Beneficial Effects of Metal- and Metalloid-Based Nanoparticles on Crop Production

11

Josef Jampílek and Katarína Kráľová

11.1 Introduction

Because of the ever-increasing number of people on the planet, the demands for their nutrition are increasing (Population Institute 2017). On the other hand, increasing urbanization, industrialization, and pollution have led to the fact that the number of hectares of arable land, the quality of the soil, the amount of water resources, and the amount of rainfall decreased, and adverse effects such as drought, high temperatures, exhalation, etc. weaken plants that are increasingly being attacked by various pests including molds, bacteria, or insects, resulting in an overall crop decrease. In addition, excessive fertilization with chemical fertilizers in order to increase the fertility of the depleted soil is counterproductive (Bread for the World 2018; World Hunger Education Service 2018). Some of the abovementioned problems can be partially solved locally by using transgenic plants (Ahmad et al. 2012; Raven 2014; Ahanger et al. 2017); however, the overall antagonism against genetically modified crop plants gives space for other possible modern solutions, namely, the application of nanomaterials (FAO 2010, 2013; Sekhon 2014; Jampílek and Kráľová 2015, 2017a, b, 2018a; Prasad et al. 2017; Achari and Kowshik 2018; Agarwal et al. 2018).

Nanotechnology is a fast-growing field – so-called the key technologies of the twenty-first century – that provides for the development of materials that have new dimensions, novel properties, and a broader array of applications (e.g., Sekhon 2014; Jampílek and Kráľová 2015, 2017a, b, c, 2018a, b, c; Prasad et al. 2017;

J. Jampílek (✉)
Department of Analytical Chemistry, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, Bratislava 842 15, Slovakia

Regional Centre of Advanced Technologies and Materials, Faculty of Science, Palacký University, Olomouc, Czech Republic

K. Kráľová
Institute of Chemistry, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, Bratislava 842 15, Slovakia

D. G. Panpatte, Y. K. Jhala (eds.), *Nanotechnology for Agriculture*,
https://doi.org/10.1007/978-981-32-9370-0_11

Ventola 2017; Achari and Kowshik 2018; Agarwal et al. 2018). Real nanoparticles (NPs) are defined by US National Nanotechnology Initiative in the range 1–100 nm (National Nanotechnology Initiative 2018). According to the Recommendation on the Definition of a Nanomaterial adopted by the European Commission, the term “nanomaterial” means “a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm” (European Commission 2018).

NPs, nanoformulations, and nanomaterials can be prepared from inorganic or organic materials or their combinations (e.g., Bhushan et al. 2014; Pisárčik et al. 2017, 2018; Jampílek and Kráľová 2018b), and, in general, nanomaterials in agriculture and food industry have been widely used as nanofertilizers/systems for delivery of nutrients, for crop protection (pesticides, agrotextiles), and for protection of foods (Campos et al. 2016, 2018; Jampílek and Kráľová 2015, 2017a, b, 2018a, c; Achari and Kowshik 2018; Kah et al. 2018, Panpatte et al. 2016). Thus, application of nanotechnology can be considered as an excellent tool for increased crop production. Nevertheless, as mentioned above, nanoscale materials change properties and behavior of all pattern materials, and thus many nanomaterials showed not only benefits but also adverse effects and toxicity. It was observed that NPs are able to generate reactive oxygen species (ROS) and oxidative stress, to interact with cellular components and many enzymatic systems (Dietz and Herth 2011; Dolez 2015; Hossain et al. 2015; Marmiroli and White 2016). At exposure to toxic metals, the oxidative stress in plants results in changes in processes at molecular, biochemical, morphophysiological, and whole levels, and therefore plants generate specific, appropriate protective/defensive mechanisms to suppress toxic effects of these pollutants (Wani et al. 2018). ROS also affect the expression of a number of genes and therefore control many processes like growth, cell cycle, programmed cell death, abiotic stress responses, pathogen defense, systemic signaling, and development, and therefore plants have antioxidant defense systems to protect plant cells from oxidative damage by scavenging of ROS, whereby the major sites for the production of $^1O_2$ and $O_2^{\bullet-}$ in chloroplasts are photosystem (PS) I and PSII (Gill and Tuteja 2010). Moreover, metallic NPs, similar to toxic metal ions, when applied in excess are particularly harmful to plants causing damage in the structure and function of the photosynthetic apparatus; reduction in concentration of photosynthetic pigments, especially chlorophyll (Chl); and disruption of grana and other malformations in chloroplasts, resulting in reduced photosynthetic efficiency of PSII and decreased net photosynthesis and finally in reduced plant growth (Masarovičová et al. 2010, 2014; Masarovičová and Kráľová 2013; Tighe-Neira et al. 2018; Kráľová et al. 2019). On the other hand, some metal NPs, e.g., TiO_2 NPs, were found to improve photosynthetic efficiency by increasing electron flow between the PSII and PSI in the Hill reaction as well as cause an increase in ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) activity in the Calvin and Benson cycle, whereby enhanced photosynthetic efficiency helps to achieve the sustainable yield (Su et al. 2007; Gao et al. 2008; Hasanpour et al. 2015; Tighe-Neira et al. 2018).

Chemical nature, size, shape, surface charge, and the dose introduced are the major factors responsible for the processes of intracellular NPs penetration (Dykman and Shchyogolev 2017; Burman and Kumar 2018). However, it is necessary exactly to estimate the concentration range for individual plant species, in which the particular metal NPs exhibit plant growth stimulation, while higher concentrations are phytotoxic, and verify it in field conditions. Investigation of transgenerational impact of metal-based NPs on the seed quality and the development of second-generation seedlings is desirable as well (Medina-Velo et al. 2018; Tan et al. 2018).

This contribution comprehensively reviews recent findings related to the beneficial effects of metal- and metalloid-based NPs on crops. Attention is focused on their potential to be used as plant growth-promoting compounds and components of fertilizer preparations and their favorable effects in reducing harmful impact of abiotic stresses (drought, salinity, flooding and waterlogging, soil acidity, temperature, UV light, elevated CO_2, toxic metal pollutants) on plants. The effects of metal-based NPs on crops based on the composition, particle size, particle shape, morphology, surface coating, and concentration of the NPs as well as their mechanism of action are discussed as well.

11.2 Metal-Based Nutrient Elements in Nanofertilizers

Application of fertilizers can significantly increase production up to 35–40%, when the right nutrients are applied at the right rate, at the right time, and in the right place for the selected crop (Mikkelsen 2011). In agricultural practice, the use of slow-release fertilizers delivering the nutrient stepwise or controlled-release fertilizers having plant nutrient in a form that plant cannot immediately absorb, and thus the uptake is delayed after application and plant will receive available nutrients for a longer time, is much-favored (Shaviv 2005; Trenkel 2010; Noh et al. 2015). Plant nutrient management is crucial to many current global sustainability issues, and the responsible nutrient management and sustainable agricultural production must include also consideration of environmental, economical, and social components (Mikkelsen 2011). Ferti-fortification, i.e., fertilizing crops with micronutrients such as Fe, Zn, Mn, Cu, S, and Mo, can largely help in alleviating micronutrient malnutrition in human population. Accumulation of essential elements in the edible tissues of crops using agro-biotechnological techniques (e.g., gene overexpression and activation control), and their direct fortification into formulation of processed foods could increase the concentration and bioaccessibility of these bioactive ingredients (Gharibzahedi and Jafari 2017; Dapkekar et al. 2018). Li et al. (2016a) assessed current foliar fertilizers in terms of their solubility, morphology, and surface properties and presented new screening criteria of new-generation micronutrient foliar fertilizers focusing on design of nanoscale foliar fertilizers and development of long-term micronutrient foliar fertilizers based on the nanotechnology.

Widespread use of chemical fertilizers in order to increase the crop productivity can disturb the soil mineral balance, decrease soil fertility, and cause severe damage to microbial flora and plants. Therefore recently increased attention is devoted to nanoscale fertilizers that are characterized not only with their size but also with high surface area, sorption capacity, and ability to increase the nutrient use efficiency through mechanisms such as targeted delivery and slow or controlled release resulting in improved crop yields. Nanofertilizers show beneficial impact on seed germination rate, seedling growth, photosynthetic activity, nitrogen metabolism, and carbohydrate and protein synthesis, and their contribution to the pollution of environment is considerably lower than that of chemical fertilizers (Liu and Lal 2015; Solanki et al. 2015; Mani and Mondal 2016; Chhipa 2017; Hatami 2017; Jampílek and Kráľová 2017b; Khan and Rizvi 2017; Dimkpa and Bindraban 2018).

In this context, it could be mentioned that toxic metals accumulated in edible part of crops could threaten human health, and therefore, it is necessary to perform life cycle assessment (LCA), i.e., quantitative assessment of emissions, resources consumed, and the potential impacts on health and the environment that can be attributed to a product over its entire life cycle (Suppan 2017).

At over-application of fertilizers, undesirable effects for plants could occur connected with the loss of these nutrients in runoff resulting finally in environmental pollution (Wilson et al. 2008). As application of chemical fertilizers also could be connected with adverse effects on the environment reflected in pollution of atmosphere and groundwater, soil acidification, eutrophication, reduced soil fertility, loss of biodiversity, and high consuming of energy in synthesis processes, the use of nanosized fertilizers requiring lower amounts of active ingredient to the same or improved effects is at most desirable (Jampílek and Kráľová 2017b; El-Ghamry et al. 2018).

Nanofertilizers could be applied as foliar sprays, by addition to soil or by soaking seeds in nanofertilizer (Duhan et al. 2017; Preetha and Balakrishnan 2017). Benefits of nanotechnology applications as nanofertilizers or nano-encapsulated nutrients used in horticulture on germination and growth of plants were reported by Feregrino-Perez et al. (2018).

Metal/metalloid nutrient elements that are required for growth of plants are as follows: K, Ca, Mg, Fe, Mn, B, Zn, Cu, and Mo; some other such as Ni, Se, V, Na, Si, Co, and Al could be also considered as important elements for plants showing at low doses beneficial effect on plant growth (Liu et al. 2015; Fernández-Luqueño et al. 2015; López-Valdez et al. 2018). Both macronutrients (K, Mg, and Ca) and micronutrients (Cu, Zn, Mn, Fe, Ni, Al, Co, and Na) are indispensable for growth and development of plants being involved in many important processes, including activation of enzymes and catalytic active cofactors or enhancement of resistance to biotic and abiotic stresses (Hänsch and Mendel 2009; Marschner 2012; Dalcorso et al. 2014; Tripathi et al. 2014, 2015a; Hasanuzzaman et al. 2018).

For slow and steady release of potassium, an alkali metal belonging to metal macronutrients, slow-release fertilizers using microporous aluminosilicate minerals, zeolites, are used. Although zeolites' particles often do not occur at nanoscale, their nanostructures are represented by channels and voids with diameters of 0.3–10 nm created by dimensional framework of SiO_4 and AlO_4 tetrahedra, which could be laden, for example, with potassium along with other slowly dissolving ingredients (e.g., Ca) and further minor and trace nutrients (Liu and Lal 2015; Zhou and

Huang 2007). Due to density of negative charge in the structure and the dimensions of interior channels, the natural zeolite can highly selectively adsorb NH_4^+ and K^+ compared to Na^+ or divalent cations such as Ca^{2+} and Mg^{2+}. Retention of these nutrients in the root zone to be used by plants as needed by zeolites contributes to improved plant growth. *Brassica alboglabra* Bailey grown in soil amended with NH_4^+- and K^+-loaded zeolite showed an increase in the total harvest weight, whereby high levels of the N and K contents were maintained in the soils (Li et al. 2013), and similar growth responses of hot pepper to application of NH_4^+- and K^+-loaded zeolite fertilizer were reported as well (Li et al. 2010).

The K^+-loaded zeolites as well-suited for plant growth applications were recommended also by Beitollah et al. (2009). Adequate levels of macronutrients (N, P, and K) for plants can be achieved by slow-release fertilizer consisting of NH_4^+- and K^+-saturated clinoptilolite phosphate rock media (Allen et al. 1993). Ball-milled clinoptilolite achieving nano-dimension (90–110 nm) that was fortified with Zn by loading $ZnSO_4$-released Zn for a period of 1176 h, while the Zn release from the $ZnSO_4$ lasted only 216 h, suggesting that the nanoscale clinoptilolite could be used as a slow-release Zn fertilizer and improve Zn use efficiency by crops (Yuvaraj and Subramanian 2018).

For the loading of NPK fertilizers, also chitosan (CS) NPs were used (Corradini et al. 2010; Hasaneen et al. 2014). Foliar treatment of *Ocimum basilicum* plants with nanocalcium and nanopotassium chelate fertilizers increased harvest index, grain yield, biological yield, calcium percentage, potassium percentage, and Chl content in plants (Ghahremani et al. 2014).

Treatment of peanut (*Arachis hypogaea*) plants grown on sand supplemented with Hoagland solution and $CaCO_3$ NPs (20–80 nm, 160 mg/L as Ca) considerably improved seedling dry biomass by 15%, and at co-application of $CaCO_3$ NPs with humic acids (1000 mg/L), even 30% increase in plant biomass was observed (Liu et al. 2005). Application of calcium phosphate nanogel fertilizer composites (CAPNGFC) increased the germination of rice and peanut (Umarani and Mala 2013a) and showed a significant increase in amylase and protease activity as well as weight per fruit in *Abelmoschus esculentus* (Umarani and Mala 2013b). Calcium phosphate NPs (CaPNPs) in combination with both the arbuscular mycorrhizal fungus *Glomus mosseae* and endosymbiont *Piriformospora indica* more effectively stimulated *Zea mays* growth than the combinations of CaPNPs + *G. mosseae*, CaPNPs + *P. indica*, or CaPNPs alone, and the treated plants showed improved Chl*a* content and performance index (Rane et al. 2015).

11.2.1 Beneficial Effects of Essential Metal-Based Nanoparticles on Plant Growth

Beneficial impact of nanoscale metal and metal oxide micronutrients on plant growth was reported by many researchers (e.g., Masarovičová and Kráľová 2013; Masarovičová et al. 2014; Liu and Lal 2015; Tripathi et al. 2015a; Jampílek and Kráľová 2017b; Ruttkay-Nedecky et al. 2017). Seed quality is an important factor for the successful cultivation of crops. Germination of seeds starts with the uptake of water, followed by rapid imbibition of water by seeds until all of the matrices and cell contents are fully hydrated, which is essential to set in motion the metabolic events in seeds that are metabolically inactive in the mature dry state. In germination process, protein synthesis and respiratory activity initially involve components stored within the mature dry seed, and increases or modifications of hormones, especially gibberellin, also play an important role (Nonogaki et al. 2010). Several metals and metalloids applied in bulk as well as nanoscale forms were reported significantly to improve seed germination (e.g., Prasad et al. 2012; Siddiqui and Al-Whaibi 2014; Anusuya and Banu 2016; Subbaiah et al. 2016; Guha et al. 2018).

11.2.1.1 Copper and Copper Oxide Nanoparticles

Application of CuNPs through hydroponic solution or as spray enhanced the growth of maize plants by 51% compared to control, and it was found that CuNPs tested in this study could enter into the plant cell, easily be assimilated by plants, and cause plant growth stimulation by regulating the different enzyme activities, showing the highest impact on glucose-6-phosphate dehydrogenase (Adhikari et al. 2016). External Cu microparticles and CuNPs applied to soil at a dose of 0–200 mg Cu/kg did not affect Chl and malondialdehyde (MDA) content and shoot length, while they increased water content (6.9-12.5%) and reduced shoot biomass of *Origanum vulgare* plants (Du et al. 2018). Based on proteomic and physiological analyses of wheat seeds exposed to 25 ppm CuNPs (a concentration causing increased spike length, number of grains per spike, and 1000 grain weight in tested wheat varieties), Yasmeen et al. (2017) estimated increased levels of proteins involved in starch degradation and glycolysis as well as increased sugar content, superoxide dismutase (SOD) activity, and Cu content in CuNP-treated seeds suggesting improved stress tolerance in wheat through CuNPs by mediating the process of starch degradation, glycolysis, and tricarboxylic acid cycle. CuNPs biosynthesized by *Citrus medica* L. fruit extract applied at doses up to 20 μg/mL increased mitotic index in actively dividing cells of *Allium cepa* (Nagaonkar et al. 2015). Lopez-Vargas et al. (2018) reported that following the treatment of tomato plants with CuNPs, the production of fruits with greater firmness, increased vitamin C and lycopene contents, enhanced ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)diammonium salt) antioxidant capacity, increased activity of SOD and catalase (CAT), and decreased APX and glutathione peroxidase (GPX) activity was observed. Biogenic CuNPs with the size 20 nm showed a significant increase in height, root length, fresh and dry weights, and performance index of pigeon pea (*Cajanus cajan* L.) seedlings (Shende et al. 2017).

Cu-CS NPs at a dose up to 0.12% enhanced percent germination, shoot and root length, root number, seedling length, fresh and dry weight, and seed vigor index of maize seedlings and induced the activities of α-amylase and protease enzymes, increased the total protein content in germinating maize seeds, and decreased content of starch suggesting that enhanced seedling growth was connected by mobilizing the reserved food, primarily starch, through the higher activity of α-amylase (Saharan et al. 2016). Beneficial impact of CuNPs absorbed on CS hydrogels on tomato growth and quality was reported also by Juarez-Maldonado et al. (2016). Cu-CS NPs exhibited promising stimulatory effects on plant height, ear length, ear weight/plot, grain yield/plot, and 100 grain weight of maize also in field experiment, and treated plants showed notable defense response reflected in higher activities of antioxidant enzymes, SOD and peroxidase (POD), and defense enzymes, polyphenol oxidase (PPO) and phenylalanine ammonia lyase, as well as higher Chl content (Choudhary et al. 2017). Both foliar spray and combined application (involving seed coat and foliar spray) of Cu-CS NPs were found to enhance the growth profile of finger millet plants and increased yield, which in the case of combined application resulted in a yield increase approx. by 89%, and increased defense enzymes in treated plants caused the suppression of blast disease (Sathiyabama and Manikandan 2018).

Application of CuNPs in CS-PVA hydrogels increased the yield and nutraceutical properties of the tomato fruits, which was reflected in increased numbers of leaves and clusters, fresh biomass of roots, and dry biomass of stems, leaves and roots of the plants as well as higher lycopene content and total antioxidant capacity in the fruits, whereby using a dose of 0.02 mg CuNPs, the lycopene content increased by 37% (Hernandez et al. 2017). Grafting is a cultivation technique that allows the plant to be more efficient in its utilization of water and nutrients, and CS-PVA hydrogels with CuNPs were found to improve the growth of grafted watermelon by inducing modifications in leaf micromorphology, increasing stoma width and primary stem and root length resulting in improved plant growth (Gonzalez et al. 2017).

Engineered NPs of essential metals have usually both stimulatory and inhibitory effects upon plant performance, whereby, in general, the concentration levels for the stimulatory effects of CuNPs were lower than for those for Fe^0NPs, but beneficial impact on plant growth showed also AuNPs at concentrations smaller than those of Fe^0NPs and CuNPs what could be attributed to effects on secondary metabolites (Tolaymat et al. 2017). Investigation of the impact of bimetallic (Cu and Au) alloy NPs in submerge root cultures of *Stevia rebaudiana* on the production of biomass and secondary metabolites showed that in the presence of naphthalene acetic acid (0.5 mg/L), application of 30 μg/L AuCu NPs stimulated biomass accumulation and enhanced total phenolic production, and total flavonoid production in adventitious root cultures of *Stevia rebaudiana* was estimated, best results being observed with AuCu NPs (1:3) (Ghazal et al. 2018).

Addition of crystalline monoclinic cubic CuO NPs with mean size 47 nm to in vitro culture of *Stevia rebaudiana* in Murashige and Skoog (MS) media using a concentration 10 mg/L resulted in notable enhancement of bioactive major steviol glycosides (rebaudioside A and stevioside) and total phenolic content as well as total flavonoid content (Javed et al. 2017a). It was found by Singh et al. (2017) that in contrast to treatments with 100 and 500 mg/L of CuO NPs, respectively, application of a low dose (10 mg/L CuO NPs) slightly increased Chl pigment and sugar content in tomato plants. Foliar application of 200 mg/L CuO NPs to 3-week-old soil-grown cucumber seedlings increased fruit fresh weight (Hong et al. 2016).

CuO NPs and ZnO NPs applied at a dose 10 mg/L were found to stimulate the growth of *Brassica napus* plants, and exposure of germinated seeds of rapeseed to these NPs caused changes in transcript levels of genes involved in signal transduction pathway including auxin-responsive protein, protein kinase, MPK3, and MPK4 both in root and shoot tissues (Rahmani et al. 2016). CuO and ZnO NPs at doses of ≥10 mg metal/kg were found to modify the production of key metabolites involved in plant protection in a root-associated microbe, *Pseudomonas chlororaphis* O6, and reprogramming of root morphology involving increases in root hair proliferation (CuO NPs) and lateral root formation (ZnO NPs) in wheat seedlings, and systemic changes in wheat shoot gene expression causing altered regulation for metal stress resilience as well as the potential for enhanced survival under stress were observed (Anderson et al. 2018).

11.2.1.2 Zinc and Zinc Oxide Nanoparticles

Foliar application of spherical Zn-CS NPs with particle diameters 250–300 nm and zeta potential of +42.34 mV containing 20 mg Zn/g (w/w) on two durum wheat cultivars grown in Zn-deficient sand media performed after anthesis (twice a week, for 5 weeks) resulted in 27 and 42% increase in grain Zn content suggesting that CS-based nanocarriers could be used in agronomic biofortification (Deshpande et al. 2017).

Presence of weathered and fresh ZnO NPs and Zn salt in soil stimulated grain yield in *Triticum aestivum* L. plants by 15% and 29%, respectively, whereby grain Zn content was increased (186% and 229% by weathered ZnO NPs and salt and 229% and 300% by fresh ZnO NPs and salt) and whereby grain Zn did not exist in ion form (Dimkpa et al. 2018). Amendments of ZnO NPs or Zn salt through soil and foliar pathways, under “low” and “high” levels of nitrogen, phosphorus, and potassium (NPK), showed that grain yield of sorghum notably increased by both Zn types; however the effect was insignificant when Zn was soil-applied at low NPK. While at all NPK levels and Zn exposure pathways, both Zn types increased N and K accumulation relative to control plants, P accumulation depended on both NPK level and Zn exposure pathway and enabled higher soil P retention (Dimkpa et al. 2017a).

ZnO NPs seed priming (25, 50, 75, 100 ppm) linearly increased the growth characteristics, photosynthesis, and biomass of wheat, and considerably higher Zn levels were estimated in the roots, shoot, and grains of treated plants compared to control indicating that such treatment could be suitable to reduce Zn deficiency in plants (Munir et al. 2018). Tomato seedlings, roots of which were treated at the 20-day stage of growth with 2–16 mg ZnO NPs/L and then transplanted and grew under natural environmental conditions, showed at the 45-day stage of growth considerably improved growth, photosynthetic efficiency, and activities of carbonic anhydrase and antioxidant systems; the best results, including maximum proline accumulation, were observed with the treatment of 8 mg ZnO NPs/L for 30 min (Faizan et al. 2018).

ZnO NPs (34 nm) applied at concentration 1 mg/L considerably enhanced steviol glycoside production in micropropagated shoots of *Stevia rebaudiana* Bertoni, while at higher concentrations, they were found to be phytotoxic, and strong decrease in the antioxidant activities and formation of secondary metabolites was observed (Javed et al. 2017b). Considerable increase in biomass, growth tolerance index, Chl contents, and antioxidant enzyme activities of rice seedlings treated with 100 mg/L ZnO NPs compared to control were estimated; however at concentrations >300 mg/L, phytotoxic effects were observed (Chutipaijit et al. 2018). Cucumber plants cultivated in soil amended with 5 mg ZnO NPs/kg soil showed enhanced yielding capacity by 36 %, and the fruits had more carotene, Zn, and Fe compared to the control, while accumulation of ZnO NPs in fruits was not estimated (Astafurova et al. 2017).

Seed priming with 100 ppm ZnO NPs for 6 h was shown to be an effective treatment in mitigating the harmful effects of Cu stress on growth as well as contents of Chl*a*, Chl*b*, soluble carbohydrates, and proteins of the 14-day-old *Vicia faba* seedlings that were irrigated with 150 mM $CuSO_4$ (Kasim et al. 2017).

Medina-Velo et al. (2018) reported that uncoated and coated ZnO NPs showed low residual transgenerational effects on seed composition, which could be beneficial in agricultural production. While ZnO NPs adversely affected the growth of eggplant in plant tissue culture, they enhanced eggplant growth under greenhouse conditions, whereby the accumulation of ZnO NPs in various parts of eggplant was observed in both plant tissue culture and greenhouse-cultivated seedlings (Thunugunta et al. 2018). Application of ZnO NPs (25 nm size) at 1000 ppm stimulated of both seed germination and seedling vigor of peanut plants, which was reflected in early flowering and higher leaf Chl content (Prasad et al. 2012). Low concentrations of ZnO NPs had beneficial impact also on seedling vigor, pigment, and protein and sugar content of tomato plants as well (Singh et al. 2016). Increased Chl content and maximal sugar accumulation were also recorded at treatment of *Brassica juncea* plants with 5 ppm ZnS NPs (Nayan et al. 2016). Germination of cucumber seeds treated with 1600 mg/L ZnO NPs increased by 10% (de la Rosa 2013).

An experiment performed under field conditions showed that foliar application of ZnO NPs and $ZnSO_4$ on wheat did not improve the grain yield or quality; however both treatments increased the grain Zn concentration (average increments were 5 and 10 mg/kg for $ZnSO_4$ and ZnO NPs, respectively), whereby Zn within the grain was always present as Zn phosphate, suggesting that the foliar application of ZnO NPs could be utilized for Zn biofortification (Zhang et al. 2018a). Application of 1500 ppm of ZnO NPs resulted not only in higher germination percentage (80%) and seedling vigor index (1923.20), but it also increased yield of maize by 42% compared to control and by 15% compared to treatment with 2000 ppm of $ZnSO_4$. Moreover, following treatment with 100 and 400 ppm ZnO NPs, accumulated Zn in grains reached 35.96 ppm and 31.05 ppm, respectively, suggesting successful biofortification with this essential metal (Subbaiah et al. 2016).

Humic acid priming was reported to improve the rice seed germination and seedling growth under ZnO NPs stress to some extent (Sheteiwy et al. 2017). Growth parameters of two rice cultivars were pronouncedly increased in seed priming with 30% polyethylene glycol (PEG) under ZnO NPs stress, and improvement in the cell structures of leaf and roots was observed as well (Salah et al. 2015).

