant defense mechanism is pivotal to counter heavy metals, artificially induced NPs play key role in reducing heavy metal phyto-toxicity (Gunjan et al. 2014; Tripathi et al. 2015).

ZnO NPs along with other micronutrients (Zn, Cu, Mn) are reported to play crucial response to reduce efflux of cadmium (Cd) in plants (Baybordi 2005; Venkatachalam et al. 2017). River tamarind (*Leucaena leucocephala*) possesses Cd and Pb phytotoxicity, which can be ameliorated by the foliar spray of ZnO NPs. The NPs are responsible for elevated soluble proteins, chlorophyll and carotenoid content in leaves, and decrease in oxidative damaged to lipids membrane (Venkatachalam et al. 2017). The induced level of antioxidative enzymes (CAT, SOD, POD) in leaves of *L. leucocephala* and lipid perodixadation was confirmed at seedling stage. Similar effects were recorded by Si NPs application to reduce Cr toxicity through activation of anti-oxidative pathways in pea plant (Tripathi et al. 2015). Enormous studies have been conducted using TiO2 against abiotic stresses in plants. Besides mitigating effects on environmental stress, TiO2 NPs proved to limit Cadmium (Cd) phytotoxicity by augmented growth and increased energy driven pathways (Singh and Lee 2016). In addition TiO2 multiple NPs evinced positive role against heavy metal challenge in plants (Table 4.1). Li and Huang (2014) exhibited that nano- hydroxyapatite ($Ca_5(PO_4)_3$) may regulate toxicity of Cd in *Brassica chinensis.*

4.3 Conclusion and Future Perspectives

Nanoparticles minimize the damage caused by environmental stresses by activating the defense system of plants. The activated defense system is the result of high ROS activities, which exhibited the toxic effects. Taking advantage of their size NPs become permeable and modulate ion channels to promote growth and germination of plants. The large surface area helps in absorption and delivery of molecules. The exact mechanism of action of MPs is still not very well studied however the omic studies revealed that NPs mimic secondary messengers and related proteins are activated. A cascade of reactions starts that leads to altered gene expression responsible for abiotic stress tolerance and plant growth. In conclusion it is merely important to further study the exact role of NPs at molecular level to confirm whether these molecules are involved in stress tolerance or stress induction.

Table 4.1 physiochemical effects of nanoparticles in plants against various Abiotic stresses

Stress Type	NPs.	Plant Name	Family	Physiological Effects on Host	References
Salinity	SiO_2	*Zea mays*	Poaceae	Formation of thing layer in cell wall, enhance resistance	Derosa et al. (2010) and Latef et al. (2018)
		Lycopersicon esculentum	Solanaceae	Better seed germination, the anti-oxidative enzyme activities, photosynthetic rate and water absorption capacity	Haghighi and Pourkhaloee (2013)
		Lycopersicon esculentum	Solanaceae	Reduced Na + ion concentration in cell wall, lower absorption of the ions	Savvasd et al. (2009)
		Cucurbita pepo	Cucurbitaceae	Better seed germination, the anti-oxidative enzyme activities, water absorption capacity and photosynthetic rate	Haghighi and Pourkhaloee (2013)
		Zea mays	Poaceae	Reducing Na + ion concentration in cell wall, lower absorption of the ions	Gao et al. (2006a, 2006b)
		Lens culinaris	Fabaceae	Increased germination rate and seedling growth	Sabaghnia and Janmohammadi (2014)
		Ocimum basilicum	Lamiaceae	Increased chlorophyll content, proline level and physiological traits	Kalteh et al. (2014)
		Cucurbita pepo	Cucurbitaceae	Decreased the electrolyte leakage,level of H_2O_2, MDA and chlorophyll degradation	Siddiqui et al. (2014)
	Fe_2O_3 NP	*Mentha piperita*	Lamiaceae	Increased fresh and dry weights and mineral contents, masked antioxidative pathway	Askary et al. (2017)
	Fe_2O_3 + ZnO	*Moringa peregrina*	Moringaceae	Increased leaf pigments, proline, carbohydrates, biomolecules and antioxidants	Soliman et al. (2015)
	ZnO NP	*Helianthus annuus*	Asteraceae	Increased chlorophyll content, photosynthesis rate, CO_2 concentration, osmotic regulation and decreased Na content	Torabian et al. (2016)
	Chitosan (S-nitroso-MSA-CS)	*Zea mays*	Poaceae	Ameliorating deleterious effects of salinity in photosystem II activity, and increased chlorophyll content and growth even at lower doses	Oliveira et al. (2016)

