Chapter 14
Plant Stress Enzymes Nanobiotechnology

Paras Porwal, Sashi Sonkar, and Akhilesh Kumar Singh

Abstract Abiotic and biotic stresses are significantly affects the plant growth, thereby limiting agricultural productivity of crops. Agricultural plants/crops should be able to cope-up with both biotic and abiotic stresses by their innate biological mechanisms, failing which affect their growth, development and productivity. As per FAO, there is a need to foster the crop productivity factor greater than 70% by 2050 to feed additional 2.3 billion people worldwide. Moreover, sustainable agriculture acts as a main pillar for the development of the mankind and national economy as well as fulfills the food demand in developing countries. Realizing these critical facts, it becomes necessary for the scientific arena to generate harmless stress-mitigating mechanisms in plants, so that the plants/crop productivity is improved. In today's world, nanobiotechnology receiving an increasing attention towards the mitigation of biotic and/or abiotic stresses of agricultural plants/crops including the challenges in the yield barriers with the development of eco-friendly technologies. Although, there exists a huge gap in our understanding of the eco-toxicity, tolerable limit, and uptake capability of various nanoparticles in plants. This chapter encapsulates the promises as well as progress in plant nanobiotechnology especially with respect to promoting plant growth factors and ways to overcome abiotic stresses.

Keywords Abiotic and biotic stresses · Antioxidant · Nanobiotechnology · Nanoparticles · Plants/crop productivity · Reactive oxygen species · Salinity

P. Porwal
Amity Institute of Biotechnology, Amity University Uttar Pradesh, Lucknow Campus, Lucknow, Uttar Pradesh 226028, India
e-mail: pporwal@lko.amity.edu

S. Sonkar
Department of Botany, Bankim Sardar College, Tangrakhali 743329, South 24 Parganas, West Bengal, India

A. K. Singh (✉)
Department of Biotechnology, School of Life Sciences, Mahatma Gandhi Central University, Motihari 845401, Bihar, India
e-mail: akhileshsingh@mgcub.ac.in

J. M. Al-Khayri et al. (eds.), *Nanobiotechnology*,
https://doi.org/10.1007/978-3-030-73606-4_14

14.1 Introduction

Sustainable agriculture acts as a backbone for the development of the national economy as well as fulfills the aspiration of food demand in developing countries. To satisfy the demand for food supply for the upcoming future with the changing environmental conditions as well as rapidly increasing population, there is urgent need to increase crop yield and stability of plants in adverse conditions by exploiting the advance approaches like nanobiotechnology (Eckardt et al. 2009; Zhang 2007). Agricultural plants/production of crops together with their protection are reliant on the various parameters such as type as well as the quantity of applied fertilizers and pesticides. The growth and development of agricultural plants/crops entirely depend on ease of availability of optimal environmental as well as nutritional factors and any deviation from it leads to plant stress. Stress is a condition in which plants are not able to fully express their genetic potential for growth, development, and reproduction, thereby limits productivity owing to damage to biomass. Being sessile, plants cannot escape from adverse climatic conditions and, thus have to meet both the stresses, i.e., biotic stresses, for instance, interactions among organisms like microbial pathogens and so on and abiotic stresses that involve interactions among organisms with their physical environment. Abiotic (physical) stresses include temperature alteration (high or low), nutrient starvation, water deficit (drought), anoxia (during the flood), salinity and alkalinity of the soil, light intensity, submergence, mineral, and metal toxicity/deficiency (Cramer et al. 2011; Hirel et al. 2007; Wang et al. 2003). These stresses are unpredictable in nature in terms of their intensity, duration, and occurrence, so sustaining the development and survival of plants in an unfavorable environment turns out to be a difficult task. So, plants need to respond distinctly to protect themselves from physical stresses like cold, drought, heat, etc., that ultimately lead to the development of some adaptative mechanism in plants (Mittler 2002). Plants have the ability to sense abiotic stress and respond accordingly as per their past exposure so that in further repetitive stress can be adjusted (Ahmad et al. 2015; Hilker et al. 2015; Jiang et al. 2016). However, on the other hand, transgenic plants/crops are still not popular among the grower or farmers owing to their high level of safety concern. Therefore, in the current scenario, plant nanobiotechnology offers promising technological approaches for achieving food safety and security by increasing the efficiency of plants/crops, protecting them from different types of biotic as well as abiotic stresses via. modulating the mechanisms of different pathways, apart from those achieved through genetic and chemical production (Giraldo et al. 2019; Iqbal et al. 2020; Kah et al. 2019). Nanobiotechnology involves the cutting edge application-oriented research in the area of Nanoscience together with biotechnology. Nanomaterials (NMs) can be defined as materials depicting diameter in the range of 1–100 nm (Porwal and Sharma 2016; Pandey et al. 2018; Porwal et al. 2020; Rani et al. 2020; Singh and Porwal 2020; Singh, Pal, et al. 2018; Singh, Yadav, et al. 2018; Singh et al. 2020). The effect of various kinds of nanomaterials on plants under normal and/or abiotic stressed environment is presented in Table 14.1.

Table 14.1 Impact of nanomaterials on plants under normal and/or abiotic stressed condition

Nanoparticle type	Abiotic stress	Plant name	Impact	Reference
Ag	Dark stress	Horseshoe pelargonium (*Pelargonium zonale* (L.) L'Hér. ex Aiton)	Elevated antioxidative enzymes activities, petal longevity, leaf carotenoids and chlorophyll content. Decreased the peroxidation of lipid and petal abscission	Ghorbanpour and Hatami (2014)
Ag	Flooding	Soybean (*Glycine max* (L.) Merr.)	Promotes seedling growth and abundance of stress-related proteins. Decreases the cytotoxic by-products of glycolysis	Mustafa et al. (2015b)
Ag	Flooding	Saffron (*Crocus sativus* L.)	Promotes root growth. Blocks signaling pathway of ethylene	Rezvani et al. (2012)
Al_2O_3	Flooding	Soybean (*Glycine max* (L.) Merr.)	Controls energy metabolism and cell death	Mustafa et al. (2015a)
Al_2O_3	Nanotoxicity	Onion (*Allium cepa* L.)	Increases the activities of CAT and SOD	Rajeshwari et al. (2015), Riahi-Madvar et al. (2012)
CeO_2	Nanotoxicity	Maize (*Zea mays* L.)	Up-regulation of heat shock protein such as HSP70 and improved generation of H_2O_2	
CeO_2	Nanotoxicity	Soybean (*Glycine max* (L.) Merr.)	Stimulates plant growth. Rubisco carboxylase activity and photosynthesis rate increases	Zhao et al. (2012)
CuO	Nanotoxicity	Chickpea (*Cicer arietinum* L.)	Increase the activity of POD	Nair and Chung (2015)
CuO	Nanotoxicity	Wheat (*Triticum aestivum* L.)	Increase the activity of CAT and POD	Dimkpa et al. (2012)
Fe_2O_3	Nanotoxicity	Watermelon *Citrullus lanatus* (Thunb.) Matsum & Nakai	Increase the activities of CAT, POD, and SOD. Changes in the root activity, ferric reductase activity as well as chlorophyll, root apoplastic iron, and MDA contents were observed	Li et al. (2013)

(continued)

Table 14.1 (continued)

Nanoparticle type	Abiotic stress	Plant name	Impact	Reference
Fe_3O_4	Nanotoxicity	Wheat (*Triticum aestivum* L.)	Increases the activities of CAT, APX, GPOX, and SOD	Iannone et al. (2016)
SiO_2	Cold	Tall wheatgrass (*Agropyron elongatum* L.)	Overcome seed dormancy. Improved seed germination and seedling weight	Azimi et al. (2014)
SiO_2	Drought	Hawthorn (*Crataegus* sp.)	Increase photosynthetic rate, plant biomass, and stomatal conductance while insignificant effect on carotenoid and chlorophyll content	Ashkavand et al. (2015)
SiO_2	Salinity	Basil (*Ocimum basilicum* L.)	Increased chlorophyll and proline content. Improves dry and fresh weight	Kalteh et al. (2014)
SiO_2	Salinity	Broad bean (*Vicia faba* L.)	Increased the activity of antioxidant enzymes. Stimulates seed germination, water content and total yield	Qados and Moftah (2015), Qados (2015)
SiO_2	Salinity	Tomato (*Lycopersicon esculentum* Mill.)	Nano-SiO_2 at low concentration improved seed germination, dry weight, and root length whereas at higher concentration suppressed seed germination	Haghighi et al. (2012)
SiO_2	Salinity	Tomato (*Solanum lycopersicum* L.)	Downregulation of six genes RBOH1, APX2, MAPK2, ERF5, MAPK3, and DDF2 and upregulation of four salt stress genes AREB, TAS14, NCED3, and CRK1 thereby suppressing the effect of salinity stress on seed germination rate, root length, and fresh weight	Almutairi (2016)
SiO_2	Salinity	Tomato (*Solanum lycopersicum* L.)	Eliminate the effect of stress on photosynthetic rate, leaf water, and chlorophyll content	Haghighi and Pessarakli (2013)