Green synthesized ZnNPs (8–32 nm; irregular shape) and spherical CuNP (15–30 nm) enhanced the in vitro germination of *Citrus reticulata*, effect of ZnNPs being more significant (Hussain et al. 2017). Zn–Al layered double hydroxides (ZnAl-LDH) with borate association exhibited controlled-release of Zn and B contents initiating from the anionic exchange of BO_3^{3-} and the transformation of Zn^{2+} from LDH basal plane resulting in improvements in plant growth when used with the NPK fertilizer (Songkhum et al. 2018). Treatment of soybean seeds with Fe, ZnO, Cu, and Co NPs stimulated germination rate and the growth of primary roots and leaves, depending on concentrations of metal NPs used, and an increase of the root mitotic index compared to the control was observed as well (Hoe et al. 2018).

A comprehensive overview related to the beneficial and detrimental aspects of the ZnO NPs exposure toward various terrestrial plants was presented by Pullagurala et al. (2018).

11.2.1.3 Iron and Iron Oxide Nanoparticles

Fe^0NPs were found to penetrate the peanut seed coats resulting in increased water uptake and stimulating seed germination, and at treatment with 40 and 80 μmol/L, they stimulated the plant growth more effectively than ethylenediaminetetraacetate–iron (EDTA-Fe) solution, probably due to the uptake of Fe^0NPs by the plants (Li et al. 2015a). Priming with low doses of Fe^0NPs increased root and shoot length, biomass, and photosynthetic pigment content, the highest activities of hydrolytic and antioxidant enzymes, along with root dehydrogenase enzyme, being estimated at a dose of 20 mg/L, and even after 14 days of growth, neither membrane damage nor reduction in proline level and antioxidant enzyme activities were observed (Guha et al. 2018). Combine foliar application of MgNPs and FeNPs solutions to black-eyed pea (*Vigna unguiculata*) resulted in improved photosynthetic efficiency of plants and enhanced uptake of Mg in aboveground plant parts as well as increased seed weight, although reduced yield was observed at treatment with MgNPs alone (Delfani et al. (2014).

Foliar treatment of *Brassica juncea* plants with FeS NPs (4 ppm) solution at the 30th days after sowing showed maximal enhancement in agronomic attributes and higher Fe contents in plant organs, and improved redox status of the treated plants resulted in higher levels of photosynthates, whereby an increase in growth and seed yield was connected also with activation of both Rubisco small and large subunits, glutamine synthetase, and glutamate synthase genes suggesting that at specific growth stage, FeS NPs could activate carbon and nitrogen assimilatory pathways (Rawat et al. 2017).

The foliar application of nanoscale iron oxide on durum wheat plants at a dose 2 g/L was found to be the most effective in increasing Chl*a*, Chl*b*, total Chl, protein, Fe, and carbohydrate contents in leaves, as well as grain yield and grain Fe and protein contents (by 38 and 58%, respectively); however these parameters decreased at the higher rate of iron oxide NPs (Ghafari and Razmjoo 2015). Colloidal magnetic NPs of 10.5 nm coated with perchloric acid and applied in form of magnetic fluid (NPs volume fraction of 4.5%) at doses 10–50 μL/L promoted photosynthesis efficacy of maize plants, which was reflected in a small but statistically significant increase of the Chl*a*/Chl*b* ratio (Racuciu and Creanga 2007). Superparamagnetic iron oxide NPs (SPIONs) were found to play a crucial role on the enhancement of

Chl content in subapical leaves of soybean; however the photosynthesis efficiency obtained with this treatment was similar to that of conventional growth medium iron chelate (Ghafariyan et al. 2013). Treatment with 0.5 M γ-Fe_2O_3 NPs induced positive changes in the contents of Chl*a*, Chl*b*, and total carotene in tomato plants and increased the crop yield; treated plants were more resistant to chlorosis (Pavani et al. 2016). The γ-Fe_2O_3 NPs applied at a dose 20 mg/L notably stimulated root elongation by 11.5% and increased germination index and vigor index of maize by 27.2% and 39.6%, respectively; however at higher concentrations, the γ-Fe_2O_3 NPs, which entered plant roots and were mostly situated around the epidermis of root without translocation to shoots, caused oxidative stress exclusively in the roots, and phytotoxic effect was reflected in reduced Chl levels (Li et al. 2016b). Beneficial impact of Fe_2O_3 NPs on root length, plant height, and biomass of peanut (*Arachis hypogaea*) plants by regulating phytohormone contents and antioxidant enzyme activity was observed as well (Rui et al. 2016).

Treatment with 20–100 mg/L γ-Fe_2O_3 NPs increased the Chl contents of watermelon during the duration of exposure lasting 3 weeks, while Chl contents of *Zea mays* exposed to γ-Fe_2O_3 NPs were higher than in control only in the first week of treatment (Hu et al. 2018). Similarly, maize plants exposed to engineered ferrihydrite and hematite NPs showed increased growth and Chl content at doses 1, 2, and 4 g/L (Pariona et al. 2017). With increasing FeO NPs concentration from 0 to 0.75 g/L, Chl contents and the levels of lipids and proteins in soybean plants increased, while in the concentration range 0.75–1.0 g/L FeO NPs reduction of these parameters was observed (Sheykhbaglou et al. 2018). Use of magnetizing irrigation water notably improved growth, pigments, yield, nutritional and amino acids value in seeds, and water-use efficiency of faba bean plants compared to irrigation with normal water and was recommended as appropriate to improve productivity of faba bean under sandy soil conditions (Hozayn et al. 2016).

Based on the differences in root phytohormone production and antioxidant enzyme activity between transgenic and non-transgenic rice plants treated with γ-Fe_2O_3 NP, which were estimated in vivo, it could be suggested that the response of genetically modified crops treated with NPs will differ from that of conventional crops (Gui et al. 2015).

Adding Fe_3O_4 NPs (2000 mg/L) to 1 mM solutions of Pb, Zn, Cd, and Cu notably reduced growth inhibition of wheat seedlings caused by tested heavy metals due to reduction of oxidative stress by increasing the enzyme activity (SOD and POD), and the alleviating effect of Fe_3O_4 NPs was associated with their adsorption capacity of heavy metals (Konate et al. 2017).

In the maize plants fertilized with F_3O_4 NPs using half of the recommended dose of Fe in salt preparation (27 vs 54 M), positive effect on morphological features such as height and biomass of plant organs, leaf area, and proline content was observed (Elanchezhian et al. 2017). Maize plants (*Zea mays* L. cv. Merit) grown in calcareous soil foliar-sprayed with Fe_3O_4 NPs at a dose 100 mgFe/g had significantly improved Ca, Fe^{2+}, total Fe, and ferritin contents (164%, 200%, 300%, and 200% of the control), whereby enhanced growth of treated maize plants could be attributed, at least in part, to the increased content of ferritin that is decisive in maintenance of Fe homeostasis and balance of the plant redox system (Jalali et al. 2016). Soaking of *Phaseolus vulgaris* L. seeds in solution of PEG-coated Fe_3O_4 NPs (at 1000 mg Fe/L) did not affect seed germination but increased radicle elongation by 37% what might be related to water uptake enhancement induced by the PEG coating (Duran et al. 2018).

The responses of Fe_3O_4-treated lettuce plants grown in soil and soil bacterial community depended on the applied concentration of Fe_3O_4 NPs. At low concentrations, plant growth stimulation accompanied by the increased abundance of *Xanthomonadales* and the decreased abundance of *Cyanobacteria* and *Sphingobacteria* as well as no significant changes in bacterial alpha diversity indices was observed. Treatment with high doses of Fe_3O_4 NPs inhibited plant growth, decreased the phylogenetic diversity of bacterial community, reduced the abundances of *Xanthomonadales* and *Sphingobacteria*, and increased the proportion of *Cyanobacteria* (Xu et al. 2017).

MnO_x NPs and FeO_x NPs applied at low concentrations (<50 ppm) pronouncedly promoted the growth of lettuce seedlings by 12–54% (Liu et al. 2016). Better germination of maize seeds treated with MgO NPs prepared using aqueous leaf extracts of betel showed better germination, and enhanced plant growth was observed as well, whereby treatment with low MgO NPs concentrations resulted in increased Chl content compared to control suggesting that these NPs could be considered as an alternative source of fertilizers (Jayarambabu et al. 2016).

11.2.1.4 Nickel Nanoparticles

NiNPs (5 nm) at low concentrations (0.01 and 0.1 mg/L) did not affect or stimulated growth of 10-day-aged wheat seedlings and pronouncedly increased the intensity of photosynthesis and transpiration, while at application of 0.01 mg/L NiNPs, also slightly increased content of Chl*a* and Chl*b* was observed. However, Ni concentration in roots and shoots of NiNPs-treated plants (50.89 ± 1.67 and 14.20 ± 2.38 μg/g d.w., respectively) was considerably higher than in control plants (3.8 ± 0.15 and 0.87 ± 0.025 μg/g d.w.) (Zotikova et al. 2018).

11.2.2 Beneficial Effects of Other Metal- and Metalloid-Based Nanoparticles Stimulating Plant Growth

11.2.2.1 Silver Nanoparticles

In cucumbers exposed to AgNPs at concentrations <200 mg/L, stimulation of root elongation was observed, while at treatment with Ag^+, stimulation was estimated already at doses <5 mg/L, whereby both radish and wheat plants were more susceptible to the toxicity of AgNPs at the vegetative growth stage than the germination stage (Cui et al. 2014). Golabadi et al. (2015) investigated the effects of AgNPs on flower expression in greenhouse cucumber (*Cucumis sativus* L.) plants. The highest values for the number of male flower, male node, period of male flowering, and the number of male and female flower were obtained at 15-leaf stage. At applying spraying with 200 ppm AgNPs at 15-leaf stage, the highest number of male flower was produced. Application of AgNPs at concentration 100 mg/L stimulated growth of *Brassica rapa* ssp. *pekinensis* plants, while at concentrations ≥250 mg/L, phytotoxic effects were observed (Baskar et al. 2015). Pronouncedly enhanced number of seeds per pod, number of pods per plant, hundred seed weight, biological yield, and green pod yield over control were observed at treatment of *Pisum sativum* seeds and application of foliar spraying with AgNPs (10–100 nm) on pea seedlings using 60 ppm AgNPs (Mehmood and Murtaza 2017). Similarly, using seed soaking and foliage spraying of broad bean with biosynthesized AgNPs (10–100 nm) resulted in improved growth and yield of crops (Rashidi et al. 2016). Priming of maize seeds with 10 ppm AuNPs showed improved promoting emergence percentage, enhanced seedling vigor (threefold over the control), as well as improved physiological and biochemical properties of maize seedlings, whereby Au translocation from seeds into plant vegetative organs was minimized (Mahakham et al. 2016).

Exposure to low AgNPs concentrations (10, 20, 40 ppm) was reported notably to increase the Chl*a* and carotenoid contents in rice accompanied with enhanced shoot and root growth and biomass of the seedlings what could be connected with AgNPs-induced changes in antioxidative enzyme activities and related gene expression levels, low ROS level, and decreased lipid peroxidation and H_2O_2 content (Gupta et al. 2018).

Treatment of chickpea seeds with Ag–CS NPs (20–50 nm; 0.1%, w/v) resulted beside of significant stimulation of seed germination, seedling length, fresh and dry weight also in pronouncedly higher Chl levels and increased activities of enzymes (α- and β-amylase, APX, POD and CAT) in *Cicer arietinum* seedlings (Anusuya and Banu 2016).

The biomass of genetically transformed hairy root cultures of *Cucumis anguria* pronouncedly increased in the presence of AgNPs, and AgNPs-elicited hairy roots produced considerably higher amount of individual phenolic compounds (flavonols, hydroxycinnamic and hydroxybenzoic acids) and total phenolic and flavonoid contents than Ag^+-elicited hairy roots, whereby antioxidant, antimicrobial, and anticancer activities were also notably higher following AgNPs elicitation compared with that observed in Ag^+-elicited hairy roots (Chung et al. 2018).

11.2.2.2 Gold Nanoparticles

An experiment using seeds of a model plant of *Arabidopsis thaliana* showed that treatment with 24 nm AuNPs at a dose 10 μg/mL resulted in three-fold higher total seed yield compared to control and pronouncedly improved germination rate and vegetative growth, and free radical scavenging activity was observed at application of AuNPs doses 10 and 80 μg/mL, respectively, whereby microRNAs expression showed correlation with seed germination, growth, and antioxidant potential of plants on AuNPs exposure (Kumar et al. 2013).

Raliya et al. (2016) who delivered various Au nanostructures (30–80 nm) by aerosol application to a watermelon plant found that AuNPs were taken up by the plant through direct penetration and transport through the stomatal opening and translocated from leaf to root by the phloem transport mechanism, whereby the efficacy of translocation expressed by number of particles recovered in root decreased as follows, cube (20,000) > rhombic dodecahedral (15,000) > sphere

(9500) > rod (9000), suggesting improved translocation of low aspect ratio particles. Pronounced stimulation of watermelon root elongation treated with Au nanorods was reported by Wang et al. (2013), although at application of high concentrations, phytotoxic effects connected with oxidative stress were observed.

In hydroponically cultivated seedlings of rice, radish, and pumpkin, the positively charged AuNPs (6–10 nm) were most readily taken up by plant roots, and also when translocation to stems and leaves was found to be more efficient for negatively charged AuNPs, none of the AuNPs accumulated in the shoots of radish and pumpkin plants, while in rice shoots, accumulation of 1.1–2.9 ng/mg AuNPs was estimated (Zhu et al. 2012). Foliar spraying of *Brassica juncea* plants under field conditions with AuNPs (10, 25, 50, and 100 ppm) showed beneficial impact on plant height, stem diameter, number of leaves per plant, number of branches, number of pods, and seed yield and improved the redox status of the treated plants, the dose of 10 ppm being most effective, whereby an increase in reducing sugar as well as total sugar contents was observed up to 25 ppm AuNPs (Arora et al. 2012).

11.2.2.3 TiO_2 Nanoparticles

Foliar spraying of 14-day-old mung bean plants with 10 mg/L TiO_2 NPs caused pronounced improvement in shoot length (17.02%), root length (49.6%), root area (43%), root nodule (67.5%), Chl content (46.4%), and total soluble leaf protein (94%) in plants, and in 6-week-old plants, an increase in activities of enzymes over control was observed, which was 67.3% for acid phosphatase, 72% for alkaline phosphatase, 64% for phytase, and 108.7% for dehydrogenase (Raliya et al. 2015). Hydroponically grown cucumber (*Cucumis sativus*) plants treated with TiO_2 NPs (0–4000 mg/L) pronouncedly increased root length (>300%), and it was found that Ti was transported from the roots to the leaf trichomes, which could be considered as possible sink or excretory system for the Ti (Servin et al. 2012).

Treatment with TiO_2 NPs increased shoot length of rice plants cultivated in phosphorus-deficient soil up to 14.5%, and application of 750 mg/kg of TiO_2 NPs resulted in 2.6-, 2.4-, and 1.3-fold increase of P contents in rice roots, shoots, and grains (Zahra et al. 2017). Low concentrations (0.5–2 g/L) of TiO_2 NPs enhanced the growth of hydroponically cultivated *Solanum lycopersicum* plants approx. by 50%, and treatment with TiO_2 NPs was connected with approx. threefold increase of glutathione synthase and glutathione *S*-transferase expressions in both roots and leaves suggesting significant role of thiols in detoxification of TiO_2 NPs in tomato. Moreover, considerable increase in photosynthetic parameters such as quantum yield, performance index, and total Chl content as well as induced expression of PSI gene was observed in tomato plant exposed to 0.5–2 g/L of TiO_2 NPs with respect to untreated plants, while treatment with 4 g/L TiO_2 NPs had adverse impact on plant growth and photosynthetic performance of plants. It could be mentioned that application of TiO_2 NPs pronouncedly affected distribution of essential elements in tomato plant organs resulting in threefold higher P levels and 25% reduction in Fe contents (Tiwari et al. 2017). In *Brassica napus* L. plants treated with TiO_2 NPs (500, 2500, and 4000 mg/L), improved morphological (root length, plant height, fresh biomass) and physiological (photosynthetic gas exchange, Chl content, nitrate reductase activity) parameters and enhanced activity of antioxidant enzymes (SOD, POD, CAT) were estimated, whereby intact and typical grana and stroma in thylakoid membranes of chloroplast suggested that treatment with TiO_2 NPs did not induce the stressful environment within chloroplast (Li et al. 2015b).

Application of nano-anatase TiO_2 increased the activity of Rubisco activase also accompanied by conformational changes what resulted in strong stimulation of Rubisco carboxylation and the high rate of photosynthesis and was reflected in improved growth of *Spinacia oleracea* plants. Moreover, at treatment with nano-anatase TiO_2, Chl content was 17-fold higher, and photosynthetic rate showed a 29% increase compared to control (Gao et al. 2008). Nano-anatase TiO_2 markedly improved whole-chain electron transport, photoreduction activity of PSII, and O_2-evolving and photophosphorylation activity of spinach chloroplasts under visible light and UV light illumination. Moreover, nano-anatase h^+, which photogenerated electron holes, captured an electron from water, which accelerated water photolysis and O_2 evolution (Lei et al. 2007). Nano-anatase TiO_2 application was found to modify PSII microenvironment and increase absorbance for visible light, improve energy transfer among amino acids within PSII protein complex, and accelerate energy transport from tyrosine residue to Chl*a* resulting in enhanced photochemical activity of PSII and oxygen-evolving rate in spinach (Su et al. 2007). According to Hong et al. (2005), nano-anatase TiO_2 might bind to the PSI reaction center complex and intensify the function of the PSI electron donor, although it does not change the configuration of the PSI reaction center complex.

TiO_2 NPs applied at a dose of 10 ppm significantly reduced the mean germination time of wheat seeds to 0.89 days compared to control (1.35 days), and treatment with 2 and 10 ppm of bulk TiO_2 and TiO_2 NPs as well stimulated shoot and seedling lengths, effects of TiO_2 NPs being more pronounced; however treatments with high TiO_2 NPs doses caused inhibitory effects (Feizi et al. 2012). Although germination of *Triticum aestivum* was not affected by TiO_2 NP exposure (5, 50, and 150 mg/L), enhanced seedling shoot length at 3rd day was estimated, while at 20th day, it was reduced, whereby TiO_2 NPs phytotoxicity was more severe after longer exposure periods and higher applied doses, causing more severe damage in shoots than in roots (Silva et al. 2017). Exposure of wheat and rapeseed plantlets to TiO_2 NPs (14 nm or 25 nm anatase) in hydroponics conditions induced increased root elongation but did not affect germination, evapotranspiration, and plant biomass. Both TiO_2 NPs were accumulated in plantlets upon root exposure, Ti content being higher in rapeseed than in wheat, but TiO_2 NPs were able to accumulate in plantlets also upon leaf exposure (Larue et al. 2012). While application of 100 mg/L TiO_2 NPs and wastewater significantly inhibited maize seed germination and seedling growth and caused accumulation of phenolics in maize plants, treatment with 25 mg/L resulted in considerable increase of shoot fresh weight, shoot dry weight, root fresh weight, root dry weight, root area, and Chl*a*, Ch, and carotenoid content, and also the adverse effects caused by wastewater on growth of maize plants were pronouncedly improved in the presence of this TiO_2 NPs concentration (Yaqoob et al. 2018). In maize plants sprayed with 0.01% and 0.03% TiO_2 NPs at the reproductive stage (appearance of male and female flowers), considerable increase of Chl*a* Chl*b*, total Chl (*a* + *b*), Chl*a*/Chl*b*, carotenoid, and anthocyanin content was observed (Morteza et al. 2013). In wheat plants grown in soil spiked with 60 mg/kg TiO_2 NPs, Chl content increased by 32.3% compared to control; however at higher TiO_2 NPs concentration (100 mg/kg), a lower Chl content by 11.1% was estimated (Rafique et al. 2018), while exogenous application of TiO_2 NPs (100–800 mg/L) to Chainat 1 rice cultivar did not affect photosynthetic pigments Chl*a*, Chl*b*, and carotenoids (Samart et al. 2018). Spraying of *Phaseolus vulgaris* L. plants with TiO_2 NPs showed beneficial impact on Ch*a* and seed protein content, biological yield, grain weight, and grain yield, the most appropriate concentrations varied in the range from 0.02% to 0.05% and depended on the stage of plant growth in that spraying was applied (rapid vegetative growth, flowering and pod fill), and at foliar application, the TiO_2 NPs can reduce the effects of photo-oxidative stress and prevent the chloroplast destruction and Chl degradation of leaf tissue (Ebrahimi et al. 2016).

11.2.2.4 CeO_2 Nanoparticles

Treatment of barley plants with 125 mg CeO_2/kg soil resulted in a 331% increase in shoot biomass compared with the control, while application of a double dose caused an increase in grain Ce accumulation (by 294%) with concurrent notable increases in P, K, Ca, Mg, S, Fe, Zn, Cu, and Al as well as enhanced methionine, aspartic acid, threonine, tyrosine, arginine, and linolenic acid contents in the grains (Rico et al. 2015).

CeO_2 NPs (25 nm) at a dose of 50 mg/kg soil enhanced the fresh biomass accumulation of radish plants, root expansion being 2.2-fold higher compared to control, and relative Chl content was enhanced by 12.5, 12.9, and 12.2% when compared to control on the 40th day of cultivation in *Raphanus sativus* seedlings cultivated in soil amended with 10, 50, and 100 mg/kg CeO_2 NPs (<25 nm) (Gui et al. 2017).

Coriandrum sativum L. plants grown in soil amended with 125 mg/kg CeO_2 NPs produced longer roots, pronouncedly increased CAT activity in shoots and APX in roots, and changed the chemical environment of carbohydrates in cilantro shoots suggesting changed nutritional properties of cilantro by CeO_2 NPs (Morales et al. 2013). CeO_2 NPs at doses up to 4000 mg/L stimulated shoot elongation in maize, cucumber, and tomato, while root growth was promoted only in cucumber and maize (Lopez-Moreno et al. 2010).

11.2.2.5 Al_2O_3 Nanoparticles

Exposure of model plant *Arabidopsis thaliana* to 98 μM Al_2O_3 NPs stimulated root weight and length by 48% and 39%, respectively, had no adverse effect on photosynthesis and plant growth, and did not induce lipid peroxidation. Favorable impact of Al_2O_3 NPs was connected with an increase in the transcription of several genes involved in root growth as well as in root nutrient uptake (e.g., upregulation of the root hair-specific gene family and root development genes) (Jin et al. 2017). Similarly, low concentrations of Al_2O_3 NPs stimulated growth of *Brassica oleracea* var. *capitata* seedlings and also enhanced pigment, sugar, and protein contents of cabbage seedlings and induced activities of antioxidant enzymes (SOD, CAT, putidaredoxin), while higher concentrations exhibited negative effects. Consequently it could be assumed that at lower Al_2O_3 NPs concentration, the metabolic processes in cabbage were supported resulting in attenuation of toxic effects of Al^{3+} ions (Amist et al. 2017). In contrast to Al^{3+} ions, the Al_2O_3 NPs did not affect adversely the growth and did not induce oxidative stress in *Vigna radiata* seedlings, and due to adsorption/restriction of Al_2O_3 NPs on root surface, translocation of Al in exposed seedlings was low and Al in shoots was not detected (Shabnam and Kim 2018).

High abundance of proteins involved in oxidation–reduction, stress signaling, and hormonal pathways related to growth and development in soybean plants exposed to Al_2O_3 NPs stress estimated using proteomics could be responsible for optimum growth of Al_2O_3 NPs-stressed plants (Hossain et al. 2016).

11.2.2.6 Selenium Nanoparticles

Selenium in proper concentration is beneficial for the health of humans and animals, and it is supplied to the human organism with food; however due to low level of Se transfer from soil to the food chain, the agronomic biofortification of Se is necessary. As plants are the main source of this element, it is important to increase its levels in plants. Se at low concentrations acts as an antioxidant and through its antioxidative mechanism can serve to counter abiotic stresses. As excess of Se can be phytotoxic causing adverse effects such as inhibition of plant growth, wilting and drying of leaves, reduced protein synthesis, and death of immature plants, the use of nanomaterials in fertilization of plants with Se could be advantageous (Brodowska et al. 2016). Production, biological effects, and use of SeNPs in agroecosystems were summarized by El-Ramady et al. (2014).

Anion-responsive carbon nanosystem fabricated using polyethylenimine modified hollow/mesoporous carbon NPs, in which selenate could be effectively loaded, was reported to be suitable for controlling Se fertilizer release and improving Se utilization efficiency in vegetables (Zhang et al. 2018b).

SeNPs at concentrations 265–530 μM significantly stimulated the organogenesis and the growth of root system (approx. by 40%) by tobacco callus cultures in contrast to selenate, which showed inhibitory effects at the same dose. Moreover, using medium supplemented with 530 μM SeNPs, the roots of regenerated plantlets accumulated even 2,947 ± 99 mg Se/kg d.w. (Domokos-Szabolcsy et al. 2012). Se enrichment in perennial onion plants *Allium nutans* L., *A. schoenoprasum* L., and *A. obliquum* L. after spaying with SeO_4^{2-}, SeNPs, and SeO_3^{2-} containing the same Se concentration (2.34 mg Se/L or 32 μg Se per plant) was observed and the ratio Se_{leaves}/Se_{roots} (indicator of Se migration intensity) decreased in the following order Se(VI) > SeNPs (Se(0)) > Se(IV). Total Se content in leaves of perennial onions as a result of foliar fortification with SeNPs, Se(IV), and Se(VI) was 720, 410, and 1085 μg/kg d.w. in *A. nutans*; 1109, 565, and 2169 μg/kg d.w. for *A. schoenoprasum*; and 1108, 267, and 1215 μg/kg d.w. for *A. obliquum*, while in control plants, it was only 82, 91, and 153 μg/kg d.w. (Golubkina et al. 2012). Fortification of Chinese cabbage with Se using a nutrient containing SeNPs was described by Bi et al. (2010).

Spherical chitooligosaccharide–Se NPs with average particle size 100 nm and weak positive charge on the surface when used in the booting stage of rice seedlings were found to enhance rice production by 8–15%, total antioxidant capacity by 30–60%, and Se content by 3–10-fold suggesting that they could be used as plant nutrient regulator. The ability of these NPs to release Se slowly, especially in plant, contributes to increasing the effect of enrichment and stability in the rice endosperm (Tong et al. 2008). Stimulation of germination of wheat seeds using treatment of water-soluble composition of SeNPs in sodium alginate with concentration 1.0–3.0 mg/L (by Se) was patented by Jurkova and Omelchenko (2016).