Drought	TiO2 (rutile)	*Spinacia oleracea*	Amaranthaceae	Increased rubisco activase activity, chlorophyll synthesis, photosynthesis, increased dry weight	Gao et al. (2008)
		Vigna unguiculata L.	Fabaceae	Increased photosynthesis,	Owolade et al. (2008)
				Augmented overall seed yield	
		Triticum aestivum	Poaceae	Increase in plant height, ear number and weight, 1000-kernal weight and seeds/plant, harvest index, and starch and gluten content	Jaberzadeh et al. (2013)
		Dracocephalum moldavica	Lamiaceae	More proline level with less H2O2 and MAD	Mohammadi et al. (2014a, b)
				Mitigation of membrane damage and oxidative stress	
	SiO2	*Vicia faba*	Fabaceae	Increase proline content,	Qados and Moftah (2015) and Qados (2015)
				Escalated catalase (CAT) and peroxidase (POD) activities	
				Alter physio-chemical processes	
		Solanum lycopersicum	Solanaceae	Increase proline content,	Siddiqui and Al-Whaibi (2014)
				Escalated catalase (CAT) and peroxidase (POD) activities	
				Alter physio-chemical processes	
		Medicago sativa	Fabaceae	Increase proline content,	Cakmak et al. (1996)
				Escalated catalase (CAT) and peroxidase (POD) activities	
				Alter physio-chemical processes	
		Crataegus monogyna	Rosaceae	Improved chlorophyll, carotenoid, carbohydrate and proline contents, and increased photosynthesis rate, MDA, (RWC) and membrane electrolyte leakage (ELI))	Ashkavand et al. (2015)
		Sorghum bicolor	Poaceae	Maintaining photosynthesis rate and improved root growth	Hattori et al. (2005)

(continued)

Table 4.1 (continued)

Stress Type	NPs.	Plant Name	Family	Physiological Effects on Host	References
	CuO	*Triticum aestivum*	Poaceae	Multiplication and elongation of root hair close to root tip	Yang et al. (2017)
		Arabidopsis thaliana	Brassicaceae	Change the water supply thus shrink the cell wall, increase lignification, cu-pectin association in cell wall	Nair and Chung (2017)
		Brassica juncea	Brassicaceae	Change the water supply thus shrink the cell wall, increase lignification, cu-pectin association in cell wall	Nair and Chung (2017)
	ZnO	*Triticum aestivum*	Poaceae	Increased lateral roots formation	Yang et al. (2017)
	AgNPs	*Lens culinaris*	Fabaceae	High germination rate and high growth and production parameters	Hojjat and Ganjali (2016)
	MWCNTs	*Hordeum vulgare*	Poaceae	Improved water absorption capacity, seedling water content	Karami and Sepehri (2017)
		Glycine max	Fabaceae	Increased antioxidants and high germination rate	Lahiani et al. (2013)
		Zea mays	Poaceae	Increased antioxidants and high germination rate	Liu et al. (2016)
		Triticum aestivum	Poaceae	High root and shoot growth	Srivastava and Rao (2014)
	CeO2	*Glycine max*	Fabaceae	Enhanced crop production	Cao et al. (2018)
	FeO2+ salicylic acid	*Fragaria ananassa*	Rosaceae	Improved growth parameters and increased leaf pigments level, RWC, MSI, iron and potassium level	Mozafari et al. (2018)

Heat	Ag NP	*Triticum aestivum*	Poaceae	Protected plants against thermal stress and improved plant growth	Husen et al. (2017)
	CeO_2	*Zea mays*	Poaceae	Enhanced degeneration of H_2O_2 and upregulation of HSP70	Zhao et al. (2012)
	MWCNTs	*Lycopersicon esculentum*	Solanaceae	Up regulated the transcript level of various stress-related genes including HSP90	Khodakovskaya et al. (2011a, b)
	Se	*Lycopersicon esculentum*	Solanaceae	Increased chlorophyll content, hydration of plants, and growth	Haghighi et al. (2014) and Djanaguiraman et al. (2018)
	TiO_2	*Lycopersicon esculentum*	Solanaceae	Promoted photosynthesis by regulating energy depletion, induced stomatal opening resulted into cooling of leaves	Qi et al. (2013)
Cold	TiO_2	*Cicer arietinum*	Fabaceae	Increased antioxidative enzymes activities, decreased H_2O_2 level and electrolyte leakage	Mohammadi et al. (2013)
			Fabaceae	Upregulation of chlorophyll binding protein and rubisco genes, decreased in H_2O_2 level, enhanced activity of PEP carboxylase	Hasanpour et al. (2015)
	SiO_2	*Agropyron elongatum*	Poaceae	Breakage of seed dormancy, enhanced germination and seedling weight	Azimi et al. (2014)
	Ag	*Arabidopsis thaliana*	Brassicaceae	Activated and enriched antioxidant genes	Kohan-Baghkheirati and Geisler-Lee (2015)
	Se	*Cucumis sativus L.*	Cucurbitaceae	Increased proline content in leaves, reduced lipid peroxidation in roots,	Hawrylak-Nowak et al. (2010)

(continued)

Table 4.1 (continued)