(continued)

Table 14.1 (continued)

Nanoparticle type	Abiotic stress	Plant name	Impact	Reference
TiO_2	Drought	Basil (*Ocimum basilicum* L.)	Ameliorate negative effects of stress on the plant	Kiapour et al. (2015)
TiO_2	Drought	Flax (*Linum usitatissimum* L.)	Improve growth, carotenoids, and chlorophyll contents. Reduces H_2O_2 and MDA contents	Aghdam et al. (2016)
TiO_2	Drought	Wheat (*Triticum aestivum* L.)	Increase in gluten and starch content. Improves the overall growth and yield of the plant	Jaberzadeh et al. (2013)
TiO_2	Cold	Chickpea (*Cicer arietinum* L.)	Enhanced the activity of antioxidant enzymes, phosphoenolpyruvate carboxylase, and expression of Rubisco and chlorophyll-binding protein genes. Decreased in H_2O_2 content and electrolyte leakage	Hasanpour et al. (2015), Mohammadi et al. (2013, 2014)
TiO_2	Heat	Tomato (*Lycopersicon esculentum* Mill.)	Induced stomatal opening and cooling of leaves	Qi et al. (2013)
TiO_2	Nanotoxicity	Broad bean (*Vicia faba* L.)	Decreased the activity of GR and APX	Foltete et al. (2011)
TiO_2	Nanotoxicity	Duckweed (*Lemna minor* L.)	Increased the activity of SOD, CAT, and POD	Song et al. (2012)
TiO_2	Nanotoxicity	Hydrilla (*Hydrilla verticillata* (L.f.) Royle)	The activity of enzymes such as CAT and GR are increased	Okupnik and Pflugmacher (2016)
TiO_2	Nanotoxicity	Peppermint (*Mentha piperita* L.)	Increase the amount of chlorophyll (a and b) and carotenoid	Samadi et al. (2014)
TiO_2	Nanotoxicity	Spinach (*Spinacia oleracea* L.)	Increased the activity of SOD, CAT, APX, and GPOX↑	Lei et al. (2008)
ZnO and Fe_3O_4	Salinity	Ben tree *Moringa peregrine* (Forssk.) Fiori	Increased enzymatic and non-enzymatic antioxidants. Promotes the chlorophyll, carotenoids, proline, N, P, K, Ca^{2+}, Mg^{2+} carbohydrates, and crude protein content. Decreased Na^+ and Cl^- content	Soliman et al. (2015)

(continued)

Table 14.1 (continued)

Nanoparticle type	Abiotic stress	Plant name	Impact	Reference
ZnO	Nanotoxicity	Green pea (*Pisum sativum* L.)	Increased the elongation of root	Mukherjee et al. (2014)
ZnO	Nanotoxicity	Mouse-ear cress (*Arabidopsis thaliana* (L.) Heynh.)	Increase in lateral root formation.	Nair and Chung (2017)
ZnO	Nanotoxicity	Wheat (*Triticum aestivum* L.)	Reduced the activity of CAT	Dimkpa et al. (2012)
ZnO	Salinity	White lupin (*Lupinus termis* L.)	Increased the activity of ascorbic acid, phenols, organic solutes, and SOD, CAT, POD, and APX whereas decreased the content of MDA	Latef et al. (2017)

APX: Ascorbate peroxidase; CAT: Catalase; GPOX: Guaiacol peroxidase; GR: Glutathione reductase; MDA: Malondialdehyde; POD: Peroxidase; SOD: Superoxide dismutase

14.2 ROS Scrounging Antioxidants of Plants

ROS (reactive oxygen species) are short-lived, unstable, and reactive (Halliwell 2006), which includes singlet oxygen ($^1O_2$), hydroxyl radical (OH•), superoxide radical ($O_2{}^{\bullet -}$) as well as hydrogen peroxide (H_2O_2), etc. These are generated in different cellular compartments such as chloroplast, mitochondria, peroxisomes, plasma membrane (Apel and Hirt 2004) as a regular (unavoidable) by-product of aerobic metabolism such as photosynthesis and respiration in plants (Miller et al. 2010; You and Chan 2015) which is regulated by both enzymatic and non-enzymatic antioxidant defense system of the plant. The low or moderate level of ROS is responsible for plant growth (reproductive and senescence) and development including leaf shape, root hair elongation, trichome development (Gapper and Dolan 2006), stomatal closure, programmed cell death (Petrov et al. 2015), gravitropism (Wassim et al. 2013) as well as act as the second messenger in mediating different series of reactions in plant cells, and promotes the tolerance from biotic and abiotic stress conditions (Nath et al. 2017). However, excessive production of ROS due to both biotic and abiotic stresses (Bhattacharjee 2012; Khare et al. 2014; Kumar and Khare 2014) was not removed then results in damage to cell membranes (lipid peroxidation), proteins, nucleic acid (DNA as well as RNA), and several other cellular components of the plants, thereby affecting plant growth including development and ultimately yield (Demidchik 2015; Mittler 2002). Various abiotic stresses induced ROS generation and the role of nanomaterials enhancing stress tolerance in the plant is depicted in Fig. 14.1.

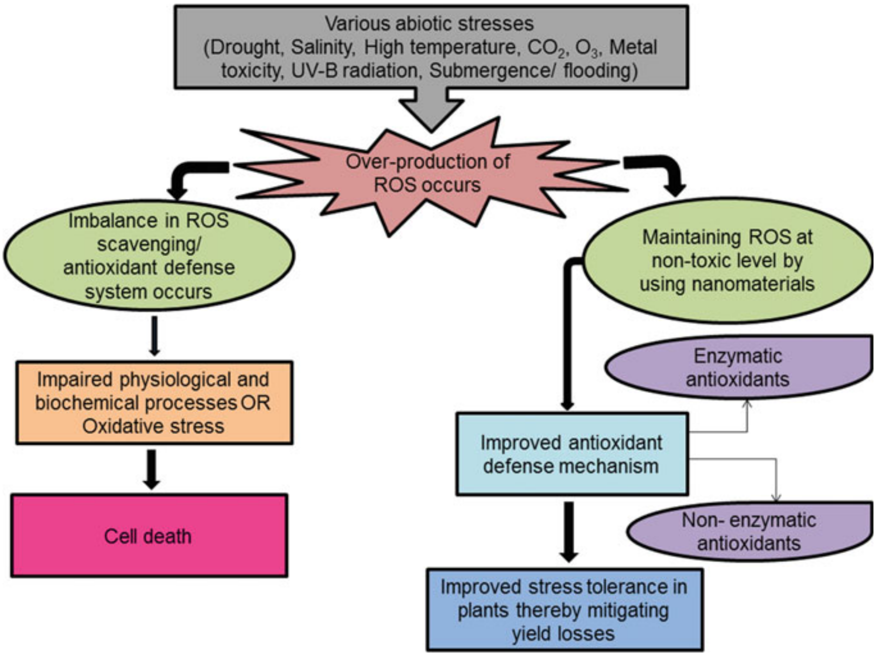

Fig. 14.1 An overview of the abiotic stress-induced ROS generation in agricultural plants/crops and the role of nanomaterials in improving stress tolerance (*Source* Modified from Meena et al. 2017; Xie et al. 2019)