11.2.2.7 SiO_2 Nanoparticles

Beneficial effects on morphological, physiological, and biochemical characteristics of plants *Hyssopus officinalis* L. and *Nigella sativa* L. and field crops *Zea mays* L. and *Phaseolus vulgaris* L. were observed at treatment with 400 mg/L SiO_2 NPs (Sharifi-Rad et al. 2016). Treatment of wheat plants with 500 and 1000 mg/L of mesoporous SiO_2 NPs caused enhancement of seed germination and resulted in increased plant biomass, total protein and Chl content, as well as photosynthetic activity of seedlings; oxidative stress or cell membrane damage was not observed even at 2000 mg/L SiO_2 NPs (Sun et al. 2016). SiO_2 NPs applied at concentrations 25, 50, and 100 mg/L increased fresh and dry weights, length and number of branches, and Chl in explants of apple rootstock MM106 in tissue culture, concentration of 100 mg/L being the most effective (Avestan et al. 2016). In maize plants grown in soil, an amendment of SiO_2 NPs to soil at a dose of 15 kg/ha positively impacted besides Chl content also proteins and phenols (Suriyaprabha et al. 2012). Application of 8 g/L SiO_2 NPs (12 nm) significantly improved seed germination percentage, mean germination time, seed germination index, seed vigor index, fresh weight, and dry weight of tomato seedlings (Siddiqui and Al-Whaibi 2014). Pre-sowing of sunflower seeds in low concentration SiO_2 NPs solutions (0.2 and 0.4 mM) considerably reduced days needed to 50% germination and mean germination time and improved root length, mean daily germination, seedling vigor index, and final germination percentage suggesting beneficial effect of SiO_2 NPs nanopriming on *Helianthus annuus* plants (Janmohammadi and Sabaghnia 2015).

Potato (*Solanum tuberosum* var. Agria) plants treated with four different silicon compounds (nanosilica, sodium silicate, nanoclay, and bentonite) in greenhouse conditions using doses 1000 and 2000 ppm, respectively, enhanced all root characteristics, and application of 1000 ppm bentonite enhanced leaf dry weight up to 18%, and increased stem diameter up to 17% was observed after treatment with 1000 ppm of nanoclay and bentonite. Moreover, treatment with Si improved minituber quality characteristics as well (Soltani et al. 2018). Co-application of NPK fertilizer in combination with NanoChisil (fertilizer CS NPs and SiO_2 NPs) and NPK fertilizer with nanosilica (fertilizer SiO_2 NPs) increased plant height, number of leaves, wet weight, and dry weight of *Zea mays* L. plants, the best results being observed for the ratio 25% NanoChisil: 75% NPK (Pertaminingsih et al. 2018).

The results of seed germination and root elongation experiments showed that Al_2O_3 and TiO_2 NPs notably reduced the germination percentage of maize seeds and inhibited root elongation, while SiO_2 NPs and microparticles (MPs) enhanced them. The tested metal oxide NPs penetrated seeds showing greater seed uptake compared to MPs, which decreased in the order $SiO_2 > TiO_2 > Al_2O_3 > ZrO_2$, whereby ZrO_2NPs and MPs did not affect germination and root growth (Karunakaran et al. 2016).

Foliar and soil application of nanosized Si and Zn to rice plants in a field experiment resulted in considerably higher yields compared to the control, although yields did not differ significantly between the fertilized treatments, whereby co-application of nanosized Si and Zn increased the grain and straw yields, yield components, and Si, Zn, and N concentrations in rice grain and straw (Kheyri et al. 2018).

11.3 Coating

The coating process of nanomaterials is reflected in modified surface properties, and thus, a negative or positive charge on the surface obtained due to coating agents affects interaction of nanomaterials with the environment and could increase or decrease their impact on plants. Metal-based nanomaterials are usually coated with natural organic compounds including CS, dextran, alginate, or citric acid (Lopez-Moreno et al. 2018).

Zou et al. (2017) compared the effects of Ag^+ ions as well as citrate- and adenosine triphosphate (ATP)-coated AgNPs on *Wolffia globosa* and found that Ag^+ and ATP-coated AgNPs inhibited Hill reaction activity, reduced soluble proteins, and caused depletion of sugars; considerable increase of SOD and POD activity as well as inhibition of P and K uptake and stimulation of Fe and Cu was observed as well. On the other hand, in the presence of the citrate-coated AgNPs, Hill reaction activity was not affected; however accumulation of sugars and stimulation of Cu uptake were estimated. Based on these findings, it was assumed that at exposure to ATP-coated AgNPs, ATP would act as an exogenous energy source of plant metabolisms, while at treatment with citrate-coated AgNPs, citrate could serve as the substrate for the tricarboxylic acid cycle, and accumulated sugar may stimulate pentose phosphate pathways.

Biosynthesized AgNPs capped with phytochemicals present in the plant extract of kaffir lime leaf (5 and 10 ppm) pronouncedly improved germination performance of aged rice seeds and seedling vigor compared to control or conventional hydropriming. These AgNPs enhanced α-amylase activity, resulting in higher soluble sugar content for supporting seedling growth, and promoted the upregulation of aquaporin genes in germinating seeds, while higher ROS production was observed in seeds treated with AgNPs nanopriming. According to researchers, nanopriming-induced seed germination could be connected with creation of nanopores for improved water uptake, rebooting ROS/antioxidant systems in seeds, and generation of OH radicals for cell wall loosening, and AgNPs could serve as nanocatalyst for fastening starch hydrolysis (Mahakham et al. 2017).

Phytochemical-capped AuNPs prepared using rhizome extract of galanga plant (*Alpinia galanga*) and applied at concentration 5 ppm as nanopriming agent to activate the germination and early seedling growth of maize aged seeds exhibited the best effects on promoting emergence percentage (83%) compared to unprimed control (43%) and hydroprimed groups (56%) and enhanced seedling vigor index by threefold over the control. Although the AuNPs were found to be internalized into seeds, they were not present in both shoots and roots, suggesting that the Au translocation from seeds into plant vegetative organs practically did not occur (Mahakham et al. 2016). Citrate- and tannate-coated AuNPs (10, 30, and 50 nm) bioaccumulated in hydroponically cultivated *Nicotiana tabacum* L. var. Xanthi nc., but no bioaccumulation of these NPs was observed in *Triticum aestivum* plants (Judy et al. 2012).

Investigation of phytotoxicity of CuO NPs to rice seedlings in the presence of humic acid (HA) showed that HA coatings on NPs surfaces, which resulted in enhanced electrostatic and steric repulsion between the CuO NPs and the plant cell wall/membrane, thus reducing contact between NPs and plant, were reflected in reduced oxidative damage in plant cells (Peng et al. 2015).

Investigation of the effect of bare and PEG-coated Fe_3O_4 NPs on the germination and seedling development of *Phaseolus vulgaris* L. showed that seed soaking in the solution of PEG-coated Fe_3O_4 NPs (at 1000 mg Fe/L) increased radicle elongation by approx. 37% (which could be connected with the enhancement of water uptake induced by the PEG), while ionic iron forms Fe^{2+}/Fe^{3+} and bar Fe_3O_4 NPs showed growth-inhibiting effect. Moreover, treatment with PEG-coated Fe_3O_4 was found to be the least harmful to α-amylase (Duran et al. 2018). In sunflower seedlings treated with sodium oleate-coated magnetite and cobalt ferrite NPs, inhibition of Chl biosynthesis was observed, while zinc ferrite NPs with the same coating enhanced the Chl and carotene levels at some concentrations, although diminished Chl ratio estimated at exposure to all three types of magnetic NPs suggested slight adverse effect on the light harvesting complex II (LHC II) from the chloroplast membranes reflected in impaired photosynthesis efficiency (Ursache-Oprisan et al. 2010).

Investigation of transgenerational effects of TiO_2 NPs in basil plants performed by Tan et al. (2018) was focused on the evaluation of the impacts of successive exposure to TiO_2 NPs with different surface properties, whereby seeds from plants exposed or re-exposed to pristine, hydrophobic, or hydrophilic TiO_2 NPs were cultivated for 65 clays in soil unamended or amended with 750 mg/kg of the respective particles. The researchers found that sequential exposure to hydrophobic or hydrophilic TiO_2 NPs resulted in more adverse effects on photosynthesis but in positive effects on plant growth, compared to pristine TiO_2 NPs.

Different responses of hydroponically cultivated wheat seedlings exposed to 20 mg/L CeO_2 NPs (approx. 4 nm) functionalized with positively or negatively charged or neutral dextran coating were observed. Independently of CeO_2 NPs surface charge, in both roots and leaves a reduction (15–20%) from Ce(IV) to Ce(III) was observed; however positively charged NPs adhered to negatively charged cell walls most strongly. On the other hand, treatment with uncharged and negatively charged CeO_2 NPs resulted in higher Ce leaf concentrations compared with positively charged ones. While in plants treated with negatively charged NPs allocation of Ce was estimated mostly in the leaf veins, in plants exposed to uncharged CeO_2 NPs Ce was found in clusters in the nonvascular leaf tissue suggesting that NP coatings can be designed to target NPs to specific parts of plants (Spielman-Sun et al. 2017). In the soil poor in organic matter, the organic citrate coating of CeO_2 NPs significantly enhanced the phytoavailability of the Ce by forming smaller aggregates, thereby facilitating the transport of NPs to the roots of tomato (Layet et al.

2017). CeO_2 NPs coated with citrate acid (CA) at 1:7 ratio applied at a dose of 200 mg/L to radish (*Raphanus sativus*) produced significantly more root biomass, increased water content, and reduced the Ce uptake by 94% compared to bare NPs suggesting that this coating decreased CeO_2 NPs toxicity to plants (Trujillo-Reyes et al. 2013). Both uncoated and citrate acid (CA)-coated CeO_2 NPs applied at a dose of 500 mg/kg increased shoot length of tomato plants (approx. by 9 and 13%, respectively) and did not affect the homeostasis of nutrient elements in roots, stems, and leaves or CAT and APX in leaves, and pronounced increase of total Chl, Chl*a*, and Chl*b* was observed only at exposure to 250 mg/kg CA-coated CeO_2 NPs. The surface coating reduced Ce uptake by roots but did not affect its translocation to the aboveground organs (Barrios et al. 2016). Coating of CeO_2 NPs with citrate reduced the impact on microbial enzymatic activities but triggered variability in the bacterial community structure near the rapeseed roots (Hamidat et al. 2016). The soil moisture content affected the physiological impact of positively charged CeO_2 NPs and negatively charged CeO_2 NPs with polyvinylpyrrolidone (PVP) coating on soybean plants whereby positive effect on plant photosynthesis was observed at the moisture content >70% (Cao et al. 2018). Treatment of soybean seedlings with both types of CeO_2 NPs using concentration 100 mg/kg resulted in stimulation of plant growth and photosynthesis rate (by 54% for bare and 36% for PVP-coated CeO_2 NPs) and improved Rubisco activity was estimated as well. On the other hand, higher concentration of CeO_2 NPs (500 mg/kg) inhibited net photosynthesis rate, and further increasing of CeO_2 NPs concentration resulted in inhibition of Rubisco activity (Cao et al. 2017). Alginate surface coating increased the uptake of Ce in *Zea mays* plants treated with CeO_2 NPs (Zhao et al. 2012).

Superhydrophobic surface on controlled-release fertilizers that was prepared using bio-based polyurethane derived from liquefied wheat straw modified with organosilicon and SiO_2 NPs to increase the nanoscale surface roughness and reduce the surface energy making it in such way superhydrophobic improved their controlled-release characteristics (Zhang et al. 2017).

11.4 Beneficial Effects of Metal- and Metalloid-Based Nanoparticles on Plants Under Abiotic Stress

Plants as sessile organisms are exposed to different abiotic stresses, i.e., environmental conditions that reduce growth and yield below optimum levels. Drought, heat, cold or chilling, flooding/waterlogging, salinity, UV light, toxic metal pollutants, and high soil acidity are abiotic stresses which represent major threat to food security due to the constant changes of climate and deterioration of environment caused by anthropogenic activities (e.g., Macedo 2012; Calanca 2017; Sha Valli Khan et al. 2018). However, abiotic stresses could also affect the amount and composition of secondary metabolites in crops and modify their nutritional value and health benefits (e.g., Szabó et al. 2003; Ramakrishna and Ravishankar 2011; Javed et al. 2017a, b; Masarovičová et al. 2019). Abiotic stress tolerance in plants is a complex process, involving many different metabolic pathways and cellular and molecular components, and improving crop tolerance is a major goal of crop improvement programs (e.g., Shanker and Venkateswarlu 2011; Onaga and Wydra 2016; Bechtold and Field 2018; Sha Valli Khan et al. 2018). Recently it was shown that also metal and metalloid NPs could be successfully used to alleviate detrimental impact of abiotic stresses on crops (e.g., Khan et al. 2017).

11.4.1 Drought

Drought is a physiological form of water deficit, where soil water available to the plant is inadequate, which adversely affects the plant's metabolism and can significantly reduce crop productivity. Water stress induces a decrease in leaf water potential and in stomatal opening resulting in the downregulation of photosynthesis-related genes and reduced availability of CO_2, loss of turgor, and changes in membrane fluidity and composition, solute concentration as well as protein–protein and protein–lipid interactions. Endogenous abscisic acid (ABA), which is rapidly produced during drought, triggers a cascade of physiological responses, including stomatal closure, which is regulated by a signal transduction network. During water stress, enhanced ABA accumulation in plants is observed, which plays also an important role in the tolerance against dehydration. In response to a water deficit stress, ion and water transport systems across membranes function to control turgor pressure changes in guard cells and stimulate stomatal closure (Chaves et al. 2003; Osakabe et al. 2014; Kumar et al. 2018). Plants could adapt to water by morphological, physiological, and biochemical responses, e.g., reduced leaf area, efficient rooting system, reduced transpiration, better water-use efficiency, stomatal activity, and accumulation of proline, polyamine, and trehalose (Haworth et al. 2013; Kumar et al. 2018). A comprehensive chapter focused on plant drought stress, its effects on plant's resistance mechanisms, and management strategies to cope with this global challenge was presented by Kumar et al. (2018). Findings related to the mechanisms of gene regulation and the roles of protective metabolites in drought stress tolerance and the progress in genetic or metabolic engineering for enhanced drought tolerance in crop plants were summarized by Valliyodan and Nguyen (2006).

A decrease of adverse effects of drought upon plants of steppe ecotype Acveduc at application of CuNPs and ZnNPs was manifested mainly in enhanced activity of antioxidative enzymes reducing the level of accumulation of thiobarbituric acid-reactive compounds, stabilizing the content of photosynthetic pigments, and increasing relative water content (RWC) in leaves, while in the forest-steppe wheat (Stolichna) ecotype, the degree of improvement of these characteristics was lower (Taran et al. 2017). Using foliar application of ZnNPs under drought stress produced by interrupted irrigation during flowering stage of wheat, it was found that treatment with ZnNPs had beneficial effect on pronouncedly reduced grain yield and its components, plant height, RWC, and Chl content caused by water deficit stress, whereby application of 2 g/L ZnNPs in flowering stage of plants was found to be most efficient (Ghassemi and Farahvash 2018).

Besides application of salicylic acid (SA) that could compensate adverse effects of drought stress on strawberry plantlets and improve their growth parameters under in vitro culture, the efficiency of tissue culture and in vitro culture of strawberries was found to be improved also by application of iron NPs suggesting that combined treatment with SA and iron NPs could ensure higher quantity and quality in the in vitro culture of strawberries and could be used for adapting strawberry plants to drought before transplanting them in the field (Mozafari et al. 2018).

Under drought condition corresponding to 50% field moisture capacity (causing a decrease of soybean shoot growth by 27% and grain yield by 54%), application of nanoscale ZnO, B_2O_3, and CuO and their salts ($ZnSO_4.7H_2O$, H_3BO_3, and $CuSO_4.5H_2O$) to soil or foliar application 3 weeks after seed germination of soybean reduced drought effects by increasing shoot growth by 33% and grain yield by 36%, and a pronounced increase in levels of N, K, Zn, B, and Cu in shoots and grains was estimated as well. At foliar application, the effects of NPs and salts were similar, but application of salts to soil mitigated drought stress more effectively than foliar application (Dimkpa et al. 2017b). Nanomaghemite (NMH; Fe_2O_3, γ-Fe_2O_3) addition to soil stimulated the growth of sunflower primarily due to the insolubilization of pore water Zn in the soil, thus reducing its availability to the plants, and in contrast to plants growing on soil without NMH amendment, during the water stress, it did not cause an increase in the accumulation of proline or total amino acids in the plants. Consequently, NMH could be a useful soil amendment during phytoremediation procedures, since it can immobilize trace elements in the soil without disrupting the plant water balance (Martinez-Fernandez et al. 2015).

Foliar pretreatment of cotton plants with TiO_2 and SiO_2 NPs increased the pigment content, total soluble sugars, total phenolics, total soluble proteins, total free amino acids, proline content, total reducing power, total antioxidant capacity, and antioxidant enzyme activities and caused enhancement of yield characteristics, which were reduced by drought stress, concentrations 50 ppm of TiO_2 and 3200 ppm of SiO_2 being the most effective (Shallan et al. 2016). Water stress induced by PEG-6000 reduced germination percentage and germination rate (GR) of tomato (*Lycopersicum esculentum* Mill cv. 'Falcato') as concentration increased from -2 to -8 bars, while treatment with SiNPs at a dose of 1 or 2 mM, respectively, was able to improve GR under PEG-induced stress at -4 and -8 bars (Haghighi et al. 2013). Silicon application was reported to be useful in the improvement of the drought tolerance of sorghum through the enhancement of water uptake ability (Ahmed et al. 2011).

Foliar-sprayed CeO_2 NPs (10 mg/L) considerably reduced leaf $O_2^{\bullet-}$ (41%) and H_2O_2 (36%) levels and decreased cell membrane lipid peroxidation (37%) in *Sorghum bicolor* (L.) Moench plants under drought imposed at the booting stage by withholding water for 21 days. Moreover, treatment with CeO_2 NPs caused an increase in leaf carbon assimilation rates (38%), pollen germination (31%), and seed yield per plant (31%) in drought-stressed plants compared to controls suggesting protection of sorghum plants from oxidative damage resulting in higher grain yield (Djanaguiraman et al. 2018a).

11.4.2 Flooding and Waterlogging

Flooding may occur as an overflow of water from waterbodies (rivers, lakes, or ocean), due to an accumulation of rainwater on saturated ground in an areal flood or when the flow rate exceeds the capacity of the river channel (Meteorology glossary 2012). In plants growing in areas prone to flooding, the roots cannot respire due to excess water in the soil profile resulting in insufficient oxygen in the pore space of plant roots. Thus, maintenance of a functional root system upon flooding is essential, because roots are vital for plant function (Sauter 2013).

Treatment of soybean under flooding stress with AgNPs was found to have beneficial effect on plant growth. In early-stage soybean plants exposed to flooding that were treated with 15 nm AgNPs at 2 ppm, enhanced growth and differentially changed 107 root proteins predominantly associated with stress, signaling, and cell metabolism were estimated. Time-dependent increase of abundances of glyoxalase II 3 and fermentation-related proteins under flooding stress decreased at addition of AgNPs, and alcohol dehydrogenase 1 and pyruvate decarboxylase 2 genes, upregulated under flooding stress, were downregulated in response to AgNPs. Moreover, in AgNPs-treated plants lower amount of cytotoxic by-products of glycolysis was estimated. Better growth performance of AgNPs-treated soybean plants under flooding stress could be connected with reduced oxygen deprivation stress (Mustafa et al. 2015). Proteomic analysis of soybean root exposed to varying sizes of silver nanoparticles under flooding stress showed that different sizes of AgNPs might affect the soybean growth under flooding by regulating the proteins related to amino acid synthesis and wax formation. Treatment with AgNPs of 15 nm promoted soybean growth under flooding compared to 2 and 50–80 nm AgNPs, and exposure to 15 nm AgNPs also resulted in the increase of ribosomal proteins, while these decreased in the presence of other NP sizes. Based on in silico protein–protein interaction, β-ketoacyl reductase 1 as the most interacted protein under AgNPs of 15 nm (while least interacted under other sizes) was upregulated in the presence of 15 nm AgNPs, and its enzyme activity was decreased (Mustafa et al. 2016).

In the waterlogging environment, when roots cannot respire due to excess water in the soil profile, the deposition of iron plaque on plant roots affects the fate of metal-based NPs. For example, at treatment with 100 mg/L CuO NPs, iron plaque dramatically reduced the Cu contents in rice roots and shoots by 89% and 78%, respectively, compared to control iron plaque; however lower percentage of CuO but higher proportion of Cu(I) in shoots was estimated in plants exposed to CuO NPs with the formation of iron plaque. From low amounts of CuO NPs absorbed by roots via root hairs or lateral roots, which were translocated to shoots and in leaf veins of rice plants with iron plaque, >90% of total Cu(II) was reduced to Cu(I)–cysteine and Cu_2O (Peng et al. 2018). However, treatment of flooded paddy soil with CuO and TiO_2 NPs (100, 500, and 1000 mg/kg soil) adversely affected soil microbes and reduced the composition and diversity of the paddy soil microbial community, toxic effect of CuO NPs being more strong, whereby CuO NPs may also indirectly affect soil microbes by changing nutrient bioavailability (Xu et al. 2015).

Proteomic technique was used to investigate the response of soybean plants under flooding exposed to various sizes (30–60 nm) of Al_2O_3 NPs. In the presence of Al_2O_3 NPs in stressed plants increased length of the root, including hypocotyl and suppression of proteins related to glycolysis was observed, whereby the scavenging activity of cells was mediated by regulating the ascorbate/glutathione pathway, and mitochondrion was found to be the target organelle of Al_2O_3 NPs under flooding stress conditions. Al_2O_3 NPs of various sizes affected mitochondrial proteins under flooding stress by regulating membrane permeability and tricarboxylic acid cycle activity (Mustafa and Komatsu 2016). Quantitative proteomic analysis of post-flooding recovery in soybean roots exposed to Al_2O_3 NPs showed that a total of 211 common proteins were changed in abundance during the recovery period after treatment without or with Al_2O_3 NPs. These proteins were related to protein synthesis, stress, cell wall, and signaling, and it was found that *S*-adenosyl-L-methionine-dependent methyltransferases and enolase might be involved in mediating recovery responses by Al_2O_3 NPs. It could be also noted that treatment with 50 ppm Al_2O_3 NPs enhanced survival percentage of seedlings, which showed also improved seedling weight and weight/length of root including hypocotyl during the period of recovery (Yasmeen et al. 2016).

11.4.3 Salt Stress

Soil salinity is established as one of the major environmental problems decreasing crop productivity worldwide, thereby threatening sustainable agriculture. Maize, rice, and wheat having a prominent role in feeding the world's population are sensitive to salinity stress, and their growth and production are significantly retarded by salinization effects (Majeed et al. 2018). Excess salt reduces water potential and causes ion imbalance or disturbances in ion homeostasis and toxicity and adversely affects germination, growth, photosynthetic pigments and photosynthesis, water relation, nutrient imbalance, oxidative stress, and crop yield. Due to the osmotic or water deficit, salinity reduces the ability of the plant to take up water due to presence of salt in soil solution, which results in reduced plant growth, and too high salt concentration in the transpiration stream causing injury to cells in the transpiring leaves contributes to plant growth reductions as well (Parihar et al. 2015). Under salt stress, plants accumulate osmotic adjustment substances and synthesize proline, soluble sugars, glycine, betaine, and other osmolytes to promote osmotic balance at the cellular level. Under high salinity stress, the increase of ROS in the plant leads to lipid peroxidation in the cell membrane (Liang et al. 2018). Strategies to mitigate the salt stress effects on photosynthetic apparatus and productivity of crop plants were reviewed by Mbarki et al. (2018).

Investigation of the impact of 5 mmol/kg of NaCl, KCl, or $CaCl_2$ and root exudates on transformation and changes of the bioactivity of CuO and ZnO NPs on wheat showed that phytotoxic effect of ZnO NPs reflected in the reduction in shoot and root elongation and lateral root induction was attenuated by the used salts, while NaCl and KCl promoted Zn loading into shoots, in contrast to $CaCl_2$, which reduced it. On the other hand, the effect of tested salts on growth and loading of CuO NPs-treated plants was comparable suggesting major interaction of the plant with CuO rather than Cu ions (Stewart et al. 2015). Salinity stress (25 and 50 mM NaCl) decreased the Chl*a*, Chl*b*, and total Chl, photochemical efficiency of PSII, and yield of wheat, while electrical conductivity, soluble sugars, proline content, and activities of CAT, POD, and PPO enzymes showed an increase. Treatment of plants grown at 50 mM NaCl with nanoscale Zn–Fe oxide increased grain yield approx. by 17.40% compared to control plants without NPs application (Babaei et al. 2017). In five tomato cultivars investigated in a callus culture exposed to NaCl, the relative callus growth rate inhibition was observed at 3.0 g/L NaCl, which strongly increased at 6.0 g/L NaCl, and Na content as well as SOD and GPX activities considerably increased with increasing exposure to NaCl. These adverse effects were found to be mitigated by ZnO NPs application, concentration of 15 mg/L being more effective than that of 30 mg/L, although degrees of tolerance to salinity in the presence of ZnO NPs between studied cultivars differed from each other (Alharby et al. 2016).

Priming of rice seeds with 10 mg/L AgNPs (20 nm diameter) resulted in notable increase of root growth when seedlings were cultivated in a nutrient solution containing 85 mM NaCl (Thuesombat et al. 2016). Yadu et al. (2018) reported that treatment with AgNPs could ameliorate also fluoride-induced oxidative injuries in *Cajanus cajan* manifested by accumulations of ROS, MDA and oxidized glutathione, gene expression of NADPH oxidase, and activity of lipoxygenase. A tolerance against fluoride toxicity in *C. cajan* at application of AgNPs was achieved via enhancing the levels of proline, total and reduced glutathione, glyoxalase I and II activities, and expression of pyrroline-5-carboxylate synthetase gene. Hernandez-Hernandez et al. (2018a) reported that CuNPs absorbed on chitosan–polyvinyl alcohol (CS-PVA) hydrogel could activate the enzymatic defense of tomato plants and increase their content of vitamin C and lycopene, respectively, as well and induce mechanisms of tolerance to salinity. The CS-PVA hydrogel and combined application of CS-PVA with Cu NPs enhanced growth of *Solanum lycopersicum* L. plants under salinity stress and also promoted the expression of jasmonic acid and SOD genes suggesting that such treatment could mitigate saline stress through the regulation of oxidative and ionic stress (Hernandez-Hernandez et al. (2018b).