Stress Type	NPs.	Plant Name	Family	Physiological Effects on Host	References
Heavy metals Cd	ZnO	*Leucaena leucocephala*	Fabaceae	Elevated soluble proteins, chlorophyll and carotenoid content in leaves, and decrease in oxidative damaged to lipids membrane, induced level of antioxidative enzymes (CAT, SOD, POD) in leaves, lipid perodixadation	Venkatachalam et al. (2017)
	TiO2	*Leucaena leucocephala*	Fabaceae	Augmented growth and increased energy driven pathways, increased leaf pigments, relative water content,	Singh and Lee (2016)
	$Ca_5(PO_4)_3$	*Brassica juncea*	Brassicaceae	Nano scale protection against cd stress	Li and Huang (2014)
	Hydroxyapatite	*Brassica chinensis L.*	Brassicaceae	High biomass, level of chlorophyll and ascorbic acid, increased antioxidant activities (SOD, CAT, POD) decreased level of MDA	Li and Huang (2014)
Cr	Si NPs	*Pisum sativum*	Fabaceae	Activation of anti-oxidative pathways	Tripathi et al. (2015)
Cr (VI)	Na2SiO3	*Pisum sativum*	Fabaceae	Reduced assimilation of Cr(VI) and oxidative stress, enhanced antioxidative defense systems, and enriched accumulation of nutrient elements, improved growth	Tripathi et al. (2015)
Pb and Cu	ZnS quantum dots	*Chlorella kesslerii, Chlamydomonas reinhardtii*	Graphidaceae, Chlamydomona-daceae	Decreased intracellular Cu and Pb in walled strains, wall-less strains contained elevated Cu and Pb	Worms et al. (2012)

References

Abou-Zeid HM, Ismail GSM (2018) The role of priming with biosynthesized silver nanoparticles in the response of Triticum aestivum L. to salt stress. Egypt J Bot 58:73–85

Ahmad J, Bashir H, Bagheri R, Baig A, Al-Huqail A, Ibrahim MM, Qureshi MI (2017) Drought and salinity induced changes in ecophysiology and proteomic profile of Parthenium hysterophorus. PLoS One 12(9):0185118

Almutairi ZM (2016) Effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato (Solanum lycopersicum L.) seedlings under salt stress. Plant Omics J 9:106–114

Ashkavand P, Tabari M, Zarafshar M, Tomášková I, Struve D (2015) Effect of SiO2 nanoparticles on drought resistance in hawthorn seedlings. Leśne Prace Badawcze/Forest Research Papers Grudzień 76(4):350–359

Askary M, Talebi SM, Amini F, Bangan ADB (2017) Effects of iron nanoparticles on Mentha piperita under salinity stress. Biologija 63:65–75

Azimi R, Borzelabad MJ, Feizi H, Azimi A (2014) Interaction of SiO2 nanoparticles with seed prechilling on germination and early seedling growth of tall wheatgrass (Agropyron elongatum L.). Pol J Chem Tech 16:25–29

Baybordi A (2005) Effect of zinc, iron, manganese and copper on wheat quality under salt stress conditions. J Water Soil 140:150–170

Beyene HD, Werkneh AA, Bezabh HK, Ambaye TG (2017) Synthesis paradigm and applications of silver nanoparticles (AgNPs), a review. Sustain Mater Technol 13:18–23

Boudsocq M, Sheen J (2013) CDPKs in immune and stress signaling. Trends Plant Sci 18:30–40

Bruna HCO, Gomes CR, Milena T, Pelegrino A, Seabra B (2016) Nitric oxide-releasing chitosan nanoparticles alleviate the effects of salt stress in maize plants. Nitric Oxide 61:10–19

Burklew CE, Ashlock J, Winfrey WB, Zhang B (2012) Effects of aluminum oxide nanoparticles on the growth, development, and microRNA expression of tobacco (Nicotiana tabacum). PLoS One 7:34783

Cakmak I, Yilmaz A, Torun B, Erenoglu B, Broun HJ (1996) Zinc deficiency as a critical nutritional problem in wheat production in Central Anatolia. Plant Soil 180:165–172

Cao Z, Rossi L, Stowers C, Zhang W, Lombardini L, Ma X (2018) The impact of cerium oxide nanoparticles on the physiology of soybean (Glycine max (L.) Merr.) under different soil moisture conditions. Environ Sci Pollut Res 25:930–939

Capuana M (2011) Heavy metals and woody plants biotechnologies for phytoremediation. J Biogeo Sci For 4:7–15

Carpenter AW, Worley BV, Slomberg DL, Schoenfisch MH (2012) Dual action antimicrobials: nitric oxide release from quaternary ammonium-functionalized silica nanoparticles. Biomacromolecules 13(10):3334–3342. https://doi.org/10.1021/bm301108x

Chandra S, Chakraborty N, Dasgupta A, Sarkar J, Panda K, Acharya K (2015) Chitosan nanoparticles: a positive modulator of innate immune responses in plants. Sci Rep 5:15195

Chen J, Liu X, Wang C, Yin SS, Li XL, Hu WJ, Simona M, Shen ZJ, Xiao Q, Chu CC, Peng XX, Zheng HL (2015) Nitric oxide ameliorates zinc oxide nanoparticles-induced phytotoxicity in rice seedlings. J Hazard Mater 297:173–182

Cheung WY (1980) Calmodulin plays a pivotal role in cellular regulation. Science 207:19–27