14.3 Stimulation of Antioxidant Mechanism in Response to Nanoparticle Exposure

Plants make use of enzymatic and non-enzymatic antioxidative systems and/or pathways to mitigate oxidative stress. The key enzymes involved in the ROS-scrounging include catalase (CAT), ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POD), glutathione reductase (GR), glutathione peroxidase (GPX), glutathione S-transferase (GST), alternative oxidases (AOX), peroxiredoxin (PRX), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), and many more (Catalá and Díaz 2016; Jaleel et al. 2009; Maxwell et al. 1999; Mittler et al. 2004). Non-enzymatic antioxidants comprised of low molecular weight metabolites such as flavonoids, polyphenols, glutathione (GSH), ascorbic acid (AsA), β-carotene, α-tocopherol, proline, glycine betaine, and many more (Gill and Tuteja 2010; Pandey et al. 2017). During stressed conditions plants protect themselves from ROS toxicity (leads to oxidative damage) by changing gene expressions as well as adapting ROS-scrounging antioxidant metabolic pathways such as ascorbate, aldarate, and shikimate phenylpropanoid biosynthesis routes (Zhang et al. 2018), using ROS as signaling molecules (Dietz 2015; Foyer and Noctor 2013; Ismail et al. 2014; Mignolet-Spruyt et al. 2016). Ascorbate-glutathione cycle (AsA-GSH) is a major ROS-scrounging pathway in plants (chloroplast, mitochondria, apoplast, and peroxisomes), which involves successive oxidation and reduction of ascorbate, glutathione, and NADPH catalyzed by APX, MDHAR, DHAR, and GR, thereby helps in combating oxidative damages triggered by abiotic stresses (Mittler 2002). Association of ROS in signaling reveals that there must be some regulation of network to maintain ROS at non-toxic level, needs a precise balance between ROS production (during cellular metabolism), ROS generating enzyme and ROS-scrounging pathways. Thus, stress tolerance of the plants/crop can be improved remarkably by manipulating the ROS levels. Numerous, research studies have demonstrated the role of nanomaterials (CeO_2, C60 as well as Fe_2O_3) in scrounging the over-accumulation of ROS, generated during abiotic stress in plants, thereby improving abiotic stress tolerance in the plant and finally mitigating yield losses (Zhao et al. 2020).

14.4 Enzymatic Antioxidants

The agricultural plants/crops depict different types of antioxidants systems (Fig. 14.2) which are as follows:

(a) Superoxide dismutases (SOD): SOD enzymes are present naturally in different living organisms like agricultural plants/crops and so on. They speed-up the dismutation of $O_2^{\bullet -}$ to H_2O_2, so act as the first line of defense against ROS

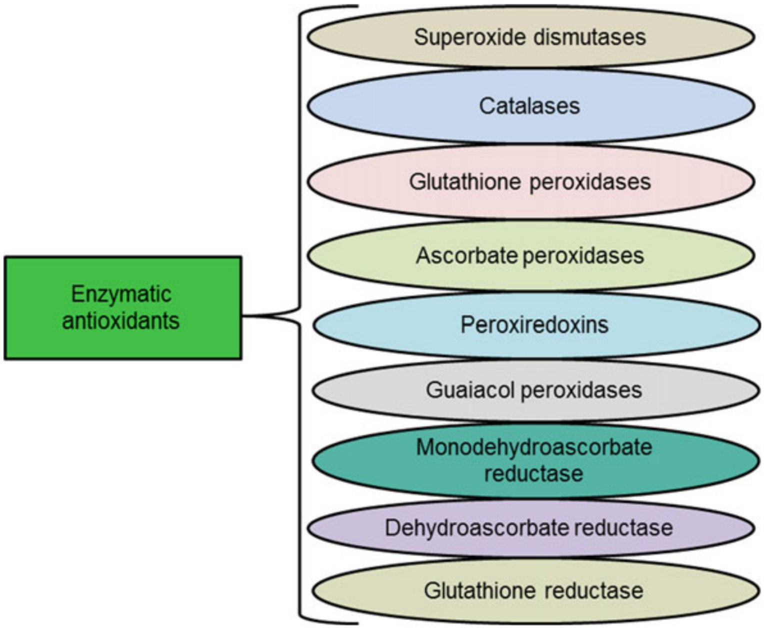

Fig. 14.2 Various types of antioxidant systems in plants

(Moustaka et al. 2015). Generally, due to the attachment of SODs to a metal ion such as Cu, Zn, Fe, Mn, and Ni, are distinguished based on their subcellular location and metal cofactor. In agricultural plants/crops, SODs encoding genes can be controlled and managed by development, tissue-specific, and abiotic stresses/signals (Scandalios 2005).

(b) Catalases: These enzymes are mostly confined to peroxisomes, known for the exclusion of H_2O_2 by reducing it into $2H_2O$. The specific gene that encodes for CATs responds separately to each abiotic stress known to produce ROS (Scandalios 2005).

(c) *Glutathione peroxidases* (GPX): These proteins are mostly confined to mitochondria, cytosol, and chloroplast. GPX is nonheme thiol peroxidases responsible for speed-up the reduction of organic H_2O_2 to H_2O (Margis et al. 2008).

(d) *Ascorbate peroxidases* (APX): These enzymes utilize ascorbate as an electron donor and are responsible for catalyzing the conversion of hydrogen peroxide into water. Different isomers of APX are present in the subcellular compartment of the plants like mitochondria, chloroplast, peroxisomes, and cytosol. The APX gene in plants is modulated by several environmental stresses (Caverzan et al. 2014) whereas the balance between APX, SOD, and CAT determines the intracellular level of $O_2^{\bullet -}$ and H_2O_2. Any alteration in the balance of these three enzymes seems to induce defense-mechanism pathways (Scandalios 2005).

(e) *Peroxiredoxins*: These antioxidant enzymes (thiol specific) are responsible for ROS detoxification in the chloroplast (Foyer and Shigeoka 2010), cell defense of plants by protecting them from oxidative damage, speed-up the reduction of peroxynitrite and various organic H_2O_2 to their corresponding alcohols (Wood et al. 2003).

(f) *Guaiacol peroxidases*: These are heme-containing enzymes known to detoxify H_2O_2 and belong to class III or secreted plant peroxidases. Guaiacol peroxidases can also carry out hydroxylic reaction (second cyclic reaction), different from the peroxidative reaction. These class III peroxidases support many activities in plants such as auxin metabolism, germination to senescence, cell wall elongation, and protection from pathogens (Passardi et al. 2004).

(g) *Monodehydroascorbate reductase* (MDAR): Different isomers of MDAR are found in the different subcellular compartments of plants such as mitochondria, peroxisomes, and cytosol. MDAR (flavin adenine dinucleotide enzyme) maintains the ascorbate pool in plants by catalyzing the regeneration of monodehydroascorbate radical utilizing NAD(P)H as an electron donor (Asada 1999; Leterrier et al. 2005).

(h) *Dehydroascorbate reductase* (DHAR): It helps to maintain ascorbate (AsA) in its reduced form and speed up dehydroascorbate reduction into ascorbate by utilizing glutathione as reducing substrate (Gratão et al. 2005).

(i) *Glutathione reductase* (GR): These enzymes are NAD(P)H dependent, speed-up the reduction of oxidized glutathione (GSSG) into reduced glutathione (GSH), and high GSH/GSSG ratio is required to protect the plant from oxidative damage (Foyer and Noctor 2005). GR plays a significant role in the ascorbate-glutathione cycle and maintains an appropriate level of reduced glutathione.