Foliar application of nanoscale Zn fertilizer at a dose of 200 ppm was reported to mitigate the adverse impact of salinity on cotton plants, and it was confirmed that diluted seawater could be used in the irrigation of these plants, although co-administration of phosphorus fertilizer is necessary to avoid P/Zn imbalance (Hussein and Abou-Baker 2018). Priming with ZnO NPs promoted growth of lupine (*Lupinus termis*) plants which were cultivated in pots for 20 days under salinity stress (150 mM NaCl) resulting in the enhancement of the levels of photosynthetic pigments, organic solutes, total phenols, ascorbic acid, and Zn, as well as in increased activities of SOD, CAT, POD, and APX enzymes compared to stressed plants alone. In treated plants, also reduction in MDA and Na contents was estimated compared to salinized plants alone, whereby priming with a dose of 60 mg/L ZnO NPs secured the best improvement in salt tolerance of plants (Latef et al. 2017). In maize plants grown under saline stress, application of ZnO and Fe_2O_3 NPs in form of spray considerably enhanced the root growth, net CO_2 assimilation rate, and sub-stomatal CO_2 concentration (5%) compared to control, and increased concentrations in leaf Fe and Zn were estimated compared with bulk metal oxide treatment, which may be connected with the shape, size, distribution, and characteristics of NPs (Fathi et al. 2017a). On the other hand, in similar experiment with wheat plants that were sprayed with bulk and nanosized ZnO and Fe_2O_3 or their mixture, although the highest plant height and leaf Fe concentration were observed for treatment with Fe_2O_3 NPs, the researchers concluded that the spray of NPs may not be superior compared with bulk forms in alleviation of salinity impacts (Fathi et al. 2017b). Beneficial effects on sunflower plants under saline condition observed with foliar application of bulk $FeSO_4$ and $FeSO_4$ NPs were manifested in increased leaf area, shoot dry weight, net carbon CO_2 assimilation rate, sub-stomatal CO_2 concentration, Chl content, maximum quantum yield of PSII (F_v/F_m, where F_v is variable fluorescence and F_m maximum fluorescence), and Fe content, while Na content in leaves decreased. It could be noted that at application of $FeSO_4$ NPs, the increase in Chl*a* content and biomass was greater (Torabian et al. 2017). Similar positive results were obtained with application of foliar spray of bulk and nanoscale ZnO on the growth of sunflower cultivars under salt stress (100 mM NaCl), with greater effect of ZnO NPs on biomass production (Torabian et al. 2016).

TiO_2 NPs (anatase) application did not affect germination but notably increased root and stem length and fresh dry weights of *Zea mays* plant organs, especially in co-administration with NaCl (300 mM), whereby treatment of maize plants under salt stress with 0.3% TiO_2 NPs resulted in 1.4-fold increase of root length and 4.8-fold increase of stem length, while fresh weight increased 1.2-fold (Mutlu et al. 2018). Combined treatment of barley plants which were grown under salt stress with TiO_2 NPs and sodium nitroprusside ($Na_2[Fe(CN)_5NO]$) acting as nitric oxide donor induced salt tolerance in barley, likely associated with increases in some antioxidant enzyme activities, whereby MDA and H_2O_2 concentrations in the shoots of barley were reduced as well (Karami and Sepehri 2018).

In *Brassica napus* plants treated with CeO_2 NPs (200 and 1000 mg/kg dry sand and clay mixture), higher plant biomass and higher efficiency of the photosynthetic apparatus were estimated in both freshwater and saline water (100 mM NaCl) irrigation conditions suggesting changes in canola growth and physiology by CeO_2 NPs application resulting in improved plant salt stress response, although the salt stress could not be completely alleviated (Rossi et al. 2016). In another experiment with *B. napus* plants grown in the presence of CeO_2 NPs applied at a dose of 500 mg/kg dry sand and/or 50 mM NaCl, the researchers found that CeO_2 NPs modified the formation of the apoplastic barriers in *B. napus* roots, whereby under salt stress, they were able to shorten the root apoplastic barriers, thus allowing higher Na^+ transport to shoots and less accumulation of Na^+ in plant roots what was reflected in better physiological performance of rapeseed plants (Rossi et al. 2017). Using model plant *Arabidopsis thaliana*, Wu et al. (2018) reported catalytic $^{\bullet}OH$ scavenging by CeO_2 NPs in *A. thaliana* leaves that pronouncedly improved mesophyll K^+ retention, a key trait associated with salinity stress tolerance. Leaves treated with poly(acrylic acid)-coated CeO_2 NPs showed approx. threefold lower NaCl-induced

K^+ efflux from leaf mesophyll cells compared to controls upon exposure to salinity stress, and the ROS-activated nonselective cation channels in the plasma membrane of leaf mesophyll cells were identified as the main $^{\bullet}OH$ -inducible K^+ efflux channels. Long-term catalytic scavenging of $^{\bullet}OH$ in *A. thaliana* leaves improved plant photosynthetic performance at saline condition, and consequently plasma membrane channels/transporters could coordinately retain higher levels of K^+ in the leaf mesophyll cell cytosol (Wu et al. 2018).

Application of Si in bulk and nanoform enhanced the salt tolerance of the tomato plants, reflected in improved photosynthesis rate, mesophyll conductance, and plant water-use efficiency under saline stress condition, although no considerable difference was found between application of bulk and nanoscale Si (Haghighi and Pessarakli 2013). Almutairi (2016) at investigating the effect of nanoscale Si application on the expression of salt tolerance genes in germinating tomato (*Solanum lycopersicum* L.) seedlings under salt stress found that of the 14 investigated salt stress genes, four genes (AREB, TAS14, NCED3, and CRK1) were upregulated and six genes (RBOH1, APX2, MAPK2, ERF5, MAPK3, and DDF2) were downregulated. Increased germination percentage, germination rate of tomato seeds, and the root length and fresh weight of tomato seedlings were also observed suggesting that SiNPs contribute to improvement of plants' tolerance of salinity.

SiO_2 NPs improved defense mechanisms of squash (*Cucurbita pepo* L. cv. white bush marrow) plants against salt stress toxicity by increasing the net photosynthetic rate, stomatal conductance, transpiration rate, water-use efficiency, total Chl, proline, and carboanhydrase activity in the leaves of plants. Reduction in oxidative damage at treatment of salt-stressed plants with SiO_2 NPs was due to the expression of antioxidant enzymes, such as CAT, POD, SOD, GR, and APX (Siddiqui et al. 2014). Application of SiO_2 NPs at a dose 50 mg/L was found to be the best dose to enhance growth of potato (*Solanum tuberosum*) plants in vitro and mitigate the negative effects of salinity (50 and 100 mM) during a longer period (35 and 90 days) (Salah et al. 2017). High Na^+ concentrations (up to 5000 mg/L) had detrimental effects on seed germination and the growth of common bean seedlings that were alleviated by treatment with SiO_2 NPs. For example, addition of 300 mg/L SiO_2 NPs increased the final germination percentage, vigor index, and germination speed for seeds, shoot and root lengths as well as root dry masses were enhanced, and low Na content in plant tissues was estimated using irrigation with 5000 mg/L Na^+ (Alsaeedi et al. 2017). Similarly, exogenous application of SiO_2 NPs notably improved germination and growth of *Cucumis sativus* plants even at a dose of 100 ppm and under elevated Na^+ stress (5000 mg/L Na^+). Treatment with 200 ppm SiO_2 NPs increased germination rate index by 116%, germination index by 110%, shoot dry mass by 384%, root dry mass by 304%, and K^+/Na^+ ratio by 77% (Alsaeedi et al. 2018). Beneficial effect of exogenous treatment of soybean plants grown under salt stress with 0.5 and 1 mM SiO_2 NPs was reflected in improved shoot and root growth of seedlings, the increase in K^+ concentration and antioxidant activities and decreased Na^+ concentration, lipid peroxidation, and ROS production caused by salt stress (Farhangi-Abriz and Torabian 2018). Treatment of fenugreek plants grown under salinity stress (50, 100, and 150 mM) with 50 ppm SiO_2 NPs alleviated negative impact of salt on shoot, root, and seedling lengths, and under salinity stress, exposure of fenugreek seeds to 50 and 100 ppm SiO_2 NPs resulted in increased shoot, root, and seedling dry weights compared to bulk SiO_2 application and control treatments, whereby a dose of 50 ppm SiO_2 NPs was more effective than 100 ppm dose (Ivani et al. 2018).

11.4.4 Soil Acidity

Soil acidification is an ongoing natural process that can be accelerated by agricultural practices. It is mainly caused by the release of H^+ ions during the transformation and cycling of carbon, nitrogen, and sulfur on the soil–plant interfaces and results in declining crop production all over the world (Iqbal 2012). pH belongs to crucial factors governing concentrations of soluble and plant available metals, whereby metal solubility tends to decrease at higher pH values and increase at lower pH, and higher concentrations of toxic metals in soil solution could result in adverse effects on plants (Rieuwerts et al. 1998).

Investigation of the impact of soil properties in a range of soils under both leached and unleached conditions on the toxicity of Ag^+ to *Hordeum vulgare* L. and *Lycopersicum esculentum* plants confirmed that variations in soil organic carbon and pH were found to be primarily responsible for mitigating Ag toxicity (Langdon et al. 2015). Investigation of CuO NPs dissolution and toxicity to wheat in rhizosphere soil using freshly added CuO NPs (500 mg Cu/kg soil) and CuO NPs aged for 28 days before planting showed that aging of CuO NPs increased their toxicity to *Triticum aestivum* (reduction in root maximal length). The presence of roots in the soil had opposite and somewhat compensatory effects on NP dissolution. The exudates from wheat roots also enhanced soluble Cu in pore water (Gao et al. 2018).

Garcia-Gomez et al. (2018a) compared phytotoxicity of ZnO NPs and Zn accumulation in nine crops (wheat, maize, radish, bean, lettuce, tomato, pea, cucumber, and beet) grown in a calcareous soil and an acidic soil. While in the calcareous soil Zn phytotoxicity was limited due to very low available Zn, in the acidic soil, the high available Zn seriously affected the germination of bean, tomato, lettuce, and beet and the growth of most of the crops (EC_{50} values ranging from 110 to 520 mg Zn/kg), whereby adverse effects on the photosynthetic pigments and most of the markers of oxidative stress were observed in maize, wheat, bean, and pea. Thus, soil pH and plant species could be considered as key factors affecting the Zn availability and phytotoxicity of ZnO NPs. Zn concentration in the leaves of *Pisum sativum* L. and *Beta vulgaris* L. plants cultivated under greenhouse conditions was 6–12-fold higher in acidic than in calcareous soil, and while in acidic soil the ZnO NPs promoted ROS generation in both plant species with increases from 47% to 130%, in calcareous soil, a 20–65% decrease of ROS levels in treated plants was estimated, obviously due to the supply of zinc in Zn-deficient soils (Garcia-Gomez et al. 2018b). In the acid soil, treatment of wheat with ZnO NPs resulted in the inhibition of root elongation, while phytotoxicity was mitigated in the calcareous alkaline soil, although uptake of Zn was twofold higher than in control plants. Soluble Zn in the acid soil was 200-fold higher, and shoot levels were 10-fold higher than from the alkaline soil (correlating with phytotoxicity), whereby variation in humic acid between soils was found not to be a major factor influencing plant responses to the NPs (Watson et al. 2015). At comparing the effect of ZnO NPs, ZnO bulk, and $ZnSO_4$ in the antioxidant defenses of *Phaseolus vulgaris* and *Solanum lycopersicon* plants growing in an acidic (soil pH 5.4) and a calcareous soil (soil pH 8.3), it was found that ZnO NPs showed comparable toxicity to their bulk counterparts and Zn salts, the effects being generally higher in the acidic soil than in the calcareous soil for the bean and the opposite for the tomato, whereby comparable uptakes and toxicities of the different Zn forms suggested that the Zn ions derived from the ZnO NPs exerted a preferential toxicity in plants. On the other hand, based on the results obtained with application of ZnO NPs at a dose of 3 mg Zn/kg, it could be suggested that other underlying mechanisms related to the intrinsic nanoparticle properties may exist, especially at low NP concentrations (Garcia-Gomez et al. 2017).

Investigation of the impact of γ-Fe_2O_3 NPs (6 nm) on root elongation and growth of rice plants grown in pots showed that due to their excessive adsorption onto soil colloids, the observed phytotoxicity was low. However, at application of Fe_2O_3 NPs coated with citric acid, the phytotoxic effect manifested in reduced CO_2 assimilation rate was similar to their bulk counterpart, although bulk citrate-coated iron oxide more effectively inhibited shoot growth due to massive accumulations of Fe plaque on the root surfaces connected with a decline in the pH of rhizoplane soils. This indicated lower phytotoxicity of γ-Fe_2O_3 NPs under reductive conditions compared to microsized iron oxide (Alidoust and Isoda 2014).

11.4.5 Heat Stress

High temperature stress induces morphological, anatomical, physiological, and biochemical changes in plants, including the changes in water relations, decrease in photosynthesis, hormonal changes, and reduced yield in plants (Waraich et al. 2012). Elevated temperatures can directly and effectively change the properties of biological membranes, highly ordered structures consisting of mosaics of lipids and proteins, including their fluidity and permeability, and can induce changes in the lipid composition and/or interactions between lipids and specific membrane proteins (Yue and Yun 2018). During the acclimation process that occurs when the plant acquires resistance to an increase in temperature, plants adjust their homeostasis and steady-state physiology to the new temperatures (Nievola et al. 2017). Investigation of proteomic responses of leaves of 24-day-old rice seedlings to sudden temperature changes in rice seedlings grown at 28/20 °C (day/night) that were subjected to 3-day exposure to 36/28 °C or 44/36 °C (day/night) for high-temperature stress showed that among identified proteins being responsive to temperature stress, 47 proteins were exclusively found at 44/36 °C (day/night) exposure (Gammulla et al. 2011).

Application of AgNPs was found to protect wheat plants exposed to heat stress (35–40 °C) that impaired their morphological growth by interfering in photosynthetic process due to enhanced level of oxidative stress. Beneficial effect of AgNPs under heat stress resulted in improved root and shoot length, root number, plant fresh and dry weight, leaf area, and number of wheat plants (Iqbal et al. 2017). The study of morphogenesis and productivity characteristics of *Cucumis sativus* parthenocarpic hybrids Marinda and Kurazh in ontogenesis grown in greenhouses under thermic films, surface of which was coated with NPs of Cu compounds (film 1) or Ag and Cu compounds (film 2) using magnetron sputtering, showed that application of film 1 improved seed germination, activated plant growth and development, caused shortening of period of the fruiting beginning, and increased productivity of both hybrids. In contrast, the use of film 2 resulted in growth inhibition of both hybrids with subsequent reduction of their productivity (Minich et al. 2016).

Effect of different temperatures (20, 25, and 30 °C) on maize (*Zea mays* L.) germination and root growth under exposure to ZnO NPs (24 ± 3 nm) at 0–1600 mg/L for 15 days was investigated by Lopez-Moreno et al. (2017). While, at 20 and 25 °C, a dose of 400 mg/L ZnO NPs pronouncedly reduced the germination (40 and 53%, respectively) and treatment with 50, 400, and 1600 mg/L ZnO NPs at 20 °C resulted in reduced root growth by 18, 47, and 26% respectively, at 25 °C, root growth increased by 22 and 27% at application of 100 and 800 mg/L ZnO NPs. However, with increasing the temperature to 30 °C, root growth reduction by 42% was observed with a dose of 100 mg/L ZnO NPs, and decreased expression of a protein band with molecular weight of 85 kDa and increased expression of protein of 75 kDa were estimated suggesting that temperature may alter the way the ZnO NPs interact with plants. On the other hand, presence on ZnO NPs in roots was detected at any temperature tested.

Qi et al. (2013) sprayed leaves of tomato seedlings grown to the six-leaf stage with different concentrations of TiO_2 NPs, and then the seedlings were exposed to 35/15 °C (day/night) suggested as a mild heat stress for 7 days in a Chinese greenhouse. At such mild temperature stress in tomato plants exposed to appropriate concentration of TiO_2 NPs, an increase of net photosynthetic rate, conductance to H_2O, and transpiration rate of leaves was observed. Treatment with TiO_2 NPs also significantly decreased the initial minimum fluorescence value (F_o) indicating that PSII is protected from damaging forms of ROS and it increased regulated and decreased non-regulated PSII energy dissipation suggesting beneficial role of these NPs in promoting photosynthesis in tomato leaves under mild heat stress.

Foliar spraying with 10 mg/L SeNPs during the booting stage of sorghum grown under high temperature stress enhanced antioxidant enzymes activity, reduced content of oxidants, contributed to higher levels of unsaturated phospholipids, and improved the pollen germination percentage resulting in considerably higher seed yield. It could be noted that enhanced antioxidant enzyme activities and reduced content of oxidants due to treatment with SeNPs were greater at high temperature (38/28 °C) than at optimum temperature conditions (32/22 °C) suggesting protection of sorghum plants against oxidative damage under high temperature stress by SeNPs (Djanaguiraman et al. 2018b).

11.4.6 Cold Stress

Cold stress is abiotic stress factor that has negative impact on the growth and development of plants resulting in poor germination, stunted seedlings, yellowing of leaves, withering, and reduced tillering. Due to cold stress-induced dehydration, plasma membrane damage occurs resulting in loss of membrane integrity, leading to solute leakage. Moreover, cold stress results in disruption of the integrity of intracellular organelles, leading to the loss of compartmentalization and reduction and impairing of photosynthesis, protein assembly, and general metabolic processes. Both cold acclimation and chilling tolerance of plants involve an array of biochemical, molecular, and metabolic processes, including signal transduction, activation of transcription factors and stress-responsive genes, detoxification of ROS, damage control and repair begin, restructuring of plasma membrane, and acceleration of osmolyte synthesis (Steponkus 1984; Zhu et al. 2007; Yadav 2010).

Cold stress adversely affected *Cicer arietinum* L., which was manifested with increased H_2O_2 and MDA contents and electrolyte leakage index (ELI) causing greater damage in cold-sensitive (C-Sus) compared to cold-tolerant (C-Tol) plants. On the other hand, in chickpea plants under cold stress that were treated with TiO_2 NPs, decreased H_2O_2 levels as well as decreased MDA content and ELI compared to control plants were observed, the changes being more intensive in C-Tol than in C-Sus plants. Protection of plants by the antioxidant enzymes exposed to cold stress was better in C-Tol compared to C-Sus plants and in TiO_2 NPs-treated plants compared to control; lipoxygenase activity was induced efficiently only in TiO_2 NPs-treated C-Tol plants under cold stress condition. Moreover, stabile contents of Chl and carotenoids were observed in TiO_2 NPs-treated plants during cold stress. Thus, an increased tolerance of chickpea plants to cold stress by TiO_2 NPs was reflected in decreasing level of injuries and increasing capacity of defense systems (Mohammadi et al. 2014). The effect of TiO_2 NPs on cold tolerance of C-Tol and C-Sus chickpea plants exposed to cold stress (4 °C) for 6 days was investigated using cDNA-amplified fragment length polymorphism analysis of transcripts induced in plants by TiO_2 NPs during cold stress. Based on differentially expressed transcript-derived fragments (TDFs) of TiO_2 NPs-treated plants, it was found that these could be related to different groups of genes involved in metabolism pathways, cellular defense, cell connections and signaling, transcriptional regulation, and chromatin architecture. Increased transcription level of these TDFs, particularly the first day of cold stress, was critical from the aspect of cold tolerance development resulting in decreased ELI in C-Tol compared to C-Sus plants as well as in TiO_2 NPs-treated plants compared to controls. It could be assumed that TiO_2 NPs could protect the plants against cold stress-induced oxidative stress. Consequently, cold tolerance development could be supported by application of TiO_2 NPs resulting in preventing and controlling the damages also in field conditions and in this way securing increasing crop productivity (Amini et al. 2017). In another experiment with C-Tol and C-Sus chickpea genotypes performed at 4 °C, more permeability to TiO_2 NPs was estimated for the C-Sus plants compared to C-Tol ones, and higher TiO_2 content was estimated during cold stress compared to optimum temperature. Whereas low temperature increased ELI in untreated C-Tol and C-Sus plants, in plants treated with TiO_2 NPs, it showed a decrease, and under thermal treatments, also lower MDA accumulation was estimated in C-Tol plants suggesting improved redox status of plants by TiO_2 NPs during cold stress what supports potential of TiO_2 NPs to be used for the increase of cold tolerance in crops (Mohammadi et al. 2013). In addition, TiO_2 NPs considerably increased the activity of Rubisco of chickpea plants compared to controls, although it markedly decreased at 4 °C compared to optimum temperature. TiO_2 NPs-treated plants were found to acclimate during cold stress to survival or recovery, which was manifested with decreased H_2O_2 content and higher photosynthetic activity, whereby phosphoenolpyruvate carboxylase activity increased particularly in C-Tol plants compared to C-Sus ones and, in TiO_2 NPs-treated plants compared to controls, which could be connected with an increase in energy efficiency through different mechanisms like malate (Hasanpour et al. 2015).

Haghighi et al. (2014) exposed some tomato (*Lycopersicum esculentum* Mill. cv. 'Halil') plants in hydroponic solution to Se and nano-Se (added to the nutrient solution in the form of Na_2SeO_4) for 3 days to optimal temperature (25/17±2 °C day/night) and then exposed them for 24 h to low temperature stress (10 °C) followed by cultivation (10 days) at optimal temperature. Nano-Se did not affect plant growth; however treatment with 2.5 μmol/L nano-Se caused an increase of the Chl content by 27%, root fresh mass by 11.7%, and root dry mass by 45.4% relative to control, and increased shoot dry mass and relative water content in stressed plants were estimated as well.

Seed prechilling of tall wheatgrass (*Agropyron elongatum* L.), a grass that could be used as a forage and for hay, in combination with SiO_2 NPs largely broke the seed dormancy and notably increased seed germination as well as dry weight of shoots and roots (Azimi et al. 2014). Beneficial effects of CS/SiO_2 NPs on postharvest quality and antioxidant capacity of white-flesh loquat (*Eriobotrya japonica* Lindl.) fruit during cold storage (5 °C for 40 days) resulting in longer storage life with acceptable external and internal quality in the fruit were connected with enhanced activities of antioxidant enzymes; lower levels of $O_2^{\bullet-}$, H_2O_2, and MDA; and membrane permeability (Song et al. 2016).

11.4.7 UV Light

Reduction of the stratospheric ozone layer due to anthropogenic activities results in increase of UV-B radiation showing adverse effects on plants due to excessive generation of ROS reflected in impaired growth, yield, and photosynthesis; modification of morphology; physiological processes; damage of DNA, lipids, and membranes; and denaturation of proteins. Physiological responses to UV-B stress and subsequent development of defense mechanism by plants to adapt to the changing environment were described by Hollósy (2002), Zlatev et al. (2012), and Sharma et al. (2017).

Chen et al. (2014) tested the impact of CdTe quantum dots (QDs) and UV-B radiation (280–315 nm) as well as their combined application on 5-day-old wheat seedlings and found that CdTe QDs and UV-B radiation inhibited growth of roots and shoots with additive inhibitory effects at combined treatment group. Moreover, CdTe QDs applied at a dose of 200 mg/mL or UV-B radiation of 10 kJ/m^2/day induced the activation of plant antioxidant enzymes and caused programmed cell death due to accumulation of CdTe QDs in root cells. Negative effect of ambient and enhanced UV-B radiation on growth of *Triticum aestivum* seedlings was manifested by declined photosynthetic performance, altered vital leaf structures, enhanced levels of $O_2^{\bullet -}$ and H_2O_2, increased lipid peroxidation, and electrolyte leakage, whereby reduction of SOD and APX activities and enhanced activities of guaiacol peroxidase and non-enzymatic antioxidants were observed as well.

Pre-additions of SiNPs as well as Si were found to protect *T. aestivum* plants against UV-B-induced oxidative stress by enhancement of antioxidants, and because the greatest increase of nitric oxide (NO) content was observed at combined application of SiNPs with UV-B enhanced treatment, it was supposed that NO-mediated triggering of antioxidant defense system of seedlings by SiNPs counterbalancing the damage of photosynthetic apparatus by ROS resulted in protection of seedlings. Higher bioavailability of SiNPs to plants compared to bulk Si was reflected in more effective reduction of UV-B stress (Tripathi et al. 2017). Hybrid nanofilms fabricated using 3-methacryloxypropyl-, vinyl- and (3-glycidoxypropyl)-polyhedral oligomeric silsesquioxane ($[RSiO_{3/2}]_n$) modified with titanium tetrabutoxide were found to provide a physical barrier for blocking the UV-B absorbed into greenhouse suggesting that these materials could be used as the sun protection ingredients (Wang et al. 2010). The protective effect of TiO_2 NPs against UV-B radiation (200 μW/cm^2 for 5 or 10 min) predominantly caused by the blockage of UV-B by TiO_2 NPs adsorption was estimated in a small planktonic crustacean *Daphnia magna* as well (Liu and Wang 2017).

Nano-anatase also decreased the oxidative stress in spinach chloroplasts caused by UV-B radiation what was manifested by notably reduced levels of $O_2^{\bullet -}$, H_2O_2, and MDA content and increased activities of SOD, CAT, APX, GPX as well as elevated O_2 evolution suggesting that nano-anatase could absorb UV-B light and convert light energy to stable chemical energy via electron transport in spinach chloroplasts (Lei et al. 2008). Photocatalytic ROS production and phototoxicity of TiO_2 NPs depend on the solar UV radiation spectrum, whereby removing UV-B (280–320 nm) from solar radiation did not affect considerably the photocatalytic ROS production of TiO_2 NPs, while removal of UV-A (320–400 nm) notably reduced ROS production, and removal of radiation with λ <400 nm resulted in negligible ROS production (Ma et al. 2012).

Irradiation with UV-A light (315–400 nm) of suspensions of TiO_2 and SiO_2 NPs agglomerates (300–600 nm) for 24 h showed remarkable adsorption on *Allium cepa* root surface only for TiO_2 NPs, while adsorption of SiO_2 NPs was minute, and no significant biological effects were observed even at high exposure concentrations of both types of NPs (up to 1000 μg/mL) suggesting protection of plants against NPs by the cell wall, which is able to shield the cell membrane from direct contact with the NPs (Koce et al. 2014). On the other hand, UV radiation pronouncedly reduced the photosynthetic capacity of the aquatic macrophyte *Elodea nuttallii*, which was indeed unaffected by Cu(II) or CuO NPs treatments. However, at combined exposure with UV, metal accumulation in plants increased in both treatments, but it was higher from CuO NPs compared to dissolved Cu(II) (Regier et al. 2015).