Chibuike GU, Obiora SC (2014) Heavy metal polluted soils: effect on plants and bioremediation methods. Appl Environ Soil Sci:1–13

Corpas FJ, Barroso JB, Carreras A, Quiros M, Leon AM, Romero-Puertas MC et al (2004) Cellular and subcellular localization of endogenous nitric oxide in young and senescent pea plants. Plant Physiol 136:2722–2733

Del Rio LA, Corpas FJ, Barroso JB (2004) Nitric oxide and nitric oxide synthase activity in plants. Phytochemistry 65:783–792

Delk NA, Johnson KA, Chowdhury NI, Braam J (2005) CML24, regulated in expression by diverse stimuli, encodes a potential Ca2þ sensor that functions in response to abscisic acid, daylength, and ion stress. Plant Physiol 139:240–253
Derosa MR, Monreal C, Schmitzer M, Walsh R, Sultan Y (2010) Nanotechnology in fertilizers. Nat Nanotechnol 1:193–225
Dimkpa CO, McLean JE, Latta DE, Manangón E, Britt DW, Johnson WP, Anderson AJ (2012) CuO and ZnO nanoparticles: phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. J Nanopart Res 14(9):1125
Djanaguiraman M, Boyle DL, Welti R, Jagadish SVK, Prasad PVV (2018) Decreased photosynthetic rate under high temperature in wheat is due to lipid desaturation, oxidation, acylation, and damage of organelles. BMC plant biology 18(1):1–17
Dos Reis SP, Marques DN, Lima AM, de Souza CRB (2016) Plant molecular adaptations and strategies under drought stress. In: Drought stress tolerance in plants. Springer, Cham, pp 91–122
Frazier TP, Burklew CE, Zhang B (2014) Titanium dioxide nanoparticles affect the growth and microRNA expression of tobacco (Nicotiana tabacum). Funct Integr Genom 14:75–83
Gao FQ, Hong FS, Liu C, Zheng L, Su MY, Wu X, Yang F, Wu C, Yang P (2006a) Mechanism of nanoanatase TiO2 on promoting photosynthetic carbon reaction of spinach: inducing complex of Rubisco-Rubisco activase. Biol Trace Elem Res 11:239–254
Gao X, Zou CH, Wang L, Zhang F (2006b) Silicon decreases transpiration rate and conductance from stomata of maize plants. J Plant Nutr 29:1637–1647
Gao F, Liu C, Qu C, Zheng L, Yang F, Su M, Hong F (2008) Was improvement of spinach growth by nano-TiO2 treatment related to the changes of rubisco activase? BioMetals 21(2):211–217
García-Sanchez S, Bernales I, Cristobal S (2015) Early response to nanoparticles in the Arabidopsis transcriptome compromises plant defence and root-hair development through salicylic acid signaling. BMC Genomics 16:341
Giacomo B, Forino LMC, Tagliasacchi AM, Bernardi R, Durante M (2010) Ozone damage and tolerance in leaves of two poplar genotypes. Caryologia 63:422–434
Giraldo JP, Landry MP, Faltermeier SM, McNicholas TP, Iverson NM, Boghossian AA, Reuel NF, Hilmer AJ, Sen F, Brew JA, Strano MS (2014) Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nat Mater 13. https://doi.org/10.1038/NMAT3890
Goyer RA (1995) Nutrition and metal toxicity. Am J Clin Nutr 61:646S–650S
Gunjan B, Zaidi MGH, Sandeep A (2014) Impact of gold nanoparticles on physiological and biochemical characteristics of Brassica juncea. J Plant Biochem Physiol 2:133
Haghighi M, Pourkhaloee A (2013) Nanoparticles in agricultural soils: their risks and benefits for seed germination. Minerva Biotecnol 25:123–132
Haghighi M, Abolghasemi R, Teixeira da Silva JA (2014) Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with Se and nano-Se amendment. Sci Hortic 178:231–240
Hartikainen H, Xue T, Piironen V (2000) Selenium as an antioxidant and prooxidant in rye grass. Plant Soil 225:193–200
Hasanpour H, Maali-Amiri R, Zeinali H (2015) Effect of TiO2 nanoparticles on metabolic limitations to photosynthesis under cold in chickpea. Russ J Plant Physiol 62:779–787
Hasanuzzaman M, Nahar K, Fujita M (2013) Extreme temperature responses, oxidative stress and antioxidant defense in plants. In: Vahdati K, Leslie C (eds) Abiotic stress – plant responses and applications in agriculture. InTech Open Access Publisher
Hasanuzzaman M, Nahar K, Fujita M (2014) Silicon and selenium: two vital trace elements that confer abiotic stress tolerance to plants. Emerging technologies and management of crop stress tolerance. Elsevier, The Netherlands, pp 377–422
Hattori T, Inanaga S, Araki H, An P, Morita S, Luxová M et al (2005) Application of silicon enhanced drought tolerance in Sorghum bicolour. Physiol Plant 123:459–466
Hawrylak-Nowak B, Matraszek R, Szymanska M (2010) Selenium modifies the effect of short-term chilling stress on cucumber plants. Biol Trace Elem Res 138:307–315