14.5 Impact of Nanoparticles on Plant Growth

Nanoparticles such as platinum (Pt), gold (Au), fullerene C60, Fe_3O_4, CeO_2, Mn_3O_4 and many more are reported to improve in the functional activities of antioxidant enzymes like SOD, CAT, and POD, that results in more improved adaptation of plants to different abiotic stresses (Chen et al. 2018; Upadhyaya et al. 2018). The fabricated nanosheets of MoS_2 resemble SODs, CATs, and PODs like activities. The nanoparticles of CeO_2 at low concentration (5 μM) efficiently decrease ROS level and protect chloroplast (Boghossian et al. 2013), whereas CeO_2 nanoparticles, when coated with polyacrylic acid, shows SOD and CAT activities, and successfully retained the photosynthetic capability of *Arabidopsis* plants under saline conditions (Wu et al. 2018). Foliar-sprayed CeO_2 nanoparticles in sorghum under drought conditions mitigate the effect of oxidative damage (Djanaguiraman et al. 2018). γ-Fe_2O_3 nanoparticles in *Brassica napus* under drought conditions protect plants from oxidative stress by efficiently reducing H_2O_2 and malondialdehyde (Palmqvist et al. 2017). In the investigation conducted by Yao et al. (2018), suggested that Mn_3O_4 may be used to enhance plant stress resistance (as Mn is micronutrient for plants) due to their stronger ROS-scrounging ability over Ce nanoparticles. When Fe_2O_3 nanoparticles are applied on watermelon in different concentrations, the activities of SOD, CAT, POD, and seedling germination were found to significantly increase and, therefore help to mitigate abiotic stress (Li et al. 2013). Nanoparticles have shown a concentration-dependent impact on the growth and development of plants (Mishra et al. 2017). For instance, onion seedlings, when exposed to TiO_2 nanoparticles, the SOD activity was increases with the increase in the concentration of TiO_2 nanoparticles, whereas onion seed germination as well as seedling growth was enhanced at low concentration and suppressed at higher concentration of TiO_2 nanoparticles (Dimkpa et al. 2017). Shallan et al. (2016) in their study, discovered that foliar spray of SiO_2 (3200 mg L^{-1}) or TiO_2 (50 mg L^{-1}) nanoparticles were found to enhance the drought tolerance of cotton plants. Siddiqui et al. (2014) reported that the application of SiO_2 nanoparticles (1.5–7.5 g L^{-1}) on squash (*Cucurbita pepo* L.) under saline condition upregulated the gene expression of SOD, CAT, POD, APX, and GR as well as increase the chlorophyll concentration, photosynthesis and biomass content of the plant. Under saline conditions, SOD and GPX gene expression are downregulated in tomato (*Solanum lycopersicum*), while on application of ZnO nanoparticles (15 and 30 mg L^{-1}) showed positive growth response (Alharby et al. 2016). On similar lines, foliar spray of ZnO in finger millet (*Eleusine coracana* (L.) Gaertn) improved salinity stress tolerance (Sathiyanarayanan 2018). Dimkpa et al. (2019), reported positive effect on drought tolerance when ZnO nanoparticles (18 nm, 5 mg kg^{-1}) are applied to soil-grown sorghum. However, several reports confirmed the negative impact of nanoparticles/engineered nanoparticles (Rico et al. 2015; Singh et al. 2016) on seed quality of plants like wheat (Rico et al. 2014) and common bean (Majumdar et al. 2015).

14.6 Effect of Nanoparticles on Plant Growth Under Salinity

Excessive accumulation of NaCl in the soil increases the salinity of soil and it affects the growth, development, and productivity of the plants in two ways: osmotic stress and ionic toxicity. Generally, osmotic pressure in the plant cell is more than the osmotic pressure in soil solution. Under high osmotic pressure, plant cell take-up water as well as other requisite minerals from soil solution into the root cells, but during saline conditions, this situation gets reversed and plant ability to take-up water and requisite minerals such as K^+ and Ca^{2+} also disturbed, meanwhile Na^+ and Cl^- ions enter into cytosol that leads to low K^+/Na^+ ratio which is responsible for increased ROS production, electrolytes leakage, toxicity to cell membranes, and also affects metabolic activities in the cytosol (Khan et al. 2012; Kumar 2013; Kumar and Khare 2014). Overall, salinity has a negative effect on various biological and physiological processes of the plant. Some major negative effects of salinity stress on the plant include nutritional imbalance, increased ionic toxicity, ROS overproduction, reduced osmotic potential, the decline in photosystem II efficiency, and stomatal conductance (Negrão et al. 2017). Recently, nanoparticles have been reported to enhance the antioxidative defense mechanism of plants. This potential approach is being exploited to mitigate the salinity stress of the plants (Sabaghnia and Janmohammad 2015). Derosa et al. (2010) reported that SiO_2 nanoparticles enunciate a layer inside the cell wall that facilitates them to conquer salinity stress and uphold yield. Silicon nanoparticles increase the rate of photosynthesis, proline accretion, seed germination, leaf water content, and antioxidant enzymes activities (Qados 2015). On the application of SiO_2 nanoparticles, improvement in salinity stress was observed in *Ocimum basilicum* (Kalteh et al. 2014), *Lens culinaris* (Sabaghnia and Janmohammadi 2014) and *Vicia faba* (Qados 2015). Similarly, SiO_2 nanoparticles were reported to enhance seed germination and antioxidant system in squash and tomato (Siddiqui et al. 2014). Further, mitigation in salinity stress was observed by the application of the foliar spray of Fe_3O_4 as well as ZnO (60 mg L^{-1}) as nano-fertilizers on *Moringa peregrina* (Soliman et al. 2015). The efficiency of a chloroplast, as well as biomass, were increased in treating *Brassica napus* L. with CeO_2 nanoparticles under both fresh and saline water irrigation (Rossi et al. 2016).

14.7 Impact of Nanoparticles on Plant Growth Under Drought Stress

Water is a prerequisite necessity for plant growth and survival, essentially needed for transporting nutrients, thus its crises result in drought stress. Drought stress affects the growth of plants, thereby ultimately influencing the agricultural plants/crops yield globally. During water crises situation, plants limit their various activities such as stomatal closure to prevent additional water loss, reduce CO_2 fixation (photosynthesis), and $NADP^+$ regeneration through the Calvin cycle (Gunjan et al. 2014). Drought stress tolerance of plant varies from species to species and depend to a larger extent on time and intensity they spend under stressful surroundings. Research studies confirm that during drought conditions plants overproduce ROS (H_2O_2, $O_2^{\bullet}$, $^1O_2$, and $OH^{\bullet}$) which causes lipid peroxidation, denaturation of protein, DNA mutation, and eventually cell death (Molassiotis et al. 2016). However, plants protect themselves from negative effects of ROS by its several antioxidant enzymes like SOD, CAT, APX, and GR, while the degree of cellular oxidative damage depends on the capacity of their antioxidant defense system (enzymatic or non-enzymatic). Drought stress can be modulated by the application of different nanoparticles such as silica, silver, copper, ZnO, CeO_2, and many more. On the application of silica nanoparticles improvement in drought tolerance was observed in two sorghum (*Sorghum bicolor* L. Moench) cultivars (Hattori et al. 2005), *Crataegus* sp., and hawthorns (Ashkavand et al. 2015). Similar results were observed in wheat on the application of 1.0 mM sodium silicate (Pei et al. 2010). Sedghi et al. (2013) reported an increased rate of germination on the application of ZnO nanoparticles in soybean under drought-stressed conditions. Foliar application of some micronutrients like iron and titanium nanoparticles were reported to improve drought stress in safflower cultivars and wheat, correspondingly (Davar et al. 2014). Further, Zn and Cu nanoparticles reported improving drought stress by enhancing SOD and CAT enzymes in wheat that results in limiting lipid peroxidation and increasing relative water content by enhancing photosynthesis (Taran et al. 2017). CeO_2 nanoparticles when applied at 100 mg kg^{-1} reported enhancing photosynthesis and Rubisco carboxylase activity (Cao et al. 2017), while composite of CuO, ZnO, and B_2O_3 improve drought stress in *Glycine max* (Dimkpa et al. 2017). Encapsulated abscisic acid (ABA) was delivered successfully to *Arabidopsis thaliana* plant through glutathione-responsive mesoporous silica nanoparticles and their controlled release in plants increased the expression of ABA inducible marker gene (AtGALK2), ultimately improved drought resistance (Sun et al. 2018).

14.8 Impact of Nanoparticles on Plant Growth Under Metallic Stress

Excessive accumulation of metals in plants causes phytotoxicity, alters plant growth, and causes oxidative damage. Metal toxicity interferes with plant growth by suppressing activities of different plant enzymes, interrupting uptake of essential elements which leads to deficiency symptoms. Metals in growth medium are responsible for the overproduction of ROS, which leads to oxidative damage to biomolecules, cell structure, and cell membrane denaturation (Sharma et al. 2012). Biophysical barriers form the first line of defense against metallic stress. If metal passes through this barrier and enters cells, then plants resist metal uptake by its accumulated biomolecules such as organic acids, metal-chelates, and polyphosphates by activating cellular defense system which is responsible for ROS scrounging. However, timely and target-oriented stimulation of these antioxidant defense systems is essential to remove the effects of metallic stress. Nanoparticles (such as nano-selenium, nano-oxides of iron, manganese, and cerium) enters the contamination zone easily due to their smaller size and large surface area, possess a strong affinity towards metal/metalloids adsorption. Nanoparticles in plants retard metal-induced oxidative stress by regulating their energy metabolism, antioxidants, ROS production, and thereby mitigating abiotic stresses. Nanoparticles immobilize metal/metalloids in soil and improve the growth and development of plants during phytoremediation (Martínez-Fernández et al. 2017). Nano-TiO_2 has been reported to limit cadmium (Cd) toxicity and enhance photosynthesis and plant growth rate (Singh and Lee 2016), nano-scale hydroxyapatite mitigates Cd toxicity in *Brassica juncea* (Li and Huang 2014), and ZnO nanoparticles attenuate uptake of Cd in plants (Venkatachalam et al. 2017). Tripathi et al. (2015) demonstrated that silicon nanoparticles hampers Cr accumulation in growth medium and prevents pea seedlings against Cr (VI) phytotoxicity by enhancing the antioxidant defense system. However, research studies reveal that nanoparticles may yield good or bad effects on plants at any level. Toxicological studies of nanomaterials done so far provide a great understanding of nanoparticle interaction with the plants and their potential risk hazards associated with the abiotic stress management and crop productivity improvement (Mustafa and Komatsu 2016; Venkatachalam et al. 2017).