11.4.8 Elevated CO_2

Although CO_2 is indispensable for photosynthesis, being one of its most limiting factors, the anthropogenic CO_2 pronouncedly contributes to greenhouse effects and could adversely affect global climate. Rising CO_2 is expected to result in changes in plant traits that will increase plant productivity, primarily in C_3 plants, because CO_2 enrichment could enhance photosynthetic capacity reflected mostly in the vegetative growth of young plants and it can also alter the partitioning of secondary metabolites in plants (Ibrahim and Jaafar 2011).

No visible signs of toxicity in rice plants cultivated at the ambient CO_2 level (370 μmol/mol CO_2) were observed in TiO_2 NPs-treated rice plants, while under 570 μmol/mol CO_2, pronouncedly reduced grain yield was observed. Moreover, at 570 μmol/mol CO_2, a dose of 200 mg/kg TiO_2 NPs increased accumulation of Ca, Mg, Mn, P, Zn, and Ti, but reduced fat and total sugar in grains suggesting effects on the nutritional quality of crops and also modified the functional composition of soil microbial communities (Du et al. 2017). Comparison of TiO_2 NPs-treated wheat plants grown at the normal CO_2 condition (400 mg/L CO_2) showed that treatment of wheat seedlings cultivated under super-elevated CO_2 conditions (5000 mg/L CO_2) with TiO_2 NPs resulted in increased root biomass and large numbers of lateral roots, increased ABA content, and pronounced decrease in indolepropionic acid and jasmonic acid content, and considerably enhanced Ti accumulation and translocation in wheat treated with certain concentrations of TiO_2 NPs was observed as well (Jiang et al. 2017).

Enhanced accumulation of Fe and Zn in hydroponically cultivated rice plants treated with Fe_2O_3 and ZnO NPs at elevated atmospheric CO_2 concentration (610 ± 10 ppm) compared to ambient one (390 ± 10 ppm) was reported by Yadav et al. (2014).

11.4.9 Toxic Metal Stress

Toxic metals or metals as bioelements in higher than normal concentrations, are harmful to living organisms including plants and their widespread accumulation in agricultural soils results in elevated uptake by crops causing not only reduced yield and economic losses but significantly affecting both food quality and safety as well. Toxic metals have an adverse impact on uptake and transport of nutrients by crops, and they can seriously damage photosynthetic apparatus. They reduce the levels of photosynthetic pigments, proteins, free amino acids, and soluble sugars; negatively affect the integrity of the cytoplasmic membrane and water relations; and induce oxidative stress resulting finally in lower yield (e.g., Masarovičová and Kráľová 2012, 2013, 2017; Masarovičová et al. 2010, 2014; Kráľová et al. 2019). One of the ways to counteract the adverse effects of toxic metals on crops is treatment with metal/metalloid NPs (e.g., Liu et al. 2015, 2018; Marchiol et al. 2016; Rizwan et al. 2018).

AgNPs used as a priming agent promoted the germination and growth of wheat pains and stimulated indole-3-butyric acid, 1-naphthalene acetic acid, and 6-benzylaminopurine contents and reduced abscisic acid content, and AgNPs priming at a dose of 1 mg/L considerably improved phytohormone balance, growth parameters, and photosynthetic efficiency of wheat plants also under salinity stress (25 and 100 mM NaCl) (Abou-Zeid and Ismail 2018).

Nanomaterials such as nanoscale hydroxyapatite ($Ca_5(PO_4)_3(OH)$; 20 and 40 nm), Fe_3O_4 NPs, and Fe^0NPs effectively reduced As uptake of hydroponically cultivated rice seedlings at low arsenic concentrations (Huang et al. 2018). Adverse effects of chromium stress on sunflower plants connected with increased Cr uptake resulting in considerable reduction in morphological and physiological parameters could be alleviated by application of Fe^0NPs or Fe^{2+} ions that are able to reduce Cr concentration in root and shoot; increase root and shoot dry weight, plastid pigments (Ch and carotenoids), and proline contents; and also pronouncedly reduce the levels of MDA and H_2O_2, whereby Fe^0NPs positively affected all abovementioned traits longer than Fe^{2+} suggesting that they could effectively prevent Cr uptake by sunflower plants (Mohammadi et al. 2018). Treatment of wheat seedlings grown on quartz sand supplemented with 2.67 mg Cd^{2+}/kg and 5.53 mg Cr^{6+}/kg (causing a 50% decrease of root length) with 1000 mg/kg magnetite (Fe_3O_4) NPs resulted in an increase of root length by 25 and 50%, and Cd and Cr accumulation in vegetable tissues was notably reduced (Lopez-Luna et al. 2016). Carbon-coated semicrystalline Fe_3O_4 NPs were found to enhance bioproductivity, photosynthetic electron transport, antioxidant enzyme activity, and Fe accumulation under Ca stress in rice plants. They reduced Ca accumulation in plants by physical adsorption, and Fe release from the NPs ameliorated Ca-induced Fe deficiency in plants (Sebastian et al. 2017). *Brassica juncea* var. Pusa Jagannath plants exposed to combined treatment with As^{3+} (150 μM) and Fe_3O_4 NPs (500 mg/L) for a period of 96 h showed besides improved plant growth also higher photosynthetic pigment and protein content compared to plants treated with As alone what could be connected with reduced oxidative stress by possible involvement of Fe_3O_4 NPs as nano-adsorbents in reducing As toxicity (Praveen et al. 2018).

Also CuO NPs applied at concentrations 50 and 100 mg/L, respectively, mitigated the negative effect of As (10 mg/kg) on the number of root branches of *Oryza sativa* Japonica seedlings (Liu et al. 2018). At studying the impact of binary combinations of metal-based nanomaterials on zucchini (*Cucurbita pepo* L.), it was found that co-exposure of plants grown on vermiculite to CeO_2 NPs and La_2O_3 NPs applied at doses 100 g/L for 21 days notably reduced La uptake, while 100 mg/L La_2O_3 NPs completely deregulated Cu uptake (two- to fivefold higher) upon CuO NPs (100 mg/L) co-exposure (Pagano et al. 2017). CeO_2 NPs were reported to reduce both the boron nutritional status of *Helianthus annuus* L. plants cultivated in original soil and the boron phytotoxicity in boron-spiked soil (Tassi et al. 2017). At co-exposure of hydroponically cultivated *Glycine max* (L.) Merr. seedlings to CeO_2 NPs and Cd, the CeO_2 NPs were found to reduce the translocation of Cd from roots to shoots by 70%; however they did not influence the total Cd associated with soybean roots, while Ce levels in soybean roots were reduced by 45% and showed notable increase (by 60%) in soybean shoots. It could be mentioned that at co-exposure of Cd and CeO_2 NPs, higher excretion of plant root exudates was observed, which could affect the chemical environment in the plant rhizosphere (Rossi et al. 2018).

After priming of wheat seeds with ZnO NPs (25, 50, 75, and 100 mg/L) and Fe NPs (5, 10, 15, and 20 mg/L) and sowing the seeds in Cd-contaminated soil, the investigation of mature plants showed beneficial effects of NPs on photosynthesis and biomass, and the metal NPs also reduced the electrolyte leakage and SOD and POD activities in leaves compared to control plants. Moreover, Cd levels in roots, shoots, and grains were considerably lower, while the concentrations of essential metals, Zn and Fe, in plant organs and grains increased with NPs application (Rizwan et al. 2018). Positive impact of foliarly applied ZnO NPs on wheat plants grown in Cd-contaminated soil was observed also by Hussain et al. (2018). The researchers estimated that foliar and soil application of ZnO NPs resulted in decreased Cd concentrations in grains by 30–77%, and 16–78%, respectively, reduced electrolyte leakage, and increased SOD and POD activities in leaves. ZnO NPs were reported to alleviate Cd- and Pb-induced toxicity in *Leucaena leucocephala* seedlings resulting in an increase in photosynthetic pigment and total soluble protein contents, considerable decrease of lipid peroxidation in leaves, and elevated level of antioxidative enzyme activities (Venkatachalam et al. 2017).

TiO_2 NPs stimulated growth of barley plants and were able to compensate the adverse effects of CeO_2 NPs in plants grown in soil enriched with both TiO_2 NPs and CeO_2 NPs (500 or 1000 mg/kg), whereby the growth cycle of plants treated with both CeO_2 NPs and TiO_2 NPs was approximately 10 days longer than that of control plants (Marchiol et al. 2016). TiO_2 NPs reduced the bioaccumulation of Pb in rice and at high TiO_2 NPs exposure levels (1000 mg/L) reduced the Pb concentration in rice roots by >80% and by 77–97% in shoots, if nanoscale pristine anatase and rutile particles as well as nanosized rutile particles with hydrophilic surface were used, while at application of bulk TiO_2 or nanoscale rutile particles with hydrophobic surface, Pb reduction in roots and shoots was only 45–61% and 11–38%, respectively (Cai et al. 2017). At co-exposure to Cd and TiO_2 NPs, the TiO_2 NPs considerably alleviated also Cd stress in rice plants, which was reflected in improved plant growth and significant increase of the net photosynthetic rate and Chl content, and they reduced the Cd uptake and distribution in rice roots and leaves (Ji et al. 2017). Positive impact of TiO_2 NPs on the reduction of Cd toxicity resulting in increased photosynthetic rate and growth parameters was observed also in soybean plants; however treatment with TiO_2 NPs notably enhanced Cd uptake by plants (Singh and Lee 2016). At application of TiO_2 NPs, higher levels of ^{133}Cs were estimated in soybean shoots (731.7 μg/g d.w.) than in the roots (597.8 μg/g d.w.) suggesting that TiO_2 NPs could be used for phytoremediation of ^{133}Cs-contaminated soils (Singh and Lee 2018). On the other hand, co-exposure to TiO_2 NPs did not affect Cd (100 and 250 mg/L) toxicity in *Raphanus sativus* seeds, and morphological alterations in nuclei, vacuoles, and shape of radish root cells, which were observed upon single Cd exposure, were not abolished in the presence of TiO_2 NPs (Manesh et al. 2018).

SiNPs showed also beneficial effects on growth of rice plants exposed to Pb, prevented Pb transfer from roots to shoots, and blocked Pb accumulation in rice grains, especially in high-Pb-accumulating rice cultivars and in heavily Pb-polluted soils (Liu et al. 2015). Also SiNPs protected *Pisum sativum* L. seedlings against adverse effect of Cr by reducing Cr accumulation and oxidative stress and upregulating antioxidant defense system and nutrient elements, which was reflected in improved plant growth (Tripathi et al. 2015b). Foliar application of SiNPs to *Oryza sativa* L. cv. Xiangzaoxian 45 plants grown in Cd-contaminated soil reduced Cd accumulation in grains by inhibiting translocation of Cd, while it enhanced translocation factors of K, Mg, and Fe from the uppermost nodes to rachises in rice plants, a dose of 25 mM SiNPs being the most effective in reducing translocation factors of Cd from roots to the uppermost nodes and from the uppermost nodes to rachises (Chen et al. 2018). Foliar application of SiNPs (2.5 mM) alleviated Cd stress in rice seedlings (*Oryza sativa* L. cv Youyou 128) hydroponically cultivated in the presence of 20 μM $CdCl_2$, which was reflected in improved plant growth, Mg, Fe, and Zn nutrition, and Chl contents of Cd-stressed plants as well as in lower oxidative stress reflected in higher glutathione content, and reduced MDA content and reduced Cd translocation from roots to shoots and reduced Cd accumulation in grains (Wang et al. 2015). Using cells cultured in suspension, investigation of beneficial effects of SiNPs on Cd-induced toxicity in rice showed that addition of SiNPs significantly enhanced the proportion of live cells and pronouncedly reduced severe structural changes in the organelle integrity of cells caused by Cd (at treatment with SiNPs, cells remained nearly intact even in the presence of high Cd concentrations). Moreover, Cd^{2+} influx at treatment with SiNPs (19 nm, 48 nm, and 202 nm) decreased by 15.7-, 11.1-, and 4.6-fold, and the gene expression of Cd uptake and transport (OsLCT1 and OsNramp5) was inhibited, while those of Cd transport into vacuole (OsHMA3) and Si uptake (OsLsi1) were enhanced, resulting in at least 1.87-fold increase in the Si uptake capacity. Thus, reduced Cd uptake capacity at co-exposure to Cd and SiNPs resulted in the alleviation of Cd toxicity (Cui et al. 2017).

Comparison of barley plants grown for 14 days under NiO NPs (120 mg/kg) single and co-exposure with SiO_2 NPs (3 mg/kg) showed that co-application of SiO_2 NPs reduced adverse impact of NiO NPs on fresh and dry biomass and photosynthesis-related parameters, lowered or maintained the levels of lipid peroxidation, and stimulated the redox pathway of thiols, and also the response of the antioxidant system was found to be more prominent at co-exposure of NiO NPs with SiO_2 NPs (Soares et al. 2018).

11.5 Conclusions

The crucial role of agriculture is to provide sufficient quality and healthy food for continuously growing population. However, the increasing anthropogenic pollution of the environment and current climate change significantly contribute to a decrease of crop production. Therefore, it is essential to develop and use effective environment-friendly agricultural preparations that will not only be able to secure higher yield of crops and prevent the entry of compounds damaging human health into the food chain but to be economically reasonable as well. In spite of the fact that NPs and nanomaterials could be considered controversial by the world public, they have an irreplaceable place in agriculture and food industry; one of their advantages is lower doses of active compounds needed to achieve the desired effect compared to the application of bulk preparations. Many of metal- and metalloid-based NPs have found their applications as fertilizers, plant growth-promoting compounds, and systems for delivery of nutrients and could be applied to increase the tolerance of crops against the harmful impact of abiotic stresses, including drought and salinity, representing a very serious global problem. However, it is necessary to estimate exactly concentration ranges for individual crop species, in which particular metal-/metalloid-based NPs exhibit growth stimulation but higher concentrations are phytotoxic, verify them in field conditions, and investigate their possible transgenerational impact on seed quality and the development of second-generation seedlings.

Acknowledgment This study was supported by the Ministry of Education of the Czech Republic (LO1305), by the Slovak Research and Development Agency (APVV-17-0373 and APVV-17-0318).

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(1):73–85. https://doi.org/10.21608/ejbo.2017.1873.1128

Achari GA, Kowshik M (2018) Recent developments on nanotechnology in agriculture: Plant mineral nutrition, health, and interactions with soil microflora. J Agric Food Chem 66(33):8647–8661. https://doi.org/10.1021/acs.jafc.8b00691

Adhikari T, Sarkar D, Mashayekhi H, Xing BS (2016) Growth and enzymatic activity of maize (*Zea mays* L.) plant: Solution culture test for copper dioxide nano particles. J Plant Nutr 39(1):102–118. https://doi.org/10.1080/01904167.2015.1044012

Agarwal V, Bajpai M, Sharma A (2018) Patented and approval scenario of nanopharmaceuticals with relevancy to biomedical application, manufacturing procedure and safety aspects. Recent Pat Drug Deliv Formul 12(1):40–52. https://doi.org/10.2174/1872211312666180105114644

Ahanger MA, Akram NA, Ashraf M, Alyemeni MN, Wijaya L, Ahmad P (2017) Plant responses to environmental stresses-from gene to biotechnology. AoB Plants 9(4):plx025. https://doi.org/10.1093/aobpla/plx025

Ahmad P, Ashraf M, Younis M, Hu X, Kumar A, Akram NA, Al-Qurainy F (2012) Role of transgenic plants in agriculture and biopharming. Biotechnol Adv 30(3):524–540. https://doi.org/10.1016/j.biotechadv.2011.09.006

Ahmed M, Fayyaz-ul-Hassen, Qadeer U, Aslam MA (2011) Silicon application and drought tolerance mechanism of sorghum. Afr J Agric Res 6(3):594–607. https://doi.org/10.5897/AJAR10.626

Alharby HF, Metwali EMR, Fuller MP, Aldhebiani AY (2016) Induction, plant regeneration, element content and antioxidant enzyme activity in tomato (*Solanum lycopersicum* MILL.) under salt stress. Arch Biol Sci 68(4):723–735. https://doi.org/10.2298/ABS151105017A

Alidoust D, Isoda A (2014) Phytotoxicity assessment of γ-Fe_2O_3 nanoparticles on root elongation and growth of rice plant. Environ Earth Sci 71(12):5173–5182. https://doi.org/10.1007/s12665-013-2920-z

Allen ER, Hossner LR, Ming DW, Henninger DL (1993) Solubility and cation exchange in phosphate rock and saturated clinoptilolite mixtures. Soil Sci Soc Am J 57:1368–1374. https://doi.org/10.2136/sssaj1993.03615995005700050034x

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 9(1):106–114

Alsaeedi AH, El-Ramady H, Alshaal T, El-Garawani M, Elhawat N, Almohsen M (2017) Engineered silica nanoparticles alleviate the detrimental effects of Na^+ stress on germination and growth of common bean (*Phaseolus vulgaris*). Environ Sci Pollut Res 24(27):21917–21928. https://doi.org/10.1007/s11356-017-9847-y

Alsaeedi A, El-Ramady H, Alshaal T, El-Garawani M, Elhawat N, Al-Otaibi A (2018) Exogenous nanosilica improves germination and growth of cucumber by maintaining K^+/Na^+ ratio under elevated Na^+ stress. Plant Physiol Biochem 125:164–171. https://doi.org/10.1016/j.plaphy.2018.02.006

Amini S, Maali-Amiri R, Mohammadi R, Kazemi-Shahandashti SS (2017) cDNA-AFLP analysis of transcripts induced in chickpea plants by TiO_2 nanoparticles during cold stress. Plant Physiol Biochem 111:39–49. https://doi.org/10.1016/j.plaphy.2016.11.011

Amist N, Singh NB, Yadav K, Singh SC, Pandey JK (2017) Comparative studies of Al^{3+} ions and Al_2O_3 nanoparticles on growth and metabolism of cabbage seedlings. J Biotechnol 254:1–8. https://doi.org/10.1016/j.jbiotec.2017.06.002

Anderson AJ, McLean JE, Jacobson AR, Britt DW (2018) CuO and ZnO nanoparticles modify interkingdom cell signaling processes relevant to crop production. J Agric Food Chem 66(26):6513–6524. https://doi.org/10.1021/acs.jafc.7b01302

Anusuya S, Banu KN (2016) Silver-chitosan nanoparticles induced biochemical variations of chickpea (*Cicer arietinum* L.). Biocatal Agric Biotechnol 8:39–44. https://doi.org/10.1016/j.bcab.2016.08.005

Arora S, Sharma P, Kumar S, Nayan R, Khanna PK, Zaidi MGH (2012) Gold-nanoparticle induced enhancement in growth and seed yield of *Brassica juncea*. Plant Growth Regul 66:303–310. https://doi.org/10.1007/s10725-011-9649-z

Astafurova TP, Burenina AA, Suchkova SA, Zotikova AP, Kulizhskiy SP, Morgalev YN (2017) Influence of ZnO and Pt nanoparticles on cucumber yielding capacity and fruit quality. Nano Hybrids and Composites 13:142–148. https://doi.org/10.4028/www.scientific.net/NHC.13.142

Avestan S, Naseri LA, Hassanzade A, Sokri SM, Barker AV (2016) Effects of nanosilicon dioxide application on *in vitro* proliferation of apple rootstock. J Plant Nutr 39(6):850–855. https://doi.org/10.1080/01904167.2015.1061550

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 Technol 16(3):25–29

Babaei K, Sharifi RS, Pirzad A, Khalilzadeh R (2017) Effects of bio fertilizer and nano Zn-Fe oxide on physiological traits, antioxidant enzymes activity and yield of wheat (*Triticum aestivum* L.) under salinity stress. J Plant Interact 12(1):381–389. https://doi.org/10.1080/17429145.2017.1371798

Baskar V, Venkatesh J, Park SW (2015) Impact of biologically synthesized silver nanoparticles on the growth and physiological responses in *Brassica rapa* ssp. *pekinensis*. Environ Sci Pollut Res 22(22):17672–17682. https://doi.org/10.1007/s11356-015-4864-1

Barrios AC, Rico CM, Trujillo-Reyes J, Medina-Velo IA, Peralta-Videa JR, Gardea-Torresdey JL (2016) Effects of uncoated and citric acid coated cerium oxide nanoparticles, bulk cerium oxide, cerium acetate, and citric acid on tomato plants. Sci Total Environ 563:956–964. https://doi.org/10.1016/j.scitotenv.2015.11.143

Bechtold U, Field B (2018) Molecular mechanisms controlling plant growth during abiotic stress. J Exp Bot 69(11):2753–2758. https://doi.org/10.1093/jxb/ery157

Beitollah H, Abdolreza S, Sadr J (2009) Recent applications of zeolites, natural nanostructure materials. Iranian J Org Chem 4:214–223. http://www.iranjoc.com/upload/04/2.pdf

Bhushan B, Luo D, Schricker SR, Sigmund W, Zauscher S (2014) Handbook of nanomaterials properties. Springer, Berlin/Heidelberg

Bi D, Liu S, Liu Y, Yin X (2010) Preparation of selenium-rich Chinese cabbage using selenium nanoparticle containing nutrient. CN Patent 101734971, Publ. date 16 Jun 2010

Bread for the World (2018) About hunger. Washington DC, USA. Available online at: http://www.bread.org/who-experiences-hunger

Brodowska MS, Kurzyna-Szklarek M, Haliniarz M (2016) Selenium in the environment. J Elementol 21(4):1173–1185. https://doi.org/10.5601/jelem.2016.21.2.1148

Cai F, Wu XY, Zhang HY, Shen XF, Zhang M, Chen WX, Gao Q, White JC, Tao S, Wang XL (2017) Impact of TiO_2 nanoparticles on lead uptake and bioaccumulation in rice (*Oryza sativa* L.). Nanoimpact 5:101–108. https://doi.org/10.1016/j.impact.2017.01.006

Calanca PP (2017) Effects of abiotic stress in crop production. In: Ahmed M, Stockle C (eds) Quantification of climate variability, adaptation and mitigation for agricultural sustainability. Springer, Cham, pp 165–180

Campos EVR, de Oliveira JL, Pascoli M, de Lima R, Fraceto LF (2016) Neem oil and crop protection: from now to the future. Front Plant Sci 7:1494. https://doi.org/10.3389/fpls.2016.01494

Campos EVR, Proença PLF, Oliveira JL, Bakshi M, Abhilash PC, Fraceto LF (2018) Use of botanical insecticides for sustainable agriculture: future perspectives. Ecol Indic. https://doi.org/10.1016/j.ecolind.2018.04.038

Cao ZM, Stowers C, Rossi L, Zhang WL, Lombardini L, Ma XM (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

Cao ZM, Rossi L, Stowers C, Zhang WL, Lombardini L, Ma XM (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 Int 25(1):930–939. https://doi.org/10.1007/s11356-017-0501-5

Chaves MM, Maroco JP, Pereira JS (2003) Understanding plant responses to drought — from genes to the whole plant. Funct Plant Biol 30:239–264

Chen HZ, Gong Y, Han R (2014) Cadmium telluride quantum dots (CdTe-QDs) and enhanced ultraviolet-B (UV-B) radiation trigger antioxidant enzyme metabolism and programmed cell death in wheat seedlings. PLoS ONE 9(10):e110400. https://doi.org/10.1371/journal.pone.0110400

Chen R, Zhang CB, Zhao YL, Huang YC, Liu ZQ (2018) Foliar application with nano-silicon reduced cadmium accumulation in grains by inhibiting cadmium translocation in rice plants. Environ Sci Pollut Res 25(3):2361–2368. https://doi.org/10.1007/s11356-017-0681-z

Chhipa H (2017) Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett 15:15–22. https://doi.org/10.1007/s10311-016-0600-4

Choudhary RC, Kumaraswamy RV, Kumari S, Sharm SS, Pal A, Raliya R, Biswas P, Saharan V (2017) Cu-chitosan nanoparticle boost defense responses and plant growth in maize (*Zea mays* L.). Sci Rep 7:9754. https://doi.org/10.1038/s41598-017-08571-0

Chung IM, Rajakumar G, Thiruvengadam M (2018) Effect of silver nanoparticles on phenolic compounds production and biological activities in hairy root cultures of *Cucumis anguria*. Acta Biol Hung 69(1):97–109. https://doi.org/10.1556/018.68.2018.1.8

Chutipaijit S, Whalley AJS, Sutjaritvorakul T (2018) *In vitro* plant growth promotion by ZnO nanomaterials in indica rice seedlings (*Oryza sativa* L.). Materials Today-Proceedings 5(7):14944–14949. https://doi.org/10.1016/j.matpr.2018.04.035

Corradini E, De Moura M, Mattoso L (2010) A preliminary study of the incorporation of NPK fertilizer into chitosan nanoparticles. eXpress Polym Lett 4:509–515. https://doi.org/10.3144/expresspolymlett.2010.64

Cui D, Zhang P, Ma YH, He X, Li YY, Zhao YC, Zhang ZY (2014) Phytotoxicity of silver nanoparticles to cucumber (*Cucumis sativus*) and wheat (*Triticum aestivum*). J Zhejiang Univ Sci A 15(8):662–670. https://doi.org/10.1631/jzus.A1400114

Cui JH, Liu TX, Li FB, Yi JC, Liu CP, Yu HY (2017) Silica nanoparticles alleviate cadmium toxicity in rice cells: mechanisms and size effects. Environ Pollut 228:363–369. https://doi.org/10.1016/j.envpol.2017.05.014

Dalcorso G, Manara A, Piasentin S, Furini A (2014) Nutrient metal elements in plants. Metallomics 6:1770–1788. https://doi.org/10.1039/c4mt00173g

Dapkekar A, Deshpande P, Oak MD, Paknikar KM, Rajwade JM (2018) Zinc use efficiency is enhanced in wheat through nanofertilization. Sci Rep 8:6832. https://doi.org/10.1038/s41598-018-25247-5

de la Rosa G, Lopez-Moreno ML, de Haro D, Botez CE, Peralta-Videa JR, Gardea-Torresdey JL (2013) Effects of ZnO nanoparticles in alfalfa, tomato, and cucumber at the germination stage: root development and X-ray absorption spectroscopy studies. Pure Appl Chem 85(12):2161–2174. https://doi.org/10.1351/PAC-CON-12-09-0

Delfani M, Firouzabadi MB, Farrokhi N, Makarian H (2014) Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. Commun Soil Sci Plant Anal 45:530–540. https://doi.org/10.1080/00103624.2013.863911