Heidarvand L, Maali-Amiri R, Naghavi MR, Farayedi Y, Sadeghzadeh B, Alizadeh KH (2011) Physiological and morphological characteristics of chickpea accessions under low temperature stress. Russ J Plant Physiol 58:157–163

Hernandez-Hernandez H, Gonzalez-Morales S, Benavides-Mendoza A, Ortega-Ortiz H, Cadenas-Pliego G, Juarez-Maldonado A (2018) Effects of chitosan–PVA and cu nanoparticles on the growth and antioxidant capacity of tomato under saline stress. Molecules 23:178

Hojjat SS, Ganjali A (2016) The effect of silver nanoparticle on lentil seed germination under drought stress. Int J Farm Allied Sci 5(3):208–212

Husen A, Iqbal M, Aref IM (2017) Plant growth and foliar characteristics of faba bean (Vicia faba L.) as affected by indole-acetic acid under water-sufficient and water-deficient conditions. Journal of Environmental Biology, 38(2):179

Hussain S, Hussain S, Qadir T, Khaliq A, Ashraf U, Parveen A, Rafiq M (2019) Drought stress in plants: an overview on implications, tolerance mechanisms and agronomic mitigation strategies. Plant Sci Today 6(4):389–402

Ismail A, Takeda S, Nick P (2014) Life and death under salt stress: same players, different timing? J Exp Bot 65:2963–2979

Jaberzadeh A, Payam M, Hamid R, Tohidi M, Hossein Z (2013) Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. Not Bot Horti Agrobot Cluj-Na 41:201–207

Kalteh M, Alipour ZT, Ashraf S, Aliabadi MM, Nosratabadi AF (2014) Effect of silica nanoparticles on basil (ocimum basilicum) under salinity stress. J Chem Health Risk 4:49–55

Karami A, Sepehri A (2017) Multiwalled carbon nanotubes and nitric oxide modulate the germination and early seedling growth of barley under drought and salinity. Agric Conspec Sci 82:331–339

Karuppanapandian T, Wang HW, Prabakaran N, Jeyalakshmi K, Kwon M, Manoharan K, Kim W (2011) 2,4-dichlorophenoxyacetic acid-induced leafsenescence in mung bean (Vigna radiate (L.) Wilczek) and senescence inhibition by co-treatment with silver nanoparticles. Plant Physiol Biochem 49:168–217

Kaveh R, Li YS, Ranjbar S, Tehrani R, Brueck CL, Aken BV (2013) Changes in Arabidopsis thaliana gene expression in response to silver nanoparticles and silver ions. Environ Sci Technol 47:10637–10,644

Khan MN, Siddiqui MH, Mohammad F, Naeem M, Khan MMA (2010) Calcium chloride and gibberellic acid protect Linseed (Linum usitatissimum L.) from NaCl stress by inducing antioxidative defence system and osmoprotectant accumulation. Acta Physiol Plant 32:121–132

Khan MN, Siddiqui MH, Mohammad F, Naeem M (2012) Interactive role of nitric oxide and calcium chloride in the tolerance of plants to salt stress. Nitric Oxide 27:210–218

Khan MIR, Syeez S, Nazar R, Anjum NA (2012a) An insight into the role of salicylic acid and jasmonic acid in salt stress tolerance. In: Khan NA, Nazar R, Iqbal N, Anjum NA (eds) Phytohormones and abiotic stress tolerance in plants. Springer, pp 277–300

Khan MIR, Asgher M, Khan NA (2014a) Alleviation of salt induced photosynthesis and growth inhibition by salicylic acid involves glycinebetaine and ethylene in mungbean (Vigna radiate L.). Plant Physiol Biochem 80:67–74

Khan MN, Mohammad F, Mobin M, Saqib MA (2014b) Tolerance of plants to abiotic stress: a role of nitric oxide and calcium. In: Khan MN, Mobin M, Mohammad F, Corpas FJ (eds) Nitric oxide in plants: Metabolism and role. Springer

Khan MN, Mobin M, Abbas ZK, AlMutairi KA, Siddiqui ZH (2017) Role of nanomaterials in plants under challenging environments. Plant Physiol Biochem 110:194–209

Khodakovskaya MV, de Silva K, Nedosekin DA, Dervishi E, Biris AS, Shashkov EV, Ekaterina IG, Zharov VP (2011a) Complex genetic, photo thermal, and photo acoustic analysis of nanoparticle-plant interactions. Proc Natl Acad Sci U S A 108:1028–1033

Khodakovskaya MV, de Silva K, Nedosekin DA, Dervishi E, Biris AS, Shashkov EV, Galanzha EI, Zharov VP (2011b) Complex genetic, photothermal, and photoacoustic analysis of nanoparticle-plant interactions. Proc Natl Acad Sci U S A 108:1028–1033

Khodakovskaya MV, de Silva K, Biris AS, Dervishi E, Villagarcia H (2012) Carbon nanotubes induce growth enhancement of tobacco cells. ACS Nano 6:2128–2135