14.9 Impact of Nanoparticles on Plant Growth Under Ultraviolet Radiation Stress

Sunlight together with the UV-B radiation (280-315 nm) is unavoidable abiotic stress for photosynthetic organisms due to the continuous depletion of the ozone layer in the stratosphere. On exposure to such non-ionizing radiation, structural changes occur in cellular components such as DNA, protein, chloroplast, and also induces accumulation of ROS, and free radical scrounging enzymes like SOD (Hideg et al. 2013). Moreover, plants also accumulate phenolic compounds which absorb detrimental UV-radiations (Shen et al. 2010). Nanoparticles are known to intensify the harmful effects of UV-B radiation on plants such as the application of CuO nanoparticles alone on *Elodea nuttallii* (waterweed species) shows no detrimental effects but in combination with the UV-B radiation, induces considerable negative effects on biochemical and physiological traits (Regier et al. 2015).

14.10 Effect of Nanoparticles on Plant Growth Under Flooding Stress

During flooding state, plants suffer from hypoxia conditions because the rate of diffusion of O_2 is slower in water than in air. Flooding stress/hypoxia condition inhibits respiration, seed germination, root, vegetative and reproductive growth, hypocotyl pigmentation, and up-regulation of genes for ethylene synthesis (Komatsu et al. 2012). ATP formation is suppressed under hypoxic conditions, thus to sustain cellular energy level, flooded plants are required to shift their carbohydrate metabolism towards fermentation (Banti et al. 2013), and up-regulation of genes for alcohol dehydrogenase and pyruvate decarboxylase (Mustafa et al. 2015a). Nanoparticles mitigate flooding stress and improve plant growth by inhibiting ethylene biosynthesis (Syu et al. 2014). For instance, the silver nanoparticle treated plant shows less O_2 distress under flooding stress. Besides, employing a gel-free proteomic technique by Mustafa et al. (2015b), reported that Al_2O_3 nanoparticles treated soybean plant under flooding stress has shown better growth performance as compared to plant treated with Ag and ZnO by regulating metabolic pathways and cell death.

14.11 Conclusion and Prospects

Globally, in the arena of agriculture, nanobiotechnology has been used to improve the productivity of crops with quality enhancement by improving cultivation methods. Plants being sessile encounter a variety of abiotic stresses such as salinity, drought, extreme low/high temperature, metal toxicity, UV-B radiation, flooding, and many more in their whole life-span. They accommodate themselves at the biochemical, physiological, and molecular levels by regulating their genes and enzymes responsible for the antioxidant defense system as well as maintaining homeostasis. Plenty of nanoparticles have been exploited for up-regulating various genes and enzymes to mitigate different abiotic stresses but still in its early stage. So far, very little work has been done on the phytotoxicity of nanoparticles on plants, and there exists a huge gap in our understanding of the eco-toxicity, tolerable limit, and uptake capability of various nanoparticles in plants. Therefore, to prevent negative effects of nanoparticles on the environment and living commodity (flora and fauna), and to harness best peculiar attributes of nanoparticles for improving plant growth, development and productivity in stressed conditions, further research is urgently needed to have a clear-cut understanding of the nanoparticle interaction with the plants and environments. Moreover, there is a need to develop a regulatory framework established on the various research evidence which will limit mankind's exposure to undesirable bioengineered nanoparticles to a harmless level, although the application of nanoparticles had increase the productivity of crops. The remarkable applications of nanomaterials presents an optimistic prospect of nanobiotechnology with well understanding of their ecotoxicity and by including all the aspects like reutilizing, feasibility, manufacturing, and framework of policy to handle them securely and utilize them in an eco-friendly manner.

References

Aghdam MTB, Mohammadi H, Ghorbanpour M (2016) Effects of nanoparticulate anatase titanium dioxide on physiological and biochemical performance of *Linum usitatissimum* (*Linaceae*) under well watered and drought stress conditions. Rev Bras Bot 39:139–146

Ahmad P, Hashem A, Abd-Allah EF et al (2015) Role of *Trichoderma harzianum* in mitigating NaCl stress in Indian mustard (*Brassica juncea* L) through antioxidative defense system. Front Plant Sci 6:868. https://doi.org/10.3389/fpls.2015.00868

Alharby HF, Metwali EM, Fuller MP, Aldhebiani AY (2016) The alteration of mRNA expression of SOD and GPX genes, and proteins in tomato (*Lycopersicon esculentum* Mill) under stress of NaCl and/or ZnO nanoparticles. Saudi J Biol Sci 23(6):773–781

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

Apel K, Hirt H (2004) Reactive oxygen species: metabolism, oxidative stress, and signal transduction. Annu Rev Plant Biol 55:373–399

Asada K (1999) The water-water cycle in chloroplasts: scavening of active oxygens and dissipation of excess photons. Annu Rev Plant Physiol Plant Mol Biol 50(NaN):601–639

Ashkavand P, Tabari M, Zarafshar M et al (2015) Effect of SiO_2 nanoparticles on drought resistance in hawthorn seedlings. For Res Pap 76(4):350–359. https://doi.org/10.1515/frp-2015-0034

Azimi R, Borzelabad MJ, Feizi H, Azimi A (2014) Interaction of SiO_2 nanoparticles with seed prechilling on germination and early seedling growth of tall wheatgrass (*Agropyron elongatum* L.). Pol J Chem Tech 16:25–29

Banti V, Giuntoli B, Gonzali S et al (2013) Low oxygen response mechanisms in green organisms. Int J Mol Sci 14:4734–4761

Bhattacharjee S (2012) The language of reactive oxygen species signaling in plants. J Bot 2012:1–22. https://doi.org/10.1155/2012/985298

Boghossian AA, Sen F, Gibbons BM et al (2013) Application of nanoparticle antioxidants to enable hyperstable chloroplasts for solar energy harvesting. Adv Energy Mater 3(7):881–893. https://doi.org/10.1002/aenm.201201014

Cao Z, Stowers C, Rossi L et al (2017) Physiological effects of cerium oxide nanoparticles on the photosynthesis and water use efficiency of soybean (*Glycine max* (L.) Merr.). Environ Sci Nano 4(5):1086–1094. https://doi.org/10.1039/c7en00015d