Deshpande P, Dapkekar A, Oak MD, Paknikar KM, Rajwade JM (2017) Zinc complexed chitosan/TPP nanoparticles: A promising micronutrient nanocarrier suited for foliar application. Carbohydr Polym 165:394–401. https://doi.org/10.1016/j.carbpol.2017.02.061

Dietz KJ, Herth S (2011) Plant nanotoxicology. Trends Plant Sci 16:582–589. https://doi.org/10.1016/j.tplants.2011.08.003

Dimkpa CO, Bindraban PS (2018) Nanofertilizers: New products for the industry? J Agric Food Chem 66:6462–6473. https://doi.org/10.1021/acs.jafc.7b02150

Dimkpa CO, White JC, Elmer WH, Gardea-Torresdey J (2017a) Nanoparticle and ionic Zn promote nutrient loading of sorghum grain under low NPK fertilization. J Agric Food Chem 65(39):8552–8559. https://doi.org/10.1021/acs.jafc.7b02961

Dimkpa CO, Bindraban PS, Fugice J, Agyin-Birikorang S, Singh U, Hellums D (2017b) Composite micronutrient nanoparticles and salts decrease drought stress in soybean. Agron Sustain Dev 37(1):5. https://doi.org/10.1007/s13593-016-0412-8

Dimkpa CO, Singh U, Bindraban PS, Elmer WH, Gardea-Torresdey JL, White JC (2018) Exposure to weathered and fresh nanoparticle and ionic Zn in soil promotes grain yield and modulates nutrient acquisition in wheat (*Triticum aestivum* L.). J Agric Food Chem 66(37):9645–9656. https://doi.org/10.1021/acs.jafc.8b03840

Djanaguiraman M, Nair R, Giraldo JP, Prasad PVV (2018a) 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

Djanaguiraman M, Belliraj N, Bossmann SH, Prasad PVV (2018b) High-temperature stress alleviation by selenium nanoparticle treatment in grain sorghum. ACS Omega 3(3):2479–2491. https://doi.org/10.1021/acsomega.7b01934

Dolez PI (2015) Nanoengineering: global approaches to health and safety issues. Elsevier, Amsterdam

Domokos-Szabolcsy E, Marton L, Sztrik A, Babka B, Prokisch J, Fari M (2012) Accumulation of red elemental selenium nanoparticles and their biological effects in *Nicotiana tabacum*. Plant Growth Regul 68(3):525–531. https://doi.org/10.1007/s10725-012-9735-x

Du WC, Gardea-Torresdey JL, Xie YW, Yin Y, Zhu JG, Zhang XW, Ji R, Gu KH, Peralta-Videa JR, Guo HY (2017) Elevated CO_2 levels modify TiO_2 nanoparticle effects on rice and soil microbial communities. Sci Total Environ 578:408–416. https://doi.org/10.1016/j.scitotenv.2016.10.197

Du WC, Tan WJ, Yin Y, Ji R, Peralta-Videa JR, Guo HY, Gardea-Torresdey JL (2018) Differential effects of copper nanoparticles/microparticles in agronomic and physiological parameters of oregano (*Origanum vulgare*). Sci Total Environ 618:306–312. https://doi.org/10.1016/j.scitotenv.2017.11.042

Duhan JS, Kumar R, Kumar N, Kaur P, Nehra K, Surekha (2017) Nanotechnology: The new perspective in precision agriculture. Biotechnol Rep (Amst). 15:11–23. https://doi.org/10.1016/j.btre.2017.03.002

Duran NM, Medina-Llamas M, Cassanji JGB, de Lima RG, de Almeida E, Macedo WR, Mattia D, de Carvalho HWP (2018) Bean seedling growth enhancement using magnetite nanoparticles. J Agric Food Chem 66(23):5746–5755. https://doi.org/10.1021/acs.jafc.8b00557

Dykman LA, Shchyogolev SY (2017) Interactions of plants with noble metal nanoparticles (review). Sel'skokhozyaistvennaya Biologiya 2017(1):13–24. https://doi.org/10.15389/agrobiology.2017.1.13eng

Ebrahimi A, Galavi M, Ramroudi M, Moaveni P (2016) Study of agronomic traits of pinto bean (*Phaseolus vulgaris* L.) under nano TiO_2 spraying at various growth stages. Int J Pharm Res Allied Sci 5(2):458–471

Elanchezhian R, Kumar D, Ramesh K, Biswas AK, Guhey A, Patra AK (2017) Morpho-physiological and biochemical response of maize (*Zea mays* L.) plants fertilized with nano-iron (Fe_3O_4) micronutrient. J Plant Nutr 40(14):1969–1977. https://doi.org/10.1080/01904167.2016.1270320

El-Ghamry AM, Mosa AA, Alshaal TA, El-Ramady HR (2018) Nanofertilizers vs. biofertilizers: new insights. Env Biodiv Soil Security 2:1–72. https://doi.org/10.21608/jenvbs.2018.3880.1029

El-Ramady H, Domokos-Szabolcsy E, Abdalla NA, Alshaal TA, Shalaby TA, Sztrik A, Prokisch J, Fari M (2014) Selenium and nano-selenium in agroecosystems. Environ Chem Lett 12:495–510. https://doi.org/10.1007/s10311-014-0476-0

European Commission (2018) Definition of a nanomaterial. Available online at: http://ec.europa.eu/environment/chemicals/nanotech/faq/definition_en.htm

Faizan M, Faraz A, Yusuf M, Khan ST, Hayat S (2018) Zinc oxide nanoparticle-mediated changes in photosynthetic efficiency and antioxidant system of tomato plants. Photosynthetica 56(2):678–686. https://doi.org/10.1007/s11099-017-0717-0

FAO (2010) Food and Agriculture Organization of the United Nations and World Health Organization expert meeting on the application of nanotechnologies in the food and agriculture sectors. Potential food safety implications in Meeting Report (Rome). Available online at: http://whqlibdoc.who.int/publications/2010/9789241563932_eng.pdf

FAO (2013) Food and Agriculture Organization of the United Nations and World Health Organization. State of the art on the initiatives and activities relevant to risk assessment and risk management of nanotechnologies in the food and agriculture sectors in FAO/WHO Technical Paper. Available online at: http://www.fao.org/docrep/018/i3281e/i3281e.pdf

Farhangi-Abriz S, Torabian S (2018) Nano-silicon alters antioxidant activities of soybean seedlings under salt toxicity. Protoplasma 255(3):953–962. https://doi.org/10.1007/s00709-017-1202-0

Fathi A, Zahedi M, Torabian S (2017a) Effect of interaction between salinity and nanoparticles (Fe_2O_3 and ZnO) on physiological parameters of *Zea mays* L. J Plant Nutr 40(19):2745–2755. https://doi.org/10.1080/01904167.2017.1381731

Fathi A, Zahedi M, Torabian S, Khoshgoftar A (2017b) Response of wheat genotypes to foliar spray of ZnO and Fe_2O_3 nanoparticles under salt stress. J Plant Nutr 40(10):1376–1385. https://doi.org/10.1080/01904167.2016.1262418

Feizi H, Moghaddam PR, Shahtahmassebi N, Fotovat A (2012) Impact of bulk and nanosized titanium dioxide (TiO_2) on wheat seed germination and seedling growth. Biol Trace Elem Res 146(1):101–106. https://doi.org/10.1007/s12011-011-9222-7

Feregrino-Perez AA, Magana-Lopez E, Guzman C, Esquivel K (2018) A general overview of the benefits and possible negative effects of the nanotechnology in horticulture. Sci Hortic 238:126–137. https://doi.org/10.1016/j.scienta.2018.03.060

Fernández-Luqueño F, López-Valdez F, Valerio-Rodríguez MF (2015) Mineral fertilizers, biofertilizers and PGPRs: advantages and disadvantages of its implementation. In: Sinha S, Pant KK, Bajpai S (eds) Fertilizer technology II, Biofertilizers. Studium Press, Houston

Gammulla CG, Pascovici D, Atwell BJ, Haynes PA (2011) Differential proteomic response of rice (*Oryza sativa*) leaves exposed to high- and low-temperature stress. Proteomics 11(14):2839–2850. https://doi.org/10.1002/pmic.201100068

Gao FQ, Liu C, Qu CX, Zheng L, Yang F, Su MG, Hong FH (2008) Was improvement of spinach growth by nano-TiO_2 treatment related to the changes of Rubisco activase? Biometals 21(2):211–217. https://doi.org/10.1007/s10534-007-9110-y

Gao X, Avellan A, Laughton S, Vaidya R, Rodrigues SM, Casman EA, Lowry GV (2018) CuO nanoparticle dissolution and toxicity to wheat (*Triticum aestivum*) in rhizosphere soil. Environ Sci Technol 52(5):2888–2897. https://doi.org/10.1021/acs.est.7b05816

Garcia-Gomez C, Obrador A, Gonzalez D, Babin M, Fernandez MD (2017) Comparative effect of ZnO NPs, ZnO bulk and $ZnSO_4$ in the antioxidant defences of two plant species growing in two agricultural soils under greenhouse conditions. Sci Total Environ 589:11–24. https://doi.org/10.1016/j.scitotenv.2017.02.153

Garcia-Gomez C, Obrador A, Gonzalez D, Babin M, Fernandez MD (2018a) Comparative study of the phytotoxicity of ZnO nanoparticles and Zn accumulation in nine crops grown in a calcareous soil and an acidic soil. Sci Total Environ 644:770–780. https://doi.org/10.1016/j.scitotenv.2018.06.356

Garcia-Gomez C, Garcia S, Obrador AF, Gonzalez D, Babin M, Fernandez MD (2018b) Effects of aged ZnO NPs and soil type on Zn availability, accumulation and toxicity to pea and beet in a greenhouse experiment. Ecotox Environ Saf 160:222–230. https://doi.org/10.1016/j.ecoenv.2018.05.019

Ghafari H, Razmjoo J (2015) Response of durum wheat to foliar application of varied sources and rates of iron fertilizers. J Agr Sci Tech-Iran 17(2):321–331

Ghafariyan MH, Malakouti MJ, Dadpour MR, Stroeve P, Mahmoudi M (2013) Effects of magnetite nanoparticles on soybean chlorophyll. Environ Sci Technol 47(18):10645–10652. https://doi.org/10.1021/es402249b

Ghahremani A, Akbari K, Yousefpour M, Ardalani H (2014) Effects of nano-potassium and nano-calcium chelated fertilizers on qualitative and quantitative characteristics of *Ocimum basilicum*. Int J Pharm Res Scholars (IJPRS) 3(2):235–241

Gharibzahedi SMT, Jafari SM (2017) The importance of minerals in human nutrition: Bioavailability, food fortification, processing effects and nanoencapsulation. Trends Food Sci Technol 62:119–132. https://doi.org/10.1016/j.tifs.2017.02.017

Ghassemi A, Farahvash F (2018) Effect of nano-zinc foliar application on wheat under drought stress. Fresen Environ Bull 27(7):5022–5026

Ghazal B, Saif S, Farid K, Khan A, Rehman S, Reshma A, Fazal H, Ali M, Ahmad A, Rahman L, Ahmad N (2018) Stimulation of secondary metabolites by copper and gold nanoparticles in submerge adventitious root cultures of *Stevia rebaudiana* (Bert.). IET Nanobiotechnol 12(5):569–573. https://doi.org/10.1049/iet-nbt.2017.0093

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

Golabadi M, Golkar P, Rajabi R (2015) Effects of nano-silver particles on flower expression in greenhouse cucumber (*Cucumis sativus* L.). Crop Res (Hisar) 49(1-3):48–54

Golubkina NA, Folmanis GE, Tananaev IG (2012) Comparative evaluation of selenium accumulation by allium species after foliar application of selenium nanoparticles, sodium selenite and sodium selenate. Doklady Biological Sciences 444:176–179. https://doi.org/10.1134/S0012496612030076

Gonzalez GH, Godina FR, Ortiz HO, Mendoza A, Torres VR, De la Fuente MC (2017) Use of chitosan-PVA hydrogels with copper nanoparticles to improve the growth of grafted watermelon. Molecules 22(7):1031. https://doi.org/10.3390/molecules22071031

Guha T, Ravikumar KVG, Mukherjee A, Mukherjee A, Kundu R (2018) Nanopriming with zero valent iron (nZVI) enhances germination and growth in aromatic rice cultivar (*Oryza sativa* cv. Gobindabhog L.). Plant Physiol Biochem 127:403–413. https://doi.org/10.1016/j.plaphy.2018.04.014

Gui X, Deng YQ, Rui YK, Gao BB, Luo WH, Chen SL, Nhan LV, Li XG, Liu ST, Han YN, Liu L, Xing B (2015) Response difference of transgenic and conventional rice (*Oryza sativa*) to nanoparticles (γ-Fe_2O_3). Environ Sci Pollut Res 22(22):17716–17723. https://doi.org/10.1007/s11356-015-4976-7

Gui X, Rui MM, Song YH, Ma YH, Rui YK, Zhang P, He X, Li YY, Zhang ZY, Liu LM (2017) Phytotoxicity of CeO_2 nanoparticles on radish plant (*Raphanus sativus*). Environ Sci Pollut Res 24(15):13775–13781. https://doi.org/10.1007/s11356-017-8880-1

Gupta SD, Agarwal A, Pradhan S (2018) Phytostimulatory effect of silver nanoparticles (AgNPs) on rice seedling growth: an insight from antioxidative enzyme activities and gene expression patterns. Ecotox Environ Saf 161:624–633. https://doi.org/10.1016/j.ecoenv.2018.06.023

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

Haghighi M, Da Silva JAT, Mozafarian M, Afifipour Z (2013) Can Si and nano-Si alleviate the effect of drought stress induced by PEG in seed germination and seedling growth of tomato? Minerva Biotecnol 25(1):17–22

Haghighi M, Abolghasemi R, da Silva JAT (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. https://doi.org/10.1016/j.scienta.2014.09.006

Hänsch R, Mendel RR (2009) Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, Cl). Curr Opin Plant Biol 12:259–266. https://doi.org/10.1016/j.pbi.2009.05.006

Hamidat M, Barakat M, Ortet O, Chaneac C, Rose J, Bottero JY, Heulin T, Achouak W, Santaella C (2016) Design defines the effects of nanoceria at a low dose on soil microbiota and the potentiation of impacts by the canola plant. Environ Sci Technol 50(13):6892–6901. https://doi.org/10.1021/acs.est.6b01056

Hasaneen MNA, Abdel-Aziz HMM, El-Bialy DMA, Omer AM (2014) Preparation of chitosan nanoparticles for loading with NPK fertilizer. Afr J Biotechnol. 3:3158–3164. https://doi.org/10.5897/AJB2014.13699

Hasanpour H, Maali-Amir R, Zeinali H (2015) Effect of TiO_2 nanoparticles on metabolic limitations to photosynthesis under cold in chickpea. Russ J Plant Physiol 62(6):779–787. https://doi.org/10.1134/S1021443715060096

Hasanuzzaman M, Bhuyan MHMB, Nahar K, Hossain MS, Mahmud JA, Hossen MS, Masud AAC, Moumita, Fujita M (2018) Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. Agronomy 8:31. https://doi.org/10.3390/agronomy8030031

Hatami M (2017) Stimulatory and inhibitory effects of nanoparticulates on seed germination and seedling vigor indices. In: Ghorbanpour M, Manika K, Varma A (eds) Nanoscience and plant–soil systems, Soil biology, vol 48, pp 357–385. https://doi.org/10.1007/978-3-319-46835-8_13

Haworth M, Elliott-Kingston C, McElwain JC (2013) Co-ordination of physiological and morphological responses of stomata to elevated CO_2 in vascular plants. Oecologia 171:71–82. https://doi.org/10.1007/s00442-012-2406-9

Hernandez HH, Benavides-Mendoza A, Ortega-Ortiz H, Hernandez-Fuentes AD, Juarez-Maldonado A (2017) Cu nanoparticles in chitosan-PVA hydrogels as promoters of growth, productivity and fruit quality in tomato. Emir J Food Agric 29(8):573–580. https://doi.org/10.9755/ejfa.2016-08-1127

Hernandez-Hernandez H, Gonzalez-Morales S, Benavides-Mendoza A, Ortega-Ortiz H, Cadenas-Pliego G, Juarez-Maldonado A (2018a) Effects of chitosan-PVA and Cu nanoparticles on the growth and antioxidant capacity of tomato under saline stress. Molecules 23(1):178. https://doi.org/10.3390/molecules23010178

Hernandez-Hernandez H, Juarez-Maldonado A, Benavides-Mendoza A, Ortega-Ortiz H, Cadenas-Pliego G, Sanchez-Aspeytia D, Gonzalez-Morales S (2018b) Chitosan-PVA and copper nanoparticles improve growth and overexpress the SOD and JA genes in tomato plants under salt stress. Agronomy-Basel 8(9):175. https://doi.org/10.3390/agronomy8090175

Hoe PT, Mai NC, Lien LQ, Ban NK, Minh CV, Chau NH, Buu NQ, Hien DT, Van NT, Hien LTT, Linh TM (2018) Germination responses of soybean seeds to Fe, ZnO, Cu and Co nanoparticle treatments. Int J Agric Biol 20(7):1562–1568. https://doi.org/10.17957/IJAB/15.0670

Hollósy F (2002) Effect of ultraviolet radiation on plant cells. Micron 33(2):179–197

Hong FS, Yang P, Gao FQ, Liu C, Zheng L, Yang F, Zhou J (2005) Effect of nano-anatase TiO_2 on spectral characterization of photosystem II particles from spinach. Chem Res Chinese U 21(2):196–200

Hong J, Wang LN, Sun YP, Zhao LJ, Niu GH, Tan WJ, Rico CM, Peralta-Videa JR, Gardea-Torresdey JL (2016) Foliar applied nanoscale and microscale CeO_2 and CuO alter cucumber (*Cucumis sativus*) fruit quality. Sci Total Environ 563:904–911. https://doi.org/10.1016/j.scitotenv.2015.08.029

Hossain Z, Mustafa G, Komatsu S (2015) Plant responses to nanoparticle stress. Int J Mol Sci 16:26644–26653. https://doi.org/10.3390/ijms161125980

Hossain Z, Mustafa G, Sakata K, Komatsu S (2016) Insights into the proteomic response of soybean towards Al_2O_3, ZnO, and Ag nanoparticles stress. J Hazard Mater 304:291–305. https://doi.org/10.1016/j.jhazmat.2015.10.071

Hozayn M, Abd El-Wahed MSA, Abd El-Monem AA, Abdelraouf RE, Abd Elhamid EM (2016) Applications of magnetic technology in agriculture, a novel tool for improving water and crop productivity: 3. Faba bean. Res J Pharm Biol Chem Sci 7(6):1288–1296

Hu J, Wu C, Ren HX, Wang YQ, Li JL, Huang J (2018) Comparative analysis of physiological impact of γ-Fe_2O_3 nanoparticles on dicotyledon and monocotyledon. J Nanosci Nanotechnol 18(1):743–752. https://doi.org/10.1166/jnn.2018.13921

Huang Q, Liu Q, Lin LN, Li FJ, Han YF, Song ZG (2018) Reduction of arsenic toxicity in two rice cultivar seedlings by different nanoparticles. Ecotox Environ Saf 159:261–271. https://doi.org/10.1016/j.ecoenv.2018.05.008

Hussain M, Raja NI, Mashwani ZUR, Iqbal M, Ejaz M, Yasmeen F, Sohail (2017) *In vitro* germination and biochemical profiling of *Citrus reticulata* in response to green synthesised zinc and copper nanoparticles. IET Nanobiotechnol 11(7):790–796. https://doi.org/10.1049/iet-nbt.2016.0256

Hussain A, Ali S, Rizwan M, Rehman MZU, Javed MR, Imran M, Chatha SAS, Nazir R (2018) Zinc oxide nanoparticles alter the wheat physiological response and reduce the cadmium uptake by plants. Environ Pollut 242:1518–1526. https://doi.org/10.1016/j.envpol.2018.08.036

Hussein MM, Abou-Baker NH (2018) The contribution of nano-zinc to alleviate salinity stress on cotton plants. Royal Soc Open Sci 5(8):171809. https://doi.org/10.1098/rsos.171809

Ibrahim MH, Jaafar HZE (2011) Increased carbon dioxide concentration improves the antioxidative properties of the Malaysian herb Kacip Fatimah (*Labisia pumila* Blume). Molecules 16:6068–6081. https://doi.org/10.3390/molecules16076068

Iqbal MT (2012) Acid tolerance mechanism in soil grown plants. Malaysian J Soil Sci (MJSS) 16:1–21

Iqbal M, Raja NI, Zia-Ur-Rehman M, Hussain N, Ejaz M, Yasmeen F (2017) Effect of silver nanoparticles on growth of wheat under heat stress. Iran J Sci Technol Trans Sci 2017:1–9. https://doi.org/10.1007/s40995-017-0417-4

Ivani R, Nejad SHS, Ghahraman B, Astaraei AR, Feizi H (2018) Role of bulk and nanosized SiO_2 to overcome salt stress during Fenugreek germination (*Trigonella foenum- graceum* L.). Plant Signal Behav 13(7):e1044190. https://doi.org/10.1080/15592324.2015.1044190

Jalali M, Ghanati F, Modarres-Sanavi AM (2016) Effect of Fe_3O_4 nanoparticles and iron chelate on the antioxidant capacity and nutritional value of soil-cultivated maize (*Zea mays*) plants. Crop Pasture Sci 67(6):621–628. https://doi.org/10.1071/CP15271

Jampílek J, Kráľová K (2015) Application of nanotechnology in agriculture and food industry, its prospects and risks. Ecol Chem Eng S 22(3):321–361. https://doi.org/10.1515/eces-2015-0018

Jampílek J, Kráľová K (2017a) Nanopesticides: preparation, targeting and controlled release. In: Grumezescu AM (ed) New pesticides and soil sensors in nanotechnology in the agri-food industry, vol 10. Elsevier, London, pp 81–127. https://doi.org/10.1016/B978-0-12-804299-1.00004-7

Jampílek J, Kráľová K (2017b) Nanomaterials for delivery of nutrients and growth-promoting compounds to plants. In: Prasad R, Kumar M, Kumar V (eds) Nanotechnology: an agricultural paradigm. Springer, Singapore, pp 177–226. https://doi.org/10.1007/978-981-10-4573-8_9

Jampílek J, Kráľová K (2017c) Nano-antimicrobials: activity, benefits and weaknesses. In: Ficai A, Grumezescu AM (eds) Nanostructures in therapeutic medicine, Vol. 2 – Nanostructures for antimicrobial therapy. Elsevier, Amsterdam, pp 23–54. https://doi.org/10.1016/B978-0-323-46152-8.00002-0

Jampílek J, Kráľová K (2018a) Benefits and potential risks of nanotechnology applications in crop protection. In: Abd-Elsalam K, Prasad R (eds) Nanobiotechnology applications in plant protection. Springer, Cham, pp 189–246. https://doi.org/10.1007/978-3-319-91161-8_8

Jampílek J, Kráľová K (2018b) Application of nanobioformulations for controlled release and targeted biodistribution of drugs. In: Sharma AK, Keservani RK, Kesharwani RK (eds) Nanobiomaterials: applications in drug delivery. CRC Press, Warentown, pp 131–208

Jampílek J, Kráľová K (2018c) Nanomaterials applicable in food protection. In: Rai RV, Bai JA (eds) Nanotechnology applications in food industry. CRC Press/Taylor & Francis Group, Boca Raton, pp 75–96

Janmohammadi M, Sabaghnia N (2015) Effect of pre-sowing seed treatments with silicon nanoparticles on germinability of sunflower (*Helianthus annuus*). Bot Lith 21(1):13–21. https://doi.org/10.1515/botlit-2015-0002

Javed R, Mohamed A, Yucesan B, Gurel E, Kausar R, Zia M (2017a) CuO nanoparticles significantly influence *in vitro* culture, steviol glycosides, and antioxidant activities of *Stevia rebaudiana* Bertoni. Plant Cell Tissue Organ Cult 131(3):611–620. https://doi.org/10.1007/s11240-017-1312-6

Javed R, Usman M, Yucesan B, Zia M, Gurel E (2017b) Effect of zinc oxide (ZnO) nanoparticles on physiology and steviol glycosides production in micropropagated shoots of *Stevia rebaudiana* Bertoni. Plant Physiol Biochem 110:94–99. https://doi.org/10.1016/j.plaphy.2016.05.032

Jayarambabu N, Kumari BS, Rao KV, Prabhu YT (2016) Enhancement of growth in maize by biogenic synthesized MgO nanoparticles. Int J Pure Appl Zool 4(3):262–270

Ji Y, Zhou Y, Ma CX, Feng Y, Hao Y, Rui YK, Wu WH, Gui X, Le VN, Han YN, Wang Y, Xing B, Liu L, Cao W (2017) Jointed toxicity of TiO_2 NPs and Cd to rice seedlings: NPs alleviated Cd toxicity and Cd promoted NPs uptake. Plant Physiol Biochem 110:82–93. https://doi.org/10.1016/j.plaphy.2016.05.010

Jiang FP, Shen YZ, Ma CX, Zhang XW, Cao WD, Rui YK (2017) Effects of TiO_2 nanoparticles on wheat (*Triticum aestivum* L.) seedlings cultivated under super-elevated and normal CO_2 conditions. PLoS ONE 12(5):e0178088. https://doi.org/10.1371/journal.pone.0178088

Jin YJ, Fan XJ, Li XX, Zhang ZY, Sun LW, Fu ZW, Lavoie M, Pan XL, Qian HF (2017) Distinct physiological and molecular responses in *Arabidopsis thaliana* exposed to aluminum oxide nanoparticles and ionic aluminum. Environ Pollut 228:517–527. https://doi.org/10.1016/j.envpol.2017.04.073

Juarez-Maldonado A, Ortega-Ortiz H, Perez-Labrada F, Cadenas-Pliego G, Benavides-Mendoza A (2016) Cu nanoparticles absorbed on chitosan hydrogels positively alter morphological, production, and quality characteristics of tomato. J Appl Bot Food Qual 89:183–189. https://doi.org/10.5073/JABFQ.2016.089.023

Judy JD, Unrine JM, Rao W, Wirick S, Bertsch PM (2012) Bioavailability of gold nanomaterials to plants: importance of particle size and surface coating. Environ Sci Technol 46(15):8467–8474. https://doi.org/10.1021/es3019397

Jurkova IN, Omelchenko AV (2016) Method of stimulation germination of wheat seeds. Patent Number: RU2601578-C1, Publ. date 10 Nov 2016

Kah M, Walch H, Hofmann T (2018) Environmental fate of nanopesticides: durability, sorption and photodegradation of nanoformulated clothianidin. Environ Sci Nano 5(4):882–889. https://doi.org/10.1039/C8EN00038G