Kim JH, Oh Y, Yoon H, Hwang I, Chang YS (2015) Iron nanoparticle-induced activation of plasma membrane Hþ-ATPase promotes stomatal opening in Arabidopsis thaliana. Environ Sci Technol 49:1113–1119

Kohan-Baghkheirati E, Geisler-Lee J (2015) Gene expression, protein function and pathways of Arabidopsis thaliana responding to silver nanoparticles in comparison to silver ions, cold, salt, drought, and heat. Nanomaterials 5:436–467

Lahiani MH, Dervishi E, Chen J, Nima Z, Gaume A, Biris AS, Khodakovskaya MV (2013) Impact of carbon nanotube exposure to seeds of valuable crops. ACS Appl Mater Interfaces 5(16):7965–7973

Lamotte O, Courtois C, Dobrowolska G, Besson A, Pugin A, Wendehenne D (2006) Mechanism of nitric-oxide-induced increase of free cytosolic Ca2þ concentration in Nicotiana plumbaginifolia cells. Free Radic Biol Med 40:1369–1376

Latef AAHA, Srivastava AK, El-Sadek MSA, Kordrostami M, Tran LP (2018) Titanium dioxide nanoparticles improve growth and enhance tolerance of broad bean plants under saline soil conditions. Land Degrad Dev 29:1065–1073

Li Z, Huang J (2014) Effects of nanoparticle hydroxyapatite on growth and antioxidant system in pakchoi (Brassica chinensis L.) from cadmium-contaminated soil. J Nanomater:1–7

Liu YF, Qi MF, Li TL (2012) Photosynthesis, photoinhibition, and antioxidant system in tomato leaves stressed by low night temperature and their subsequent recovery. Plant Sci 196:8–17

Liu FY, Xiong FX, Fan YK, Li J, Wang HZ, Xing GM, He R (2016) Facile and scalable fabrication engineering of fullerenol nanoparticles by improved alkaline-oxidation approach and its antioxidant potential in maize. J Nanopart Res 18(11):338

Lopez CJ, Banowetz GM, Peterson CJ, Kronstad WE (2003) Dehydrin expression and drought tolerance in seven wheat cultivars. Crop Sci 43:577–582

Ma X, Geiser-Lee J, Deng Y, Kolmakov A (2010) Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. Sci Total Environ 408:3053–3061

Maali Amiri R, Yur'eva NO, Shimshilashvili KR, Goldenkova-Pavlova IV, Pchelkin VP, Kuznitsova EI et al (2010) Expression of acyl-lipid D 12-desaturase gene in prokaryotic and eukaryotic cells and its effect on cold stress tolerance of potato. J Integr Plant Biol 52:289–297

Marmiroli M, Imperiale D, Pagano L, Villani M, Zappettini A, Marmiroli N (2015) The Proteomic response of Arabidopsis thaliana to cadmium sulphide quantum dots, and its correlation with the transcriptomic response. Front Plant Sci 6:1104

Martinez-Ballesta MC, Zapata L, Chalbi N, Carvajal M (2016) Multiwalled carbon nanotubes enter broccoli cells enhancing growth and water uptake of plants exposed to salinity. J Nanobiotech 14:42

Miao Y, Xu J, Shen Y, Chen L, Bian Y, Hu Y et al (2014) Nanoparticle as signalling protein mimic: robust structural and functional modulation of CaMKII upon specific binding to fullerene C60 nanocrystals. ACS Nano 8:6131–6144

Mirzajani F, Askari H, Hamzelou S, Schober Y, Rhompp A, Ghassempour A et al (2014) Proteomics study of silver nanoparticles toxicity on Oryza sativa L. Ecotoxicol Environ Saf 108:335–339

Mohamed AKSH, Qayyum MF, Abdel-Hadi AM, Rehman RA, Ali S, Rizwan M (2017) Interactive effect of salinity and silver nanoparticles on photosynthetic and biochemical parameters of wheat. Arch Agron Soil Sci 63(12):1736–1747

Mohammadi R, Maali-Amiri R, Abbasi A (2013) Effect of TiO2 nanoparticles on chickpea response to cold stress. Biol Trace Elem Res 152:403–410

Mohammadi H, Esmailpour M, Gheranpaye A (2014a) Effects of TiO2 nanoparticles and water-deficit stress on morpho-physiological characteristics of dragonhead (Dracocephalum moldavica L.) plants. Acta Agri Slovenica 107(2):385–396

Mohammadi R, MaaliAmiri R, Mantri N (2014b) Effect of TiO2 nanoparticles on oxidative damage and antioxidant defense systems in chickpea seedlings during cold stress. Russ J Plant Physiol 61:768–775

Moller IM, Jensen PE, Hansson A (2007) Oxidative modifications to cellular components in plants. Ann Rev Plant Biol 58:459–481

Mozafari AA, Havas F, Ghaderi N (2018) Application of iron nanoparticles and salicylic acid in in vitro culture of strawberries (Fragaria × ananassa Duch.) to cope with drought stress. Plant Cell Tissue Organ Cult 132:511–523