Catalá A, Díaz M (2016) Editorial: impact of lipid peroxidation on the physiology and pathophysiology of cell membranes. Front Physiol 7:423. https://doi.org/10.3389/fphys.2016.00423
Caverzan A, Bonifacio A, Carvalho FEL et al (2014) The knockdown of chloroplastic ascorbate peroxidases reveals its regulatory role in the photosynthesis and protection under photo–oxidative stress in rice. Plant Sci 214:74–87. https://doi.org/10.1016/j.plantsci.2013.10.001
Chen T, Zou H, Wu X et al (2018) Nanozymatic antioxidant system based on mos_2 nanosheets. ACS Appl Mater Interfaces 10(15):12453–12462. https://doi.org/10.1021/acsami.8b01245
Cramer GR, Urano K, Delrot S et al (2011) Effects of abiotic stress on plants: a systems biology perspective. BMC Plant Biol 11:163. https://doi.org/10.1186/1471-2229-11-163
Davar F, Zareii AR, Amir H (2014) Evaluation the effect of water stress and foliar application of Fe nanoparticles on yield, yield components and oil percentage of safflower (*Carthamus tinctorious* L.). Int J Adv Biol Biomed Res 2(4):1150–1159
Demidchik V (2015) Mechanisms of oxidative stress in plants: from classical chemistry to cell biology. Environ Exp Bot 109:212–228. https://doi.org/10.1016/j.envexpbot.2014.06.021
DeRosa MC, Monreal C, Schnitzer M et al (2010) Nanotechnology in fertilizers. Nat Nanotechnol 5:91–94. https://doi.org/10.1038/nnano.2010.2
Dietz KJ (2015) Efficient high light acclimation involves rapid processes at multiple mechanistic levels. J Exp Bot 66:2401–2414
Dimkpa CO, Bindraban PS, Fugice J et al (2017) Composite micronutrient nanoparticles and salts decrease drought stress in soybean. Agron Sustain Dev 37:5. https://doi.org/10.1007/s13593-016-0412-8
Dimkpa CO, McLean JE, Latta DE et al (2012) CuO and ZnO nanoparticles: phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. J Nanopart Res 14(9):1125. https://doi.org/10.1007/s11051-012-1125-9
Dimkpa CO, Singh U, Bindraban PS et al (2019) Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. Sci Total Environ 688:926–934. https://doi.org/10.1016/j.scitotenv.2019.06.392
Djanaguiraman M, Nair, R, Giraldo, JP, Venkata Vara Prasad, P. (2018) Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. ACS Omega 3(10):14406–14416. https://doi.org/10.1021/acsomega.8b01894
Eckardt NA, Cominelli E, Galbiati M, Tonelli C (2009) The future of science: food and water for life. Plant Cell 21:368–372. https://doi.org/10.1105/tpc.109.066209
Foltete AS, Masfaraud JF, Bigorgne E et al (2011) Environmental impact of sunscreen nanomaterials: ecotoxicity and gentoxicity of altered TiO_2 nanocomposites on *Vicia faba*. Environ Pollut 159(10):2515–2522. https://doi.org/10.1016/j.envpol.2011.06.020
Foyer CH, Noctor G (2005) Redox homeostasis and antioxidant signaling: a metabolic inter-face between stress perception and physiological responses. Plant Cell 17(7):1866–1875. https://doi.org/10.1105/tpc.105.033589
Foyer CH, Noctor G (2013) Redox signaling in plants. Antioxid Redox Signal 18(16):2087–2090. https://doi.org/10.1089/ars.2013.5278
Foyer CH, Shigeoka S (2010) Understanding oxidative stress and antioxidant functions to enhance photosynthesis. Plant Physiol 155(1):93–100. https://doi.org/10.1104/pp.110.166181
Gapper C, Dolan L (2006) Control of plant development by reactive oxygen species. Plant Physiol 141:341–345
Ghorbanpour M, Hatami M (2014) Spray treatment with silver nanoparticles plus thidiazuron increases antioxidant enzyme activities and reduces petal and leaf abscission in four cultivars of geranium (*Pelargonium zonale*) during storage in the dark. J Hort Sci Biotech 89:712–718
Gill SS, Tuteja N (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol Biochem 48(12):909–930. https://doi.org/10.1016/j.plaphy.2010.08.016
Giraldo JP, Wu H, Newkirk GM, Kruss S (2019) Nanobiotechnology approaches for engineering smart plant sensors. Nat Nanotechnol 14(6):541–553. https://doi.org/10.1038/s41565-019-0470-6

Gratão PL, Polle A, Lea PJ, Azevedo RA (2005) Making the life of heavy metal-stressed plants a little easier. Function Plant Biol 32(6):481–494
Gunjan B, Zaidi MGH, Sandeep A (2014) Impact of gold nanoparticles on physiological and biochemical characteristics of *Brassica juncea*. J Plant Biochem Physiol 2(3):133–138. https://doi.org/10.4172/2329-9029.1000133
Haghighi M, Afifipour Z, Mozafarian M (2012) The effect of N-Si on tomato seed germination under salinity levels. J Biol Environ Sci 6(16):87–90
Haghighi M, Pessarakli M (2013) Influence of silicon and nano-silicon on salinity tolerance of cherry tomatoes (*Solanum lycopersicum* L.) at early growth stage. Sci Hortic 161:111–117. https://doi.org/10.1016/j.scienta.2013.06.034
Halliwell B (2006) Reactive species and antioxidants Redox biology is a fundamental theme of aerobic life. Plant Physiol 141:312–322
Hasanpour H, Maali-Amiri R, Zeinali H (2015) Effect of TiO_2 nanoparticles on metabolic limitations to photosynthesis under cold in *chickpea*. Russ J Plant Physiol 62:779–787
Hattori T, Inanaga S, Araki H et al (2005) Application of silicon enhanced drought tolerance in *Sorghum bicolour*. Physiol Plant 123:459–466
Hideg E, Jansen MA, Strid A (2013) UV-B exposure, ROS, and stress: inseparable companions or loosely linked associates? Trends Plant Sci 18(2):107–115. https://doi.org/10.1016/j.tplants.2012.09.003
Hilker M, Schwachtje J, Baier M et al (2015) Priming and memory of stress responses in organisms lacking a nervous system. Biol Rev 91:1118–1133. https://doi.org/10.1111/brv.12215
Hirel B, Le-Gouis J, Ney B, Gallais A (2007) The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. J Exp Bot 58:2369–2387. https://doi.org/10.1093/jxb/erm097
Iannone MF, Groppa MD, Desousa ME et al (2016) Impact of magnetite iron oxide nanoparticles on wheat (*Triticum aestivum* L.) development: evaluation of oxidative damage. Environ Exp Bot 131:77–88
Iqbal MS, Singh AK, Singh SP, Ansari MI (2020) Nanoparticles and Plant Interaction with Respect to Stress Response. In: Bhushan I, Singh V, Tripathi D (ed) Nanomaterials and environmental biotechnology. Nanotechnology in the life sciences. Springer, Cham, p 1–15. https://doi.org/10.1007/978-3-030-34544-0_1
Ismail A, Takeda S, Nick PR (2014) Life and death under salt stress: same players, different timing. J Exp Bot 65(12):2963–2979. https://doi.org/10.1093/jxb/eru159
Jaberzadeh A, Moaveni P, Reza H et al (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 Napoca 41:201–207. https://doi.org/10.15835/nbha4119093
Jaleel CA, Riadh K, Gopi R et al (2009) Antioxidant defense responses: Physiological plasticity in higher plants under abiotic constraints. Acta Physiol Plant 31(3):427–436. https://doi.org/10.1007/s11738-009-0275-6
Jiang QY, Zhuo F, Long SH et al (2016) Can arbuscular mycorrhizal fungi reduce Cd uptake and alleviate Cd toxicity of *Lonicera japonica* grown in Cd–added soils? Sci Rep 6(1):21805. https://doi.org/10.1038/srep21805
Kah M, Tufenkji N, White JC (2019) Nano-enabled strategies to enhance crop nutrition and protection. Nat Nanotechnol 14(6):532–540
Kalteh M, Alipour ZT, Ashraf S et al (2014) Effect of silica nanoparticles on basil (*Ocimum basilicum*) under salinity stress. J Chem Health Risks 4:49–55
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. https://doi.org/10.1016/j.niox.2012.07.005
Khare T, Kumar V, Kishor PBK (2014) Na^+ and Cl^- ions show additive effects under NaCl stress on induction of oxidative stress and the responsive antioxidative defense in rice. Protoplasma 252:1149–1165. https://doi.org/10.1007/s00709-014-0749-2

Kiapour H, Moaveni P, Habibi D, Sani B (2015) Evaluation of the application of gibbrellic acid and titanium dioxide nanoparticles under drought stress on some traits of basil (*Ocimum basilicum* L.). Int J Agr and Agrl Res 6(4):138–150

Komatsu S, Hiraga S, Yanagawa Y (2012) Proteomics techniques for the development of flood tolerant crops. J Proteome Res 11:68–78. https://doi.org/10.1021/pr2008863

Kumar M (2013) Crop plants and abiotic stresses. J Biomol Res Ther 3:125. https://doi.org/10.4172/2167-7956.1000e125

Kumar V, Khare T (2014) Individual and additive effects of Na^+ and Cl^- ions on rice under salinity stress. Arch Agron Soil Sci 61(3):381–395. https://doi.org/10.1080/03650340.2014.936400

Latef AAHA, Alhmad MFA, Abdelfattah KE (2017) The possible roles of priming with ZnO nanoparticles in mitigation of salinity stress in lupine (*Lupinus termis*) plants. J Plant Growth Regul 36(1):60–70

Lei Z, Mingyu S, Xiao W et al (2008) Antioxidant stress is promoted by nano-anatase in spinach chloroplasts under UV-B radiation. Biol Trace Elem Res 121:69–79. https://doi.org/10.1007/s12011-007-8028-0

Leterrier M, Corpas FJ, Barroso JB et al (2005) Peroxisomal monodehydroascorbate reductase Genomic clone characterization and functional analysis under environmental stress conditions. Plant Physiol 138(4):2111–2123. https://doi.org/10.1104/pp.105.066225