Karami A, Sepehri A (2018) Nano titanium dioxide and nitric oxide alleviate salt induced changes in seedling growth, physiological and photosynthesis attributes of barley. Zemdirbyste 105(2):123–132. https://doi.org/10.13080/z-a.2018.105.016

Karunakaran G, Suriyaprabha R, Rajendran V, Kannan N (2016) Influence of ZrO_2, SiO_2, Al_2O_3 and TiO_2 nanoparticles on maize seed germination under different growth conditions. IET Nanobiotechnol 10(4):171–177. https://doi.org/10.1049/iet-nbt.2015.0007

Kasim WA, Abokassem EM, Ragab GA (2017) Ameliorative effect of yeast extract, IAA and green-synthesized nano zinc oxide on the growth of Cu-stressed *Vicia faba* seedlings. Egypt J Bot 57:1–16. https://doi.org/10.21608/ejbo.2017.885.1065

Khan MR, Rizvi TF (2017) Application of nanofertilizer and nanopesticides for improvements in crop production and protection. In: Ghorbanpour M, Manika K, Varma A (eds) Nanoscience and plant–soil systems, Soil biology, vol 48. Springer, Cham, pp 405–427. https://doi.org/10.1007/978-3-319-46835-8_15

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. https://doi.org/10.1016/j.plaphy.2016.05.038

Kheyri N, Norouzi AH, Mobasser HR, Torabi B (2018) Application on agronomic traits, nutrient uptake and grain yield of rice (*Oryza sativa* L.). Appl Ecol Environ Res 16(5):5781–5798. https://doi.org/10.15666/aeer/1605_57815798

Koce JD, Drobne D, Klancnik K, Makovec D, Novak S, Hocevar M (2014) Oxidative potential of ultraviolet-A irradiated or nonirradiated suspensions of titanium dioxide or silicon dioxide nanoparticles on *Allium cepa* roots. Environ Toxicol Chem 33(4):858–867. https://doi.org/10.1002/etc.2496

Konate A, He X, Zhang ZY, Ma YH, Zhang P, Alugongo GM, Rui YK (2017) Magnetic (Fe_3O_4) nanoparticles reduce heavy metals uptake and mitigate their toxicity in wheat seedling. Sustainability 9(5):790. https://doi.org/10.3390/su9050790

Kráľová K, Masarovičová E, Jampílek J (2019) Plant responses to stress induced by toxic metals and their nanoforms. In: Pessarakli M (ed) Handbook of plant and crop stress, 4rd edn. CRC Press, Boca Raton

Kumar V, Guleria P, Kumar V, Yadav SK (2013) Gold nanoparticle exposure induces growth and yield enhancement in *Arabidopsis thaliana*. Sci Total Environ 461:462–468. https://doi.org/10.1016/j.scitotenv.2013.05.018

Kumar S, Sachdeva S, Bhat KV, Vats S (2018) Plant responses to drought stress: Physiological, biochemical and molecular basis. In: Vats S (ed) Biotic and abiotic stress tolerance in plants. Springer, Singapore, pp 1–25. https://doi.org/10.1007/978-981-10-9029-5_1

Langdon KA, McLaughlin MJ, Kirby JK, Merrington G (2015) Influence of soil properties and soil leaching on the toxicity of ionic silver to plants. Environ Toxicol Chem 34(11):2503–2512. https://doi.org/10.1002/etc.3067

Larue C, Veronesi G, Flank AM, Surble S, Herlin-Boime N, Carriere M (2012) Comparative uptake and impact of TiO_2 nanoparticles in wheat and rapeseed. J Toxicol Environ Health A 75(13-15):722–734. https://doi.org/10.1080/15287394.2012.689800

Latef AAHA, Abu Alhmad MF, 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. https://doi.org/10.1007/s00344-016-9618-x

Layet C, Auffan M, Santaella C, Chevassus-Rosset C, Montes M, Ortet P, Barakat M, Collin B, Legros S, Bravin MN, Angeletti B, Kieffer I, Proux O, Hazemann JL, Doelsch E (2017) Evidence that soil properties and organic coating drive the phytoavailability of cerium oxide nanoparticles. Environ Sci Technol 51(17):9756–9764. https://doi.org/10.1021/acs.est.7b02397

Lei Z, Su MY, Chao L, Liang C, Hao H, Xiao W, Liu XP, Fan Y, Gao FQ, Hong FS (2007) Effects of nanoanatase TiO_2 on photosynthesis of spinach chloroplasts under different light illumination. Biol Trace Elem Res 119(1):68–76. https://doi.org/10.1007/s12011-007-0047-3

Lei Z, Su MY, Xiao W, Chao L, Qu CX, Liang C, Hao H, Liu XQ, Hong FS (2008) Antioxidant stress is promoted by nano-anatase in spinach chloroplasts under UV-B radiation. Biol Trace Elem Res 121(1):69–79. https://doi.org/10.1007/s12011-007-8028-0

Li JX, Wee CD, Sohn BK (2010) Growth response of hot pepper applicated with ammonium (NH_4^+) and potassium (K^+)-loaded zeolite. Korean J Soil Sci Fert 43(5):619–625

Li JX, Wee C, Sohn BY (2013) Effect of ammonium- and potassium-loaded zeolite on kale (*Brassica alboglabra*) growth and soil property. Am J Plant Sci 4:1976–1982. https://doi.org/10.4236/ajps.2013.410245

Li X, Yang YC, Gao B, Zhang M (2015a) Stimulation of peanut seedling development and growth by zero-valent iron nanoparticles at low concentrations. PLoS ONE 10(4):e0122884. https://doi.org/10.1371/journal.pone.0122884

Li J, Naeem MS, Wang XP, Liu LX, Chen C, Ma N, Zhang CL (2015b) Nano-TiO_2 is not phytotoxic as revealed by the oilseed rape growth and photosynthetic apparatus ultra-structural response. PLoS ONE 10(12):e0143885. https://doi.org/10.1371/journal.pone.0143885

Li P, Du Y, Huang LB, Mitter N, Xu ZP (2016a) Nanotechnology promotes the R&D of new-generation micronutrient foliar fertilizers. RSC Adv 6(73):69465–69478. https://doi.org/10.1039/c6ra09428g

Li JL, Hu J, Ma CX, Wang YQ, Wu C, Huang J, Xing B (2016b) Uptake, translocation and physiological effects of magnetic iron oxide (γ-Fe_2O_3) nanoparticles in corn (*Zea mays* L.). Chemosphere 159:326–334. https://doi.org/10.1016/j.chemosphere.2016.05.083

Liang WJ, Ma XL, Wan P, Liu LY (2018) Plant salt-tolerance mechanism: A review. Biochem Biophys Res Commun 495:286–291. https://doi.org/10.1016/j.bbrc.2017.11.043

Liu RQ, Lal R (2015) Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Sci Total Environ 514:131–139

Liu J, Wang WX (2017) The protective roles of TiO_2 nanoparticles against UV-B toxicity in *Daphnia magna*. Sci Total Environ 593:47–53. https://doi.org/10.1016/j.scitotenv.2017.03.155

Liu X, Zhang D, Zhang S, He X, Wang Y, Feng Z, Wang Y (2005) Responses of peanut to nano-calcium carbonate. J Plant Nutr Fert (Chin) 11:385–389

Liu JG, Cai H, Mei CC, Wang MX (2015) Effects of nano-silicon and common silicon on lead uptake and translocation in two rice cultivars. Front Environ Sci Eng 9(5):905–911. https://doi.org/10.1007/s11783-015-0786-x

Liu RQ, Zhang HY, Lal R (2016) Concentrations on lettuce (*Lactuca sativa*) seed germination: Nanotoxicants or nanonutrients? Water Air Soil Pollut 227(1):42. https://doi.org/10.1007/s11270-015-2738-2

Liu J, Dhungana B, Cobb GP (2018) Copper oxide nanoparticles and arsenic interact to alter seedling growth of rice (*Oryza sativa* japonica). Chemosphere 206:330–337. https://doi.org/10.1016/j.chemosphere.2018.05.021

Lopez-Luna J, Silva-Silva MJ, Martinez-Vargas S, Mijangos-Ricardez OF, Gonzalez-Chavez MC, Solis-Dominguez FA, Cuevas-Diaz MC (2016) Magnetite nanoparticle (NP) uptake by wheat plants and its effect on cadmium and chromium toxicological behavior. Sci Total Environ 565:941–950. https://doi.org/10.1016/j.scitotenv.2016.01.029

Lopez-Moreno ML, de la Rosa G, Hernandez-Viezcas JA, Peralta-Videa JR, Gardea-Torresdey JL (2010) X-ray absorption spectroscopy (XAS) corroboration of the uptake and storage of CeO_2 nanoparticles and assessment of their differential toxicity in four edible plant species. J Agric Food Chem 58(6):3689–3693. https://doi.org/10.1021/jf904472e

Lopez-Moreno ML, de la Rosa G, Cruz-Jimenez G, Castellano L, Peralta-Videa JR, Gardea-Torresdey JL (2017) Effect of ZnO nanoparticles on corn seedlings at different temperatures; X-ray absorption spectroscopy and ICP/OES studies. Microchem J 134:54–61. https://doi.org/10.1016/j.microc.2017.05.007

Lopez-Moreno ML, Cedeno-Mattei Y, Bailon-Ruiz SJ, Vazquez-Nunez E, Hernandez-Viezcas JA, Perales-Perez OJ, de la Rosa G, Peralta-Videa JR, Gardea-Torresdey JL (2018) Environmental behavior of coated NMs: Physicochemical aspects and plant interactions. J Hazard Mater 347:196–217. https://doi.org/10.1016/j.jhazmat.2017.12.058

López-Valdez F, Miranda-Arámbula M, Ríos-Cortés AM, Fernández-Luqueño F, de-la-Luz V. (2018) Nanofertilizers and their controlled delivery of nutrients. In: López-Valdez F, Fernández-Luqueño F (eds) Agricultural nanobiotechnology. Springer, Cham, pp 35–48. https://doi.org/10.1007/978-3-319-96719-6_3

Lopez-Vargas ER, Ortega-Ortiz H, Cadenas-Pliego G, Romenus KD, de la Fuente MC, Benavides-Mendoza A, Juarez-Maldonado A (2018) Foliar application of copper nanoparticles increases the fruit quality and the content of bioactive compounds in tomatoes. Appl Sci-Basel 8(7):1020. https://doi.org/10.3390/app8071020

Ma HB, Brennan A, Diamond SA (2012) Photocatalytic reactive oxygen species production and phototoxicity of titanium dioxide nanoparticles are dependent on the solar ultraviolet radiation spectrum. Environ Toxicol Chem 31(9):2099–2107. https://doi.org/10.1002/etc.1916

Macedo AF (2012) Abiotic stress responses in plants: metabolism to productivity. In: Ahmad P, Prasad MNV (eds) Abiotic stress responses in plants: metabolism, productivity and sustainability. Springer, New York, pp 41–61

Mahakham W, Theerakulpisut P, Maensiri S, Phumying S, Sarmah AK (2016) Environmentally benign synthesis of phytochemicals-capped gold nanoparticles as nanopriming agent for promoting maize seed germination. Sci Total Environ 573:1089–1102. https://doi.org/10.1016/j.scitotenv.2016.08.120

Mahakham W, Sarmah AK, Maensiri S, Theerakulpisut P (2017) Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. Sci Rep 7:8263. https://doi.org/10.1038/s41598-017-08669-5

Majeed A, Muhammad Z, Islam S, Ahmad H (2018) Salinity imposed stress on principal cereal crops and employing seed priming as a sustainable management approach. Acta Ecologica Sinica. https://doi.org/10.1016/j.chnaes.2018.09.004

Manesh RR, Grassi G, Bergami E, Marques-Santos LF, Faleri C, Liberatori G, Corsi I (2018) Co-exposure to titanium dioxide nanoparticles does not affect cadmium toxicity in radish seeds (*Raphanus sativus*). Ecotox Environ Saf 148:359–366. https://doi.org/10.1016/j.ecoenv.2017.10.051

Mani PK, Mondal S (2016) Agri-nanotechniques for plant availability of nutrients. In: Kole C, Kumar DS, Khodakovskaya MV (eds) Plant nanotechnology. Springer, Switzerland, pp 263–303. https://doi.org/10.1007/978-3-319-42154-4_11

Marchiol L, Mattiello A, Poscic F, Fellet G, Zavalloni C, Carlino E, Musetti R (2016) Changes in physiological and agronomical parameters of barley (*Hordeum vulgare*) exposed to cerium and titanium dioxide nanoparticles. Int J Environ Res Public Health 13(3). https://doi.org/10.3390/ijerph13030332

Marmiroli N, White JC (2016) Nanotoxicology and environmental risk assessment of engineered nanomaterials (ENMs) in plants. Front Plant Sci 7:1370. https://doi.org/10.3389/fpls.2016.01370

Marschner H (2012) In: Marschner P (ed) Marschner's mineral nutrition of higher plants, 3rd edn. Academic Press, Amsterdam

Martinez-Fernandez D, Vitkova M, Bernal MP, Komarek M (2015) Effects of nano-maghemite on trace element accumulation and drought response of *Helianthus annuus* L. in a contaminated mine soil. Water Air Soil Pollut 226(4):101. https://doi.org/10.1007/s11270-015-2365-y

Masarovičová E, Kráľová K (2012) Plant-heavy metal interaction: Phytoremediation, biofortification and nanoparticles. In: Montanaro G, Dichio B (eds) Advances in selected plant physiology aspects. InTech, Rijeka, pp 75–102. https://doi.org/10.5772/33722

Masarovičová E, Kráľová K (2013) Metal nanoparticles and plants. Ecol Chem Eng S 20:9–22. https://doi.org/10.2478/eces-2013-0001

Masarovičová E, Kráľová K (2017) Essential elements and toxic metals in some crops, medicinal plants and trees. In: Ansari A, Gill S, Gill R, Lanza G, Newman L (eds) Phytoremediation. Springer, Cham, pp 183–255. https://doi.org/10.1007/978-3-319-52381-1_7

Masarovičová E, Kráľová K, Šeršeň F (2010) Plant responses to toxic metal stress. In: Pessarakli M (ed) Handbook of plant and crop stress, 3rd edn. CRC Press, Boca Raton, pp 595–634

Masarovičová E, Kráľová K, Zinjarde SS (2014) Metal nanoparticles in plants. Formation and action. In: Pessarakli M (ed) Handbook of plant and crop physiology, 3rd edn. CRC Press, Boca Raton, pp 683–731. https://doi.org/10.1201/b16675-39

Masarovičová E, Kráľová K, Vykouková I, Kriššáková Z (2019) Responses of medicinal plants to abiotic stresses. In: Pessarakli M (ed) Handbook of plant and crop stress, 4rd edn. CRC Press, Boca Raton

Mbarki M, Sytar O, Cerda A, Zivcak M, Rastogi A, He XL, Zoghlami A, Abdelly C, Brestic M (2018) Strategies to mitigate the salt stress effects on photosynthetic apparatus and productivity of crop plants. In: Kumar V, Wani SH, Suprasanna P, Tran L-SP (eds) Salinity responses and tolerance in plants, vol 1. Springer, New York, pp 85–136. https://doi.org/10.1007/978-3-319-75671-4_4

Medina-Velo IA, Zuverza-Mena N, Tamez C, Ye YQ, Hernandez-Viezcas JA, White JC, Peralta-Videa JR, Gardea-Torresdey JL (2018) Minimal transgenerational effect of ZnO nanomaterials on the physiology and nutrient profile of *Phaseolus vulgaris*. ACS Sustain Chem Eng 6(6):7924–7930. https://doi.org/10.1021/acssuschemeng.8b01188

Mehmood A, Murtaza G (2017) Application of SNPs to improve yield of *Pisum sativum* L. (pea). IET Nanobiotechnol 11(4):390–394. https://doi.org/10.1049/iet-nbt.2016.0041

Meteorology glossary (2012) American Meteorological Society. http://glossary.ametsoc.org/wiki/Flooding; http://glossary.ametsoc.org/wiki/Flood

Mikkelsen RL (2011) The “4R” nutrient stewardship framework for horticulture. HortTechnol. 21(6):658–662. http://academic.uprm.edu/dsotomayor/agro6505/4R_Mikkelsen_Framework.pdf

Minich AS, Minich IB, Chursina NL, Ivanitckiy AE, Butsenko ES, Rozhdestvenskiy EA (2016) Morphogenesis and productivity of *Cucumis sativus* L. hybrids under the thermic polyethylene films modified by coating of metals by magnetron sputtering. HortScience 43(2):59–66. https://doi.org/10.17221/93/2015-HORTSCI

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 NL (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

Mohammadi H, Hatami M, Feghezadeh K, Ghorbanpour M (2018) Mitigating effect of nano-zerovalent iron, iron sulfate and EDTA against oxidative stress induced by chromium in *Helianthus annuus* L. Acta Physiol Plant 40(4):69. https://doi.org/10.1007/s11738-018-2647-2

Morales MI, Rico CM, Hernandez-Viezcas JA, Nunez JE, Barrios AC, Tafoya A, Flores-Marges JP, Peralta-Videa JR, Gardea-Torresdey JL (2013) Toxicity assessment of cerium oxide nanoparticles in cilantro (*Coriandrum sativum* L.) plants grown in organic soil. J Agric Food Chem 61(26):6224–6230. https://doi.org/10.1021/jf401628v

Morteza E, Moaveni P, Farahani HA, Kiyani M (2013) Study of photosynthetic pigments changes of maize (*Zea mays* L.) under nano TiO_2 spraying at various growth stages. Springerplus 2:247. https://doi.org/10.1186/2193-1801-2-247

Mozafari AA, Havas F, Ghaderi N (2018) Application of iron nanoparticles and salicylic acid in *in vitro* culture of strawberries (*Fragaria* x *ananassa* Duch.) to cope with drought stress. Plant Cell Tissue Organ Cult 132(3):511–523. https://doi.org/10.1007/s11240-017-1347-8

Munir T, Rizwan M, Kashif M, Shahzad A, Ali S, Amin N, Zahid R, Alam MFE, Imran M (2018) Effect of zinc oxide nanoparticles on the growth and Zn uptake in wheat (*Triticum aestivum* L.) by seed priming method. Dig J Nanomater Biostruct 13(1):315–323

Mustafa G, Komatsu S (2016) Insights into the response of soybean mitochondrial proteins to various sizes of aluminum oxide nanoparticles under flooding stress. J Proteome Res 15(12):4464–4475. https://doi.org/10.1021/acs.jproteome.6b00572

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

Mustafa G, Sakata K, Komatsu S (2016) Proteomic analysis of soybean root exposed to varying sizes of silver nanoparticles under flooding stress. J Proteomics 148:113–125. https://doi.org/10.1016/j.jprot.2016.07.027

Mutlu F, Yurekli F, Mutlu B, Emre FB, Okusluk F, Ozgul O (2018) Assessment of phytotoxic and genotoxic effects of anatase TiO_2 nanoparticles on maize cultivar by using RAPD analysis. Fresen Environ Bull 27(1):436–445

Nagaonkar D, Shende S, Rai M (2015) Biosynthesis of copper nanoparticles and its effect on actively dividing cells of mitosis in *Allium cepa*. Biotechnol Prog 31(2):557–565. https://doi.org/10.1002/btpr.2040

National Nanotechnology Initiative (2018) Nanotechnology: Big things from a tiny world. Arlington. Available online at: https://www.nano.gov/sites/default/files/pub_resource/nanotechnology_bigthingsfromatinyworld-print.pdf

Nayan R, Rawat M, Negi B, Pande A, Arora S (2016) Zinc sulfide nanoparticle mediated alterations in growth and anti-oxidant status of *Brassica juncea*. Biologia 71(8):896–902. https://doi.org/10.1515/biolog-2016-0107

Nievola CC, Carvalho CP, Carvalho V, Rodrigues E (2017) Rapid responses of plants to temperature changes. Temperature (Austin) 4(4):371–405. https://doi.org/10.1080/23328940.2017.1377812

Noh YD, Komarneni S, Park M (2015) Mineral-based slow release fertilizers: a review. Korean Journal of Soil Science and Fertilizer 48(1):1–7. https://doi.org/10.7745/KJSSF.2015.48.1.001

Nonogaki H, Bassel GW, Bewley JD (2010) Germination—still a mystery. Plant Sci 179:574–581. https://doi.org/10.1016/j.plantsci.2010.02.010

Onaga G, Wydra K (2016) Advances in plant tolerance to abiotic stresses. In: Abdurakhmonov I (ed) Plant genomics. InTech, Rijeka. https://doi.org/10.5772/64350

Osakabe Y, Osakabe K, Shinozaki K, Tran LSP (2014) Response of plants to water stress. Front Plant Sci 2:86. https://doi.org/10.3389/fpls.2014.00086

Pagano L, Pasquali F, Majumdar S, De la Torre-Roche R, Zuverza-Mena N, Villani M, Zappettini A, Marra RE, Isch SM, Marmiroli M, Maestri E, Dhankher OP, White JC, Marmiroli N (2017) Exposure of *Cucurbita pepo* to binary combinations of engineered nanomaterials: physiological and molecular response. Environ Sci-Nano 4(7):1579–1590. https://doi.org/10.1039/c7en00219j

Panpatte DG, Jhala YK, Shelat HN, Vyas RV (2016) Nanoparticles – the next generation technology for sustainable agriculture. In: Singh DP, Singh HB, Prabha R (eds) Microbial inoculants in sustainable agricultural productivity Volume 2: functional applications. Springer, India, pp 289–300

Parihar P, Singh S, Singh R, Singh VP, Prasad SM (2015) Effect of salinity stress on plants and its tolerance strategies: a review. Environ Sci Pollut Res 22:4056–4075. https://doi.org/10.1007/s11356-014-3739-1

Pariona N, Martinez AI, Hdz-Garcia HM, Cruz LA, Hernandez-Valdes A (2017) Effects of hematite and ferrihydrite nanoparticles on germination and growth of maize seedlings. Saudi J Biol Sci 24(7):1547–1554. https://doi.org/10.1016/j.sjbs.2016.06.004

Pavani T, Rao KV, Chakra CS, Prabhu YT (2016) Synthesis and characterization of γ-ferric oxide nanoparticles and their effect on *Solanum lycopersicum*. Environ Sci Pollut Res 23(10):9373–9380. https://doi.org/10.1007/s11356-015-5215-y

Peng C, Zhang H, Fang HX, Xu C, Huang HM, Wang Y, Sun LJ, Yuan XF, Chen YX, Shi JY (2015) Natural organic matter-induced alleviation of the phytotoxicity to rice (*Oryza sativa* L.) caused by copper oxide nanoparticles. Environ Toxicol Chem 34(9):1996–2003. https://doi.org/10.1002/etc.3016

Peng C, Chen S, Shen CS, He M, Zhang YQ, Ye J, Liu JS, Shi JY (2018) Iron plaque: A barrier layer to the uptake and translocation of copper oxide nanoparticles by rice plants. Env Sci Technol. https://doi.org/10.1021/acs.est.8b02687

Pertaminingsih LD, Prihastanti E, Parman S, Subagio A, Ngadiwiyana (2018) Application of inorganic fertilizer with nanoChisil and nanosilica on black corn plant growth (*Zea mays* L.). J Phys Conf Ser 1025:UNSP 012128. https://doi.org/10.1088/1742-6596/1025/1/012128

Pisárčik M, Jampílek J, Lukáč M, Horáková R, Devínsky F, Bukovský M, Kalina M, Tkacz J, Opravil T (2017) Silver nanoparticles stabilised by cationic gemini surfactants with variable spacer length. Molecules 22:1794. https://doi.org/10.3390/molecules22101794

Pisárčik M, Lukáč M, Jampílek J, Bilka F, Bilková A, Pašková Ľ, Devínsky F, Horáková R, Opravil T (2018) Silver nanoparticles stabilised with cationic single-chain surfactants. Structure-physical properties-biological activity relationship study. J Mol Liq 272:60–72. https://doi.org/10.1016/j.molliq.2018.09.042

Population Institute (2017) FAO says food production must rise by 70%. Available online at: https://www.populationinstitute.org/resources/populationonline/issue/1/8

Prasad TNVKV, Sudhakar P, Sreenivasulu Y, Latha P, Munaswamy V, Reddy KR, Sreeprasad TS, Sajanlal PR, Pradeep T (2012) Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. J Plant Nutr 35(6):905–927. https://doi.org/10.1080/01904167.2012.663443

Prasad R, Bhattacharyya A, Nguyen QD (2017) Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Front Microbiol 8:1014. https://doi.org/10.3389/fmicb.2017.01014

Praveen A, Khan E, Ngiimei SD, Perwez M, Sardar M, Gupta M (2018) Iron oxide nanoparticles as nano-adsorbents: A possible way to reduce arsenic phytotoxicity in Indian mustard plant (*Brassica juncea* L.). J Plant Growth Regul 37(2):612–624. https://doi.org/10.1007/s00344-017-9760-0

Preetha PS, Balakrishnan N (2017) A review of nano fertilizers and their use and functions in soil. Int J Curr Microbiol Appl Sci 6(12):3117–3133. https://doi.org/10.20546/ijcmas.2017.612.364

Pullagurala VLR, Adisa IO, Rawat S, Kim B, Barrios AC, Medina-Velo IA, Hernandez-Viezcas JA, Peralta-Videa JR, Gardea-Torresdey JL (2018) Finding the conditions for the beneficial use of ZnO nanoparticles towards plants-A review. Environ Pollut 241:1175–1181. https://doi.org/10.1016/j.envpol.2018.06.036

Qi MF, Liu YF, Li TL (2013) Nano-TiO_2 improve the photosynthesis of tomato leaves under mild heat stress. Biol Trace Elem Res 156(1–3):323–328. https://doi.org/10.1007/s12011-013-9833-2

Racuciu M, Creanga D (2007) Biocompatible magnetic fluid nanoparticles internalized in vegetal tissue. Rom J Phys 54(1–2):115–124.