Nair PMG, Chung IM (2017) Regulation of morphological, molecular and nutrient status in Arabidopsis thaliana seedlings in response to ZnO nanoparticles and Zn ion exposure. Sci Total Environ 575:187–198

Oliveira HC, Gomes BC, Pelegrino MT, Seabra AB (2016) Nitric oxide-releasing chitosan nanoparticles alleviate the effects of salt stress in maize plants. Nitric Oxide 61:10–19

Oukarroum A, Bras S, Perreault F, Popovic R (2012) Inhibitory effects of silver nanoparticles in two green algae, Chlorella vulgaris and Dunaliella tertiolecta. Ecotoxicol Environ Saf 78:80–85

Owolade OF, Ogunleti DO, Adenekan MO (2008) Titanium dioxide affected diseases, development and yield of edible cowpea. Elec J Environ Agricult Food Chem 7(5):2942–2947

Paleg LG, Stewart GR, Bradbeer JW (1984) Proline and glycine betaine influence protein solvation. Plant Physiol 75:974–978

Prasad PVV, Pisipati SR, Mom I, Ristic Z (2011) Independent and combined effects of high temperature and drought stress during grain filling on plant yield and chloroplast EF-Tu expression in spring wheat. J Agron Crop Sci 197:430–441

Qados AMSA (2015) Mechanism of nanosilicon-mediated alleviation of salinity stress in faba bean (Vicia faba L.) plants. Am J Exp Agric 7:78–95

Qados AMSA, Moftah AE (2015) Influence of silicon and nano-silicon on germination, growth and yield of faba bean (Vicia faba L.) under salt stress conditions. Am J Exp Agric 5:509–524

Qi M, Liu Y, Li T (2013) Nano-TiO2 improve the photosynthesis of tomato leaves under mild heat stress. Biol Trace Elem Res 156:323–328

Rahimi R, Mohammakhani A, Roohi V, Armand N (2012) Effects of salt stress and silicon nutrition on cholorophyll content, yield and yield components in fennel (Foeniculum vulgare Mill.). Int J Agric Crop Sci 4:1591–1595

Rascio N, Navari-Izzo F (2011) Heavy metal hyperaccumulating plants: how and why do they do it? and what makes them so interesting? Plant Sci 180:169–181

Sabaghnia N, Janmohammadi M (2014) Effect of nano-silicon particles application on salinity tolerance in early growth of some lentil genotypes. Ann UMCS Biol 69:39–55

Savicka M, Skute N (2010) Effects of high temperature on malondialdehyde content, superoxide production and growth changes in wheat seedlings (Triticum aestivum L.). Ekologija 56:26–33

Savvasd G, Giotes D, Chatzieustratiou E, Bakea M, Patakioutad G (2009) Silicon supply in soilless cultivation of Zucchini alleviates stressinduced by salinity and powdery mildew infection. Environ Exp Bot 65:11–17

Schulze ED, Beck E, Buchmann N, Clemens S, Müller-Hohenstein K, Scherer-Lorenzen M (2019) Water deficiency (Drought). In: Plant ecology. Springer, Berlin, pp 165–202

Shahrokh S, Hosseinkhani B, Emtiazi G (2014) The impact of silver nanoparticles on bacterial aerobic nitrate reduction process. J Bioprocess Biotech 4:152

Sharma P, Jha AB, Dubey RS, Pessarakli M (2012) Reactive oxygen species, oxidative damage, and antioxidant defense mechanisms in plants under stressful conditions. J Bot:1–26

Siddiqui MH, Al-Whaibi MH (2014) Role of nano-SiO2 in germination of tomato (Lycopersicum esculentum seeds Mill.). Saudi J Biolog Sci 21:13–17

Siddiqui MH, Al-Whaibi MH, Faisal M, Al Sahli AA (2014) Nano-silicon dioxide mitigates the adverse effects of salt stress on Cucurbita pepo L. Environ Toxicol Chem 33:2429–2437

Simon DF, Domingos RF, Hauser C, Hutchins CM, Zerges W, Wilkinson KJ (2013) Transcriptome sequencing (RNA-seq) analysis of the effects of metal nanoparticle exposure on the transcriptome of Chlamydomonas reinhardtii. Appl Environ Microbiol 79:4774–4785

Singh J, Lee BK (2016) Influence of nano-TiO2 particles on the bioaccumulation of Cd in soybean plants (Glycine max): a possible mechanism for the removal of Cd from the contaminated soil. J Environ Manag 170:88–96

Singh S, Vishwakarma K, Singh S, Sharma S, Dubey NK, Singh VK, Liu S, Tripathi DK, Chauhan DK (2017) Understanding the plant and nanoparticle interface at transcriptomic and proteomic level: a concentric overview. Plant Gene 11:265–272

Soliman AS, El-feky SA, Darwish E (2015) Alleviation of salt stress on Moringa peregrina using foliar application of nanofertilizers. J Hortic For 7:36–47