Li J, Chang PR, Huang J et al (2013) Physiological effects of magnetic iron oxide nanoparticles towards watermelon. J Nanosci Nanotechnol 13(8):5561–5567. https://doi.org/10.1166/jnn.2013.7533

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 2014:1–7. https://doi.org/10.1155/2014/470962

Majumdar S, Almeida IC, Arigi EA et al (2015) Environmental effects of nanoceria on seed production of common bean (*Phaseolus vulgaris*): a proteomic analysis. Environ Sci Technol 49:13283–13293

Margis R, Dunand C, Teixeira FK, Margis-Pinheiro M (2008) Glutathione peroxidase family-an evolutionary overview. FEBS J 275(15):3959–3970. https://doi.org/10.1111/j.1742-4658.2008.06542.x

Martínez-Fernández D, Vitkova M, Vaňková Z, Komárek M (2017) Engineered nanomaterials for phytoremediation of metal/metalloid-contaminated soils: implications for plant physiology. In: Ansari A, Gill S, Gill R et al (eds) Phytoremediation. Springer, Cham, p 369–403. https://doi.org/10.1007/978-3-319-52381-1_14

Maxwell DP, Wang Y, Mcintosh L (1999) The alternative oxidase lowers mitochondrial reactive oxygen production in plant cells. Proc Natl Acad Sci USA 96(14):8271–8276. https://doi.org/10.1073/pnas.96.14.8271

Meena KK, Sorty AM, Bitla UM et al (2017) Abiotic Stress Responses and Microbe-Mediated Mitigation in Plants: The Omics Strategies. Front Plant Sci 8:172. https://doi.org/10.3389/fpls.2017.00172

Mignolet-Spruyt L, Xu E, Idanheimo N et al (2016) Spreading the news: subcellular and organellar reactive oxygen species production and signalling. J Exp Bot 67:3831–3844

Miller G, Suzuki N, Ciftci-Yilmaz S, Mittler R (2010) Reactive oxygen species homeostasis and signalling during drought and salinity stresses. Plant, Cell Environ 33:453–467. https://doi.org/10.1111/j.1365-3040.2009.02041.x

Mishra S, Keswani C, Abhilash PC et al (2017) Integrated approach of agri-nanotechnology: challenges and future trends. Front Plant Sci 8:471. https://doi.org/10.3389/fpls.2017.00471

Mittler R (2002) Oxidative stress, antioxidants and stress tolerance. Trends Plant Sci 7(9):405–410. https://doi.org/10.1016/s1360-1385(02)02312-9

Mittler R, Vanderauwera S, Gollery M, Breusegem VF (2004) Reactive oxygen gene network of plants. Trends Plant Sci 9(10):490–498. https://doi.org/10.1016/j.tplants.2004.08.009

Mohammadi R, Maali-Amiri R, Abbasi A (2013) Effect of TiO_2 nanoparticles on chickpea response to cold stress. Biol Trace Elem Res 152(3):403–410. https://doi.org/10.1007/s12011-013-9631-x

Mohammadi R, Maali-Amiri R, Mantri N (2014) Effect of TiO_2 nanoparticles on oxidative damage and antioxidant defense systems in chickpea seedlings during cold stress. Russ J Plant Physiol 61(6):768–775. https://doi.org/10.1134/s1021443714050124

Molassiotis A, Job D, Ziogas V, Tanou G (2016) Citrus plants: a model system for unlocking the secrets of NO and ROS-inspired priming against salinity and drought. Front Plant Sci 7:229. https://doi.org/10.3389/fpls.2016.00229

Moustaka J, Tanou G, Adamakis ID et al (2015) Leaf age-dependent photoprotective and antioxidative response mechanisms to paraquat-induced oxidative stress in *Arabidopsis thaliana.* Int J Mol Sci 16(12):13989–14006. https://doi.org/10.3390/ijms160613989

Mukherjee A, Peralta-Videa JR, Bandopadhyay S et al (2014) Physiological effects of nanoparticulate ZnO in green peas (*Pisum sativum* L.) cultivated in soil. Metallomics 6(1):132–138. https://doi.org/10.1039/c3mt00064h

Mustafa G (1864) Komatsu S (2016) Toxicity of heavy metals and metal-containing nanoparticles on plants. Biochim Biophys Acta Bioenerg 8:932–944. https://doi.org/10.1016/j.bbapap.2016.02.020

Mustafa G, Sakata K, Hossain Z, Komatsu S (2015a) Proteomic analysis of flooded soybean root exposed to aluminum oxide nanoparticles. J Proteom 128:280–297. https://doi.org/10.1016/j.jprot.2015.08.010

Mustafa G, Sakata K, Hossain Z, Komatsu S (2015b) Proteomic study on the effects of silver nanoparticles on soybean under flooding stress. J Proteom 122:100–118. https://doi.org/10.1016/j.jprot.2015.03.030

Nair PMG, Chung IM (2015) Changes in the growth, redox status and expression of oxidative stress related genes in chickpea (*Cicer arietinum* L.) in response to copper oxide nanoparticle exposure. J Plant Growth Regul 34:350–361. https://doi.org/10.1007/s00344-014-9468-3

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. https://doi.org/10.1016/j.scitotenv.2016.10.017

Nath M, Bhatt D, Prasad R, Tuteja N (2017) Reactive oxygen species (ROS) metabolism and signaling in plant-mycorrhizal association under biotic and abiotic stress conditions. In: Varma A, Prasad R, Tuteja N. (eds) Mycorrhiza-eco-physiology, secondary metabolites, nanomaterials. Springer, Cham, Switzerland, p 223–232. https://doi.org/10.1007/978-3-319-57849-1_12

Negrão S, Schmöckel SM, Tester M (2017) Evaluating physiological responses of plants to salinity stress. Ann Bot 119(1):1–11

Okupnik A, Pflugmacher S (2016) Oxidative stress response of the aquatic macrophyte *Hydrilla verticillata* exposed to TiO_2 nanoparticles. Environ Toxicol Chem 35:2859–2866. https://doi.org/10.1002/etc.3469

Palmqvist NGM, Seisenbaeva GA, Svedlindh P, Kessler VG (2017) Maghemite nanoparticles acts as nanozymes, improving growth and abiotic stress tolerance in *Brassica napus.* Nanoscale Res Lett 12(1):631

Pandey B, Singh AK, Singh SP (2018) Nanoparticles mediated gene knock out through miRNA replacement: recent progress and challenges. In: Mishra RK, Thomas S, Mohapatra S et al (eds) Applications of targeted nano-drugs and delivery systems. Elsevier, p 469–497

Pandey S, Fartyal D, Agarwal A (2017) Abiotic stress tolerance in plants: myriad roles of ascorbate peroxidase. Front Plant Sci 8:581. https://doi.org/10.3389/fpls.2017.00581

Passardi F, Longet D, Penel C, Dunand C (2004) The class III peroxidase multigenic family in rice and its evolution in land plants. Phytochem 65(13):1879–1893

Pei S, Zhao J, Du J et al (2010) Direct reduction of graphene oxide films into highly conductive and flexible graphene films by hydrohalic acids. Carbon 48(15):4466–4474

Petrov V, Hille J, Mueller-Roeber B, Gechev TS (2015) ROS-mediated abiotic stress-induced programmed cell death in plants. Front Plant Sci 18(6):69. https://doi.org/10.3389/fpls.2015.00069

Porwal P, Porwal S, Singh SP et al (2020) Improving futuristic nanomaterial researches in forestry sector: An overview. In: Husen A, Jawaid M (eds.), In micro and nano technologies, Nanomaterials for agriculture and forestry applications, Elsevier, pp 505–518. https://doi.org/10.1016/B978-0-12-817852-2.00021-4

Porwal P, Sharma A (2016) Improving water quality through nanotechnology. Int J Appl Res Technol 1(2):119–133

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-TiO_2 improve the photosynthesis of tomato leaves under mild heat stress. Biol Trace Elem Res 156:323–328

Rajeshwari A, Kavitha S, Alex SA et al (2015) Cytotoxicity of aluminum oxide nanoparticles on *Allium cepa* root tip-effects of oxidative stress generation and biouptake. Environ Sci Pollut Res 22(14):11057–11066. https://doi.org/10.1007/s11356-015-4355-4