Rafique R, Zahra Z, Virk N, Shahid M, Pinelli E, Park TJ, Kallerhoff J, Arshad M (2018) Dose-dependent physiological responses of *Triticum aestivum* L. to soil applied TiO_2 nanoparticles: alterations in chlorophyll content, H_2O_2 production, and genotoxicity. Agric Ecosyst Environ 255:95–101. https://doi.org/10.1016/j.agee.2017.12.010

Rahmani F, Peymani A, Daneshvand E, Biparva P (2016) Impact of zinc oxide and copper oxide nano-particles on physiological and molecular processes in *Brassica napus* L. Indian J Plant Physiol 21(2):122–128. https://doi.org/10.1007/s40502-016-0212-9

Raliya R, Biswas P, Tarafdae JC (2015) TiO_2 nanoparticle biosynthesis and its physiological effect on mung bean (*Vigna radiata* L.). Biotechnol Rep (Amst) 5:22–26. https://doi.org/10.1016/j.btre.2014.10.009

Raliya R, Franke C, Chavalmane S, Nair R, Reed N, Biswas P (2016) Quantitative understanding of nanoparticle uptake in watermelon plants. Front Plant Sci 7:1288. https://doi.org/10.3389/fpls.2016.01288

Ramakrishna A, Ravishankar GA (2011) Influence of abiotic stress signals on secondary metabolites in plants. Plant Signal Behav 6(11):1720–1731. https://doi.org/10.4161/psb.6.11.17613

Rane M, Bawskar M, Rathod D, Nagaonkar D, Rai M (2015) Influence of calcium phosphate nanoparticles, *Piriformospora indica* and *Glomus mosseae* on growth of *Zea mays*. Adv Nat Sci 6(4):045014. https://doi.org/10.1088/2043-6262/6/4/045014

Rashidi R, Abasi S, Kermanchi M, Bastani M, Faraji A (2016) The use of nano-silver particles to increase yield of broad bean. J Pure App Microbiol 10(3):1933–1936

Raven PH (2014) The use of transgenic crops in agriculture: Safety and other features. Council for Biotechnology Information. Available online at: https://gmoanswers.com/use-transgenic-crops-agriculture-safety-and-other-features

Rawat M, Nayan R, Negi B, Zaidi MGH, Arora S (2017) Physio-biochemical basis of iron-sulfide nanoparticle induced growth and seed yield enhancement in *B. juncea*. Plant Physiol Biochem 118:274–284. https://doi.org/10.1016/j.plaphy.2017.06.021

Regier N, Cosio C, von Moos N, Slaveykova VI (2015) Effects of copper-oxide nanoparticles, dissolved copper and ultraviolet radiation on copper bioaccumulation, photosynthesis and oxidative stress in the aquatic macrophyte *Elodea nuttallii*. Chemosphere 128:56–61. https://doi.org/10.1016/j.chemosphere.2014.12.078

Rico CM, Barrios AC, Tan WJ, Rubenecia R, Lee SC, Varela-Ramirez A, Peralta-Videa JR, Gardea-Torresdey JL (2015) Physiological and biochemical response of soil-grown barley (*Hordeum vulgare* L.) to cerium oxide nanoparticles. Environ Sci Pollut Res 22(14):10551–10558. https://doi.org/10.1007/s11356-015-4243-y

Rieuwerts JS, Thornton I, Farago ME, Ashmore MR (1998) Factors influencing metal bioavailability in soils: preliminary investigations for the development of a critical loads approach for metals. Chem Spec Bioavailab 10(2):61–75. https://doi.org/10.3184/095422998782775835

Rizwan M, Ali S, Ali B, Adrees M, Arshad M, Hussain A, Zia Ur Rehman M, Waris AA (2018) Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. Chemosphere 214:269–277. https://doi.org/10.1016/j.chemosphere.2018.09.120

Rossi L, Zhang WL, Lombardini L, Ma XM (2016) The impact of cerium oxide nanoparticles on the salt stress responses of *Brassica napus* L. Environ Pollut 219:28–36. https://doi.org/10.1016/j.envpol.2016.09.060

Rossi L, Zhang WL, Ma XM (2017) Cerium oxide nanoparticles alter the salt stress tolerance of *Brassica na*pus L. by modifying the formation of root apoplastic barriers. Environ Pollut 229:132–138. https://doi.org/10.1016/j.envpol.2017.05.083

Rossi L, Sharifan H, Zhang WL, Schwab AP, Ma XM (2018) Mutual effects and in planta accumulation of co-existing cerium oxide nanoparticles and cadmium in hydroponically grown soybean (*Glycine max* (L.) Merr.). Environ Sci-Nano 5(1):150–157. https://doi.org/10.1039/c7en00931c

Rui MM, Ma CX, Hao Y, Guo J, Rui YK, Tang XL, Zhao Q, Fan X, Zhang ZT, Hou TQ, Zhu SY (2016) Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). Front Plant Sci 7:815. https://doi.org/10.3389/fpls.2016.00815

Ruttkay-Nedecky B, Krystofova O, Nejdl L, Adam V (2017) Nanoparticles based on essential metals and their phytotoxicity. J Nanobiotechnol 15:33. https://doi.org/10.1186/s12951-017-0268-3

Saharan V, Kumaraswamy RV, Choudhary RC, Kumari S, Pal A, Raliya R, Biswas P (2016) Cu-chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. J Agric Food Chem 64(31):6148–6155. https://doi.org/10.1021/acs.jafc.6b02239

Salah SM, Guan YJ, Cao DD, Li J, Aamir N, Hu QK, Hu WM, Ning MY, Hu J (2015) Seed priming with polyethylene glycol regulating the physiological and molecular mechanism in rice (*Oryza sativa* L.) under nano-ZnO stress. Sci Rep 5:14278. https://doi.org/10.1038/srep14278

Salah MHG, Al-Zahrani HSM, Metwali EMR (2017) Improving the salinity tolerance in potato (*Solanum tuberosum*) by exogenous application of silicon dioxide nanoparticles. Int J Agric Biol 19(1):183–192. https://doi.org/10.17957/IJAB/15.0262

Samart S, Phakamas N, Chutipaijit S (2018) Assessment of antioxidant enzymes in response to exogenous titanium dioxide (TiO_2) nanoparticles in Chainat 1 rice cultivar. Mater Today Proc 5(6):14160–14165. https://doi.org/10.1016/j.matpr.2018.02.083

Sathiyabama M, Manikandan A (2018) Application of copper-chitosan nanoparticles stimulate growth and induce resistance in finger millet (*Eleusine coracana* Gaertn.) plants against blast disease. J Agric Food Chem 66(8):1784–1790. https://doi.org/10.1021/acs.jafc.7b05921

Sauter M (2013) Root responses to flooding. Curr Opin Plant Biol 16(3):282–286. https://doi.org/10.1016/j.pbi.2013.03.013

Sebastian A, Nangia A, Prasad MN (2017) Carbon-bound iron oxide nanoparticles prevent calcium-induced iron deficiency in *Oryza sativa* L. J Agric Food Chem 65(3):557–564. https://doi.org/10.1021/acs.jafc.6b04634

Sekhon BS (2014) Nanotechnology in agri-food production: an overview. Nanotechnol Sci Appl 7:31–53. https://doi.org/10.2147/NSA.S39406

Servin AD, Castillo-Michel H, Hernandez-Viezcas JA, Diaz BC, Peralta-Videa JR, Gardea-Torresdey JL (2012) Translocation of TiO_2 nanoparticles in cucumber (*Cucumis sativus*) plants. Environ Sci Technol 46(14):7637–7643. https://doi.org/10.1021/es300955b

Sha Valli Khan PS, Nagamallaiah GV, Dhanunjay RM, Sergeant K, Hausman JF (2018) Abiotic stress tolerance in plants: insights from proteomics. In: Ahmad P, Rosool S (eds) Emerging technologies and management of crop stress tolerance, Vol. 2: A sustainable approach. Academic Press, San Diego, pp 23–68

Shabnam N, Kim H (2018) Non-toxicity of nano alumina: a case on mung bean seedlings. Ecotox Environ Saf 165:423–433. https://doi.org/10.1016/j.ecoenv.2018.09.033

Shallan MA, Hassan HMM, Namich AAM, Ibrahim AA (2016) Biochemical and physiological effects of TiO_2 and SiO_2 nanoparticles on cotton plant under drought stress. Res J Pharm Biol Chem Sci 7(4):1540–1551

Shanker AK, Venkateswarlu B (2011) Abiotic stress in plants – mechanisms and adaptations. InTech, Rijeka. http://library.umac.mo/ebooks/b28109600.pdf

Sharifi-Rad J, Sharifi-Rad M, da Silva JAT (2016) Morphological, physiological and biochemical responses of crops (*Zea mays* L., *Phaseolus vulgaris* L.), medicinal plants (*Hyssopus officinalis* L., *Nigella sativa* L.), and weeds (*Amaranthus retroflexus* L., *Taraxacum officinale* F. H. Wigg) exposed to SiO_2 nanoparticles. J Agric Sci Technol 18(4):1027–1040

Sharma S, Chatterjee S, Kataria S, Joshi J, Datta S, Vairale MG, Veer V (2017) A review on responses of plants to UV-B radiation related stress. In: Singh CP, Singh S, Prasad SM, Parihar P (eds) UV-B radiation: from environmental stressor to regulator of plant growth. Wiley-Blackwell, Hoboken, pp 75–95

Shaviv A (2005) Controlled release fertilizers. IFA International Workshop on Enhanced-Efficiency Fertilizers/International Fertilizer Industry Association, Frankfurt Paris

Shende S, Rathod D, Gade A, Rai M (2017) Biogenic copper nanoparticles promote the growth of pigeon pea (*Cajanus cajan* L.). IET Nanobiotechnol 11(7):773–781. https://doi.org/10.1049/iet-nbt.2016.0179

Sheteiwy MS, Dong Q, An JY, Song WJ, Guan YJ, He F, Huang YE, Hu J (2017) Regulation of ZnO nanoparticles-induced physiological and molecular changes by seed priming with humic acid in *Oryza sativa* seedlings. Plant Growth Regul 83(1):27–41. https://doi.org/10.1007/s10725-017-0281-4

Sheykhbaglou R, Sedghi M, Fathi-Achachlouie B (2018) The effect of ferrous nano-oxide particles on physiological traits and nutritional compounds of soybean (*Glycine max* L.) seed. An Acad Bras Cienc 90(1):485–494. https://doi.org/10.1590/0001-3765201820160251

Siddiqui MH, Al-Whaibi MH (2014) Role of nano-SiO_2 in germination of tomato (*Lycopersicum esculentum* seeds Mill.). Saudi J Biol Sci 21(1):13–17. https://doi.org/10.1016/j.sjbs.2013.04.005

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(11):2429–2437. https://doi.org/10.1002/etc.2697

Silva S, Craveiro SC, Oliveira H, Calado AJ, Pinto RJB, Silva AMS, Santos C (2017) Wheat chronic exposure to TiO_2-nanoparticles: Cyto- and genotoxic approach. Plant Physiol Biochem 121:89–98. https://doi.org/10.1016/j.plaphy.2017.10.013

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 Manage 170:88–96. https://doi.org/10.1016/j.jenvman.2016.01.015

Singh J, Lee BK (2018) Effects of nano-TiO_2 particles on bioaccumulation of ^{133}Cs from the contaminated soil by soybean (*Glycine max*). Process Saf Environ 116:301–311. https://doi.org/10.1016/j.psep.2018.02.016

Singh A, Singh NB, Hussain I, Singh H, Yadav V, Singh SC (2016) Green synthesis of nano zinc oxide and evaluation of its impact on germination and metabolic activity of *Solanum lycopersicum*. J Biotechnol 233:84–94. https://doi.org/10.1016/j.jbiotec.2016.07.010

Singh A, Singh NB, Hussain I, Singh H (2017) Effect of biologically synthesized copper oxide nanoparticles on metabolism and antioxidant activity to the crop plants *Solanum lycopersicum* and *Brassica oleracea* var. *botrytis*. J Biotechnol 262:11–27. https://doi.org/10.1016/j.jbiotec.2017.09.016

Soares C, Branco-Neves S, de Sousa A, Azenha M, Cunha A, Pereira R, Fidalgo F (2018) SiO_2 nanomaterial as a tool to improve *Hordeum vulgare* L. tolerance to nano-NiO stress. Sci Total Environ 622:517–525. https://doi.org/10.1016/j.scitotenv.2017.12.002

Solanki P, Bhargava A, Chhipa H, Jain N, Panwar J (2015) Nano-fertilizers and their smart delivery system. In: Rai M, Ribeiro C, Mattoso L, Duran N (eds) Nanotechnologies in food and agriculture. Springer, Cham, pp 81–101. https://doi.org/10.1007/978-3-319-14024-7_4

Soltani M, Kafi M, Nezami A, Taghiyari HR (2018) Effects of silicon application at nano and micro scales on the growth and nutrient uptake of potato minitubers (*Solanum tuberosum* var. Agria) in greenhouse conditions. Bionanoscience 8(1):218–228. https://doi.org/10.1007/s12668-017-0467-2

Song HW, Yuan WM, Jin P, Wang W, Wang XF, Yang LM, Zhang YF (2016) Effects of chitosan/nano-silica on postharvest quality and antioxidant capacity of loquat fruit during cold storage. Postharvest Biol Technol 119:41–48. https://doi.org/10.1016/j.postharvbio.2016.04.015

Songkhum P, Wuttikhun T, Chanlek N, Khemthong P, Laohhasurayotin K (2018) Controlled release studies of boron and zinc from layered double hydroxides as the micronutrient hosts for agricultural application. Appl Clay Sci 152:311–322. https://doi.org/10.1016/j.clay.2017.11.028

Spielman-Sun E, Lombi E, Donner E, Howard D, Unrine JM, Lowry GV (2017) Impact of surface charge on cerium oxide nanoparticle uptake and translocation by wheat (*Triticum aestivum*). Environ Sci Technol 51(13):7361–7368. https://doi.org/10.1021/acs.est.7b00813

Steponkus PL (1984) Role of the plasma membrane in freezing injury and cold acclimation. Ann Rev Plant Physiol 35:543–584. https://doi.org/10.1146/annurev.pp.35.060184.002551

Stewart J, Hansen T, McLean JE, McManus P, Das S, Britt DW, Anderson AJ, Dimkpa CO (2015) Salts affect the interaction of ZnO or CuO nanoparticles with wheat. Environ Toxicol Chem 34(9):2116–2125. https://doi.org/10.1002/etc.3037

Su MY, Wu X, Liu C, Qu CX, Liu XQ, Chen L, Huang H, Hong FS (2007) Promotion of energy transfer and oxygen evolution in spinach photosystem II by nano-anatase TiO_2. Biol Trace Elem Res 119(2):183–192. https://doi.org/10.1007/s12011-007-0065-1

Subbaiah LV, Prasad TNVKV, Krishna TG, Sudhakar P, Reddy BR, Pradeep T (2016) Novel effects of nanoparticulate delivery of zinc on growth, productivity, and zinc biofortification in maize (*Zea mays* L.). J Agric Food Chem 64(19):3778–3788. https://doi.org/10.1021/acs.jafc.6b00838

Sun DQ, Hussain HI, Yi ZF, Rookes JE, Kong LX, Cahill DM (2016) Mesoporous silica nanoparticles enhance seedling growth and photosynthesis in wheat and lupin. Chemosphere 152:81–91. https://doi.org/10.1016/j.chemosphere.2016.02.096

Suppan (2017) Applying nanotechnology to fertilizer rationales, research, risks and regulatory challenges. Institute for Agriculture and Trade Policy, Washington, DC. https://www.iatp.org/sites/default/files/2017-10/2017_10_10_Nanofertilizer_SS_f.pdf

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(12):1294. https://doi.org/10.1007/s11051-012-1294-6

Szabó B, Tyihák E, Szabó LG, Botz L (2003) Mycotoxin and drought stress induced change of alkaloid content *of Papaver somniferum* plantlets. Acta Bot Hung 45(3/4):409–417. https://doi.org/10.1556/ABot

Tan WJ, Du WC, Darrouzet-Nardi AJ, Hernandez-Viezcas JA, Ye YQ, Peralta-Videa JR, Gardea-Torresdey JL (2018) Effects of the exposure of TiO_2 nanoparticles on basil (*Ocimum basilicum*) for two generations. Sci Total Environ 636:240–248. https://doi.org/10.1016/j.scitotenv.2018.04.263

Taran N, Storozhenko V, Svietlova N, Batsmanova L, Shvartau V, Kovalenko M (2017) Effect of zinc and copper nanoparticles on drought resistance of wheat seedlings. Nanoscale Res Lett 12:60. https://doi.org/10.1186/s11671-017-1839-9

Tassi E, Giorgetti L, Morelli E, Peralta-Videa JR, Gardea-Torresdey JL, Barbafieri M (2017) Physiological and biochemical responses of sunflower (*Helianthus annuus* L.) exposed to nano-CeO_2 and excess boron: Modulation of boron phytotoxicity. Plant Physiol Biochem 110:50–58. https://doi.org/10.1016/j.plaphy.2016.09.013

Thuesombat P, Hannongbua S, Ekgasit S, Chadchawan S (2016) Effects of silver nanoparticles on hydrogen peroxide generation and antioxidant enzyme responses in rice. J Nanosci Nanotechnol 16(8):8030–8043. https://doi.org/10.1166/jnn.2016.12754

Thunugunta T, Reddy AC, Seetharamaiah SK, Hunashikatti LR, Chandrappa SG, Kalathil NC, Reddy LRDC (2018) Impact of zinc oxide nanoparticles on eggplant (*S-melongena*): studies on growth and the accumulation of nanoparticles. IET Nanobiotechnol 12(6):706–713. https://doi.org/10.1049/iet-nbt.2017.0237

Tighe-Neira R, Carmora E, Recio G, Nunes-Nesi A, Reyes-Diaz M, Alberdi M, Rengel Z, Inostroza-Blancheteau C (2018) Metallic nanoparticles influence the structure and function of the photosynthetic apparatus in plants. Plant Physiol Biochem 130:408–417. https://doi.org/10.1016/j.plaphy.2018.07.024

Tiwari M, Sharma NC, Fleischmann P, Burbage J, Venkatachalam P, Sahi SV (2017) Nanotitania exposure causes alterations in physiological, nutritional and stress responses in tomato (*Solanum lycopersicum*). Front Plant Sci 8:633. https://doi.org/10.3389/fpls.2017.00633

Tolaymat T, Genaidy A, Abdelraheern W, Dionysiou D, Andersen C (2017) The effects of metallic engineered nanoparticles upon plant systems: an analytic examination of scientific evidence. Sci Total Environ 579:93–106. https://doi.org/10.1016/j.scitotenv.2016.10.229

Tong CY, Xiao SY, Wang B, Xiao XJ, Zheng YQ, Xue CG, Wang QM, Liu XM (2008) Preparation and application of chitooligosaccharides-selenium nanoparticles for plant nutrition regulator. J Hunan Univ (Nat Sci) 35:60–64

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(2):172–180. https://doi.org/10.1080/01904167.2015.1009107

Torabian S, Zahedi M, Khoshgoftar AH (2017) Effects of foliar spray of nano-particles of $FeSO_4$ on the growth and ion content of sunflower under saline condition. J Plant Nutr 40(5):615–623. https://doi.org/10.1080/01904167.2016.1240187

Trenkel ME (2010) Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. International Fertilizer Industry Association (IFA), Paris

Tripathi D, Singh V, Chauhan D, Prasad S, Dubey N (2014) Role of macronutrients in plant growth and acclimation: recent advances and future prospective. In: Ahmad P, Wani M, Azooz M, Phan Tran LS (eds) Improvement of crops in the era of climatic changes. Springer, New York. https://doi.org/10.1007/978-1-4614-8824-8_8

Tripathi DK, Singh S, Singh S, Mishra S, Chauhan DK, Dubey NK (2015a) Micronutrients and their diverse role in agricultural crops: advances and future prospective. Acta Physiol Plant 37:1–14. https://doi.org/10.1007/s11738-015-1870-3

Tripathi DK, Singh VP, Prasad SM, Chauhan DK, Dubey NK (2015b) Silicon nanoparticles (SiNp) alleviate chromium (VI) phytotoxicity in *Pisum sativum* (L.) seedlings. Plant Physiol Biochem 96:189–198. https://doi.org/10.1016/j.plaphy.2015.07.026

Tripathi DK, Singh S, Singh VP, Prasad SM, Dubey NK, Chauhan DK (2017) Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (*Triticum aestivum*) seedlings. Plant Physiol Biochem 110:70–81. https://doi.org/10.1016/j.plaphy.2016.06.026

Trujillo-Reyes J, Vilchis-Nestor AR, Majumdar S, Peralta-Videa JR, Gardea-Torresdey JL (2013) Citric acid modifies surface properties of commercial CeO_2 nanoparticles reducing their toxicity and cerium uptake in radish (*Raphanus sativus*) seedlings. J Hazard Mater 26:677–684. https://doi.org/10.1016/j.jhazmat.2013.10.030

Umarani R, Mala R (2013a) Influence of calcium phosphate nano gel fertilizer composites on germination of crop plants. Asian J Microbiol Biotechnol Environ Sci 15:327–331

Umarani R, Mala R (2013b) Influence of calcium phosphate nano gel fertilizer composite on enzymes, biomolecules and yield of *Abelmoschus esculentus*. Int J Agric Environ Biotechnol. 6(4S):771

Ursache-Oprisan M, Foca-nici E, Cirlescu A, Caltun O, Creanga D (2010) Nanoparticles - preparation, physical characterization and biological impact on *Helianthus annuus* photosynthesis. AIP Conf Proceed 1311:425–430

Valliyodan B, Nguyen HT (2006) Understanding regulatory networks and engineering for enhanced drought tolerance in plants. Cur Opin Plant Biol 9:1–7. https://doi.org/10.1016/j.pbi.2006.01.019

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 11:59–69. https://doi.org/10.1016/j.plaphy.2016.08.022

Ventola CL (2017) Progress in nanomedicine: approved and investigational nanodrugs. P T 42(12):742–755

Wang D, Wei SY, Hu LJ (2010) POSS/TiO_2 nanohybrids as sun protection ingredients for greenhouse covers. Adv Mater Res 113–116:2077–2080. https://doi.org/10.4028/www.scientific.net/AMR.113-116.2077

Wang WN, Tarafdar JC, Biswas P (2013) Nanoparticle synthesis and delivery by an aerosol route for watermelon plant foliar uptake. J Nanopart Res 15:1413–1417. https://doi.org/10.1007/s11051-013-1417-8

Wang SH, Wang FY, Gao SC (2015) Foliar application with nano-silicon alleviates Cd toxicity in rice seedlings. Environ Sci Pollut Res 22(4):2837–2845. https://doi.org/10.1007/s11356-014-3525-0

Wani W, Masoodi KZ, Zaid A, Wani SH, Shah F, Meena VS, Wani SA, Mosa KA (2018) Engineering plants for heavy metal stress tolerance. Rend Lincei Sci Fis Nat 29(3):709–723. https://doi.org/10.1007/s12210-018-0702-y

Waraich EA, Ahmad R, Halim A, Aziz T (2012) Alleviation of temperature stress by nutrient management in crop plants: a review. J Soil Sci Plant Nutr 12(2):221–244. https://doi.org/10.4067/S0718-95162012000200003

Watson JL, Fang T, Dimkpa CO, Britt DW, McLean JE, Jacobson A, Anderson AJ (2015) The phytotoxicity of ZnO nanoparticles on wheat varies with soil properties. Biometals 28(1):101–112. https://doi.org/10.1007/s10534-014-9806-8

Wilson MA, Tran NH, Milev AS, Kannangara GSK, Volk H, Lu GHM (2008) Nanomaterials in soils. Geoderma 146:291–302

World Hunger Education Service (2018) Hunger notes. Washington, DC. Available online at: https://www.worldhunger.org/

Wu HH, 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(7):1567–1583. https://doi.org/10.1039/c8en00323h

Xu C, Peng C, Sun LJ, Zhang S, Huang HM, Chen YX, Shi JY (2015) Distinctive effects of TiO_2 and CuO nanoparticles on soil microbes and their community structures in flooded paddy soil. Soil Biol Biochem 86:24–33. https://doi.org/10.1016/j.soilbio.2015.03.011

Xu JB, Wang YL, Luo XS, Feng YZ (2017) Influence of Fe_3O_4 nanoparticles on lettuce (*Lactuca sativa* L.) growth and soil bacterial community structure. Yingyong Shengtai Xuebao 28(9):3003–3010. https://doi.org/10.13287/j.1001-9332.201709.033

Yadav SK (2010) Cold stress tolerance mechanisms in plants. A review. Agron Sustain Dev 30:515–527. https://doi.org/10.1051/agro/2009050

Yadav RC, Patra AK, Purakayastha TJ, Bhattacharyya R, Singh R (2014) Response of rice plant to application of nanoparticles of Fe and Zn at elevated CO_2: a hydroponic experiment under phytotron. IJBSM 5:207–212

Yadu B, Chandrakar V, Korram J, Satnami ML, Kumar M, Keshavkant S (2018) Silver nanoparticle modulates gene expressions, glyoxalase system and oxidative stress markers in fluoride stressed *Cajanus cajan* L. J Hazard Mater 353:44–52. https://doi.org/10.1016/j.jhazmat.2018.03.061

Yaqoob S, Ullah F, Mehmood S, Mahmood T, Ullah M, Khattak A, Zeb MA (2018) Effect of waste water treated with TiO_2 nanoparticles on early seedling growth of *Zea mays* L. J Water Reuse Desal 8(3):424–431. https://doi.org/10.2166/wrd.2017.163

Yasmeen F, Raja NI, Mustafa G, Sakata K, Komatsu S (2016) Quantitative proteomic analysis of post-flooding recovery in soybean root exposed to aluminum oxide nanoparticles. J Proteomics 143:136–150. https://doi.org/10.1016/j.jprot.2016.03.014

Yasmeen F, Raja NI, Razzaq A, Komatsu S (2017) Proteomic and physiological analyses of wheat seeds exposed to copper and iron nanoparticles. BBA Proteins Proteom 1865(1):28–42. https://doi.org/10.1016/j.bbapap.2016.10.001

Yue N, Yun X (2018) An overview of biomembrane functions in plant responses to high-temperature stress. Front Plant Sci. https://doi.org/10.3389/fpls.2018.00915

Yuvaraj M, Subramanian KS (2018) Development of slow release Zn fertilizer using nano-zeolite as carrier. J Plant Nutr 41(3):311–320. https://doi.org/10.1080/01904167.2017.1381729

Zahra Z, Waseem N, Zahra R, Lee H, Badshah MA, Mehmood A, Choi HK, Arshad M (2017) Growth and metabolic responses of rice (*Oryza sativa* L.) cultivated in phosphorus-deficient soil amended with TiO_2 nanoparticles. J Agric Food Chem 65(28):5598–5606. https://doi.org/10.1021/acs.jafc.7b01843

Zhang SG, Yang YC, Gao B, Li YC, Liu ZG (2017) Superhydrophobic controlled-release fertilizers coated with bio-based polymers with organosilicon and nano-silica modifications. J Mater Chem A 5(37):19943–19953. https://doi.org/10.1039/c7ta06014a

Zhang T, Sun HD, Lv ZY, Cui LL, Mao H