Srivastava A, Rao DP (2014) Enhancement of seed germination and plant growth of wheat, maize, peanut and garlic using multiwalled carbon nanotubes. Eur Chem Bull 3(5):502–504

Suriyaprabha R, Karunakaran G, Yuvakkumar R, Prabu P, Rajendran V, Kannan N (2012) Growth and physiological responses of maize (Zea mays L.) to porous silica nanoparticles in soil. J Nanopart Res 14:1–14

Suzuki K, Nagasuga K, Okada M (2008) The chilling injury induced by high root temperature in the leaves of rice seedlings. Plant Cell Physiol 49:433–442

Torabian S, Zahedi M, Khoshgoftar AH (2016) Effects of foliar spray of two kinds of zinc oxide on the growth and ion concentration of sunflower cultivars under salt stress. J Plant Nutr 39:172–180

Tripathi DK, Singh VP, Prasad SM, Chauhan DK, Dubey NK (2015) Silicon nanoparticles (SiNp) alleviate chromium (VI) phytotoxicity in Pisum sativum (L.) seedlings. Plant Physiol Biochemist 96:189–198

Tuteja N, Mahajan S (2007) Calcium signalling network in plants. Plant Sig Behav 2:79–85

Van Hoecke K, De Schamphelaere KA, Van der Meeren P, Lucas S, Janssen CR (2008) Ecotoxicity of silica nanoparticles to the green alga Pseudokirchneriella subcapitata: importance of surface area. Environ Toxicol Chem 9:1948–1957

Vannini C, Domingo G, Onelli E, Prinsi B, Marsoni M, Espen L, Bracale M (2013) Morphological and proteomic responses of Eruca sativa exposed to silver nanoparticles or silver nitrate. PLoS One 8:68752

Venkatachalam P, Jayaraj M, Manikandan R, Geetha N, Rene ER, Sharma NC, Sahi SV (2017) Zinc oxide nanoparticles (ZnONPs) alleviate heavy metal-induced toxicity in Leucaena leucocephala seedlings: a physiochemical analysis. Plant Physiol Biochem 110:59–69

Wahid A (2007) Physiological implications of metabolites biosynthesis in net assimilation and heat stress tolerance of sugarcane (Saccharum officinarum) sprouts. J Plant Res 120:219–228

Wahid A, Gelani S, Ashraf M, Foolad M (2007) Heat tolerance in plants: an overview. Environ Exp Bot 61(3):199–223

Wei H, Wang E (2013) Nanomaterials with enzyme-like characteristics (nanozymes): next-generation artificial enzymes. Chem Soc Rev 42:6060–6093

Welti R, Li W, Li M, Sang Y, Biesiada H, Zhou HE, Rajashekar C, Williams TD, Wang X (2002) Profiling membrane lipids in plant stress responses. Role of phospholipase Da in freezing induced lipid changes in Arabidopsis. J Biol Chem 277:31994–32,002

Worms IAM, Boltzman J, Garcia M, Slaveykova VI (2012) Cell-wall-dependent effect of carboxyl-CdSe/ZnS quantum dots on lead and copper availability to green microalgae. Environmental pollution 167:27–33

Xu GY, Rocha P, Wang ML, Xu ML, Cui YC, Li LY, Zhu YX, Xia X (2011) A novel rice calmodulin-like gene, OsMSR2, enhances drought and salt tolerance and increases ABA sensitivity in Arabidopsis. Planta 234:47–59

Xu J, Yang J, Duan X, Jiang Y, Zhang P (2014) Increased expression of native cytosolic Cu/Zn superoxide dismutase and ascorbate peroxidase improves tolerance to oxidative and chilling stresses in cassava (Manihot esculenta Crantz). BMC Plant Biol 14:208

Yang KY, Doxey S, McLean JE, Britt D, Watson A, Al Qassy D, Jacobson AR, Anderson A (2017) Remodeling of root morphology by CuO and ZnO nanoparticles: effects on drought tolerance for plants colonized by a beneficial pseudomonad. Botany 96(3):175–186

Yordanova R, Popova L (2007) Effect of exogenous treatment with salicylic acid on photosynthetic activity and antioxidant capacity of chilled wheat plants. Gen Appl Plant Physiol 33:155–170

Ze Y, Liu C, Wang L, Hong M, Hong F (2011) The regulation of TiO2 nanoparticles on the expression of light-harvesting complex II and photosynthesis of chloroplasts of Arabidopsis thaliana. Biol Trace Elem Res 143:1131–1141

Zhao L, Peng B, Hernandez-Viezcas JA, Rico C, Sun Y, Peralta-Videa JR, Tang X, Niu G, Jin L, Ramirez AV, Zhang JY, Gardea-Torresdey JL (2012) Stress response and tolerance of Zea mays to CeO2 nanoparticles: cross talk among H2O2, heat shock protein and lipid peroxidation. ACS Nano 6:9615–9622

Zhu J, Wei G, Li J, Qian Q, Yu J (2004) Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (Cucumis sativus L.). Plant Sci 167:527–533