Rani H, Singh SP, Yadav TP et al (2020) In-vitro catalytic, antimicrobial and antioxidant activities of bioengineered copper quantum dots using *Mangifera indica* (L.) leaf extract. Mater Chem Phys 239:122052. https://doi.org/10.1016/j.matchemphys.2019.122052

Regier N, Cosio C, Moos VN, Slaveykova VI (2015) Effects of copper-oxide nanoparticles, dissolved copper and ultraviolet radiation on copper bio–accumulation, photosynthesis and oxidative stress in the aquatic macrophyte *Elodea nuttallii.* Chemosphere 128:56–61

Rezvani N, Sorooshzadeh A, Farhadi N (2012) Effect of nano-silver on growth of saffron in flooding stress. Int J Biol Biomol Agric Food Biotechnol Eng 6:11–16

Riahi-Madvar A, Rezaee F, Jalili V (2012) Effects of alumina nanoparticles on morphological properties and antioxidant system of *Triticum aestivum.* Iran J Plant Physiol 3:595–603

Rico CM, Lee SC, Rubenecia R et al (2014) Cerium oxide nanoparticles impact yield and modify nutritional parameters in wheat (*Triticum aestivum* L.). J Agric Food Chem 62:9669–9675

Rico CM, Peralta-Videa JR, Garadea-Torresdey JL (2015) Chemistry, biochemistry of nanoparticles, and their role in antioxidant defense system in plants. In: Siddiqui HM et al (eds) Nanotechnology and plant sciences. Springer International Publishing, Switzerland, pp 1–17

Rossi L, Zhang W, Lombardini L, Ma X (2016) The impact of cerium oxide nanoparticles on the salt stress responses of *Brassica napus* L. Environ Pollut 219:28–36

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

Sabaghnia N, Janmohammad M (2015) Effect of nano-silicon particles application on salinity tolerance in early growth of some lentil genotypes. Ann UMCS Biol 69(2):39–55

Samadi N, Yahyaabadi S, Rezayatmand Z (2014) Effect of TiO_2 and TiO_2 nanoparticle on germination, root and shoot length and photosynthetic pigments of *Mentha piperita.* Int J Plant Soil Sci 3:408–418

Sathiyanarayanan A (2018) Foliar Spray of Zinc Oxide Nanoparticles Improves salt tolerance in finger millet crops under glasshouse condition. SCIOL Biothnol 1(1):20–29

Scandalios JG (2005) Oxidative stress: molecular perception and transduction of signals triggering antioxidant gene defenses. Brazilian J Medic Biologic Res 38(7):995–1014

Sedghi M, Hadi M, Toluie SG (2013) Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. Ann WUT-ser Biol XVI(2):73–78

Shallan M, Hassan H, Namich AM, Ibrahim A (2016) Biochemical and physiological effects of tio_2 and sio_2 nanoparticles on cotton plant under drought stress. Res J Pharm Bio and Chem Sci 7(4):1540–1551

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. https://doi.org/10.1155/2012/217037

Shen X, Zhou Y, Duan L et al (2010) Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. J Plant Physiol 167:1248–1252

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

Singh AK, Pal P, Gupta V et al (2018) Green synthesis, characterization and antimicrobial activity of zinc oxide quantum dots using Eclipta alba. Mater Chem Phys 203:40–48
Singh AK, Porwal P (2020) Nanotechnology as Potential and innovative platform toward wastewater treatment: an overview. In: Bhushan I, Singh V, Tripathi D (eds) Nanomaterials and environmental biotechnology. Nanotechnology in the life sciences. Springer Nature Switzerland, p 201–220. https://doi.org/10.1007/978-3-030-34544-0_12
Singh AK, Yadav TP, Pandey B et al (2018b) Engineering nanomaterials for smart drug release: recent advances and challenges. In: Mishra RK, Thomas S, Mohapatra S et al (eds) Applications of targeted nano-drugs and delivery systems. Elsevier, p 411–449. https://doi.org/10.1016/B978-0-12-814029-1.00015-6
Singh J, Lee BK (2016) Influence of nano-TiO_2 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, Tripathi DK, Dubey NK, Chauhan DK (2016) Effects of nano-materials on seed germination and seedling growth: striking the slight balance between the concepts and controversies. Mater Focus 5(3):195–201
Singh SP, Ansari MI, Pandey B et al (2020) Recent trends and advancement toward phyto-mediated fabrication of noble metallic nanomaterials: focus on silver, gold, platinum and palladium. In: Singh VK, Tripathi DK (eds) Bhushan I. Nanomaterials and environmental biotechnology, Springer, pp 87–105
Soliman ASH, El-feky SA, Darwish E (2015) Alleviation of salt stress on *Moringa peregrina* using foliar application of nanofertilizers. J Hortic For 7:36–47
Song G, Gao Y, Wu H et al (2012) Physiological effect of anatase TiO_2 nanoparticle on *Lemna minor*. Environ Toxicol Chem 31:2147–2152
Sun D, Hussain HI, Yi Z et al (2018) Delivery of abscisic acid to plants using glutathione responsive mesoporous silica nanoparticles. J Nanosci Nanotechnol 18(3):1615–1625
Syu YY, Hung JH, Chen JC, Chuang HW (2014) Impact of size and shape of silver nanoparticles on *Arabidopsis* plant growth and gene exp-ression. Plant Physiol Biochem 83:57–64
Taran N, Storozhenko V, Svietlova N et al (2017) Effect of zinc and copper nanoparticles on drought resistance of wheat seedlings. Nanoscale Res Lett 12(1):60
Tripathi DK, Singh VP, Prasad SM et al (2015) Silicon nanoparticles (SiNp) alleviate chromium (VI) phytotoxicity in *Pisum sativum* (L.) seedlings. Plant Physiol Biochem 96:189–198
Upadhyaya H, Dutta BK, Panda SK (2018) Impact of zinc on dehydration and rehydration responses in tea. Biol Plant 62(2):395–399. https://doi.org/10.1007/s10535-017-0758-z
Venkatachalam P, Jayaraj M, Manikandan R et al (2017) Zinc oxide nanoparticles (ZnONPs) alleviate heavy metal-induced toxicity in *Leucaena leucocephala* seedlings: a physiochemical analysis. Plant Physiol Biochem 110:59–69
Wang W, Vinocur B, Altman A (2003) Plant responses to drought, salinity and extreme temperatures: towards genetic engineering for stress tolerance. Planta 218:1–14. https://doi.org/10.1007/s00425-003-1105-5
Wassim A, Ichrak BR, Sa¨ıda A (2013) Putative role of proteins involved in detoxification of reactive oxygen species in the early response to gravitropic stimulation of poplar stems. Plant Signal Behav 8(1):1–6
Wood ZA, Schroder E, Harris JR, Poole LB (2003) Structure, mechanism and regulation of peroxiredoxins. Trends Biochem Sci 28(1):23–40
Wu H, Shabala L, Shabala S, Giraldo JP (2018) Hydroxyl radical scavenging by cerium oxide nanoparticles improves *Arabidopsis* salinity tolerance by enhancing leaf mesophyll potassium retention. Environ Sci Nano 5:1567–1583
Xie X, He Z, Chen N et al (2019) The Roles of Environmental Factors in Regulation of Oxidative Stress in Plant. Biomed Res Int 2019:1–11. https://doi.org/10.1155/2019/9732325
Yao J, Cheng Y, Zhou M et al (2018) ROS scavenging Mn_3O_4 nanozymes for *in vivo* anti-inflammation. Chem Sci 9(11):2927–2933

You J, Chan Z (2015) ROS regulation during abiotic stress responses in crop plants. Front Plant Sci 6:1092. https://doi.org/10.3389/fpls.2015.01092
Zhang H, Du W, Peralta-Videa JR (2018) Metabolomics reveals how cucumber (*Cucumis sativus*) reprograms metabolites to cope with silver ions and silver nanoparticle-induced oxidative stress. Environ Sci Technol 52(14):8016–8026
Zhang Q (2007) Strategies for developing Green Super Rice. Proc Natl Acad Sci USA 104:16402–16409. https://doi.org/10.1073/pnas.0708013104
Zhao L, Lu L, Wang A et al (2020) Nanobiotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance. J Agric Food Chem. https://doi.org/10.1021/acs.jafc.9b06615
Zhao L, Peng B, Hernandez-Viezcas JA et al (2012) Stress response and tolerance of *Zea mays* to CeO_2 nanoparticles: cross talk among H_2O_2, heat shock protein and lipid peroxidation. ACS Nano 6:9615–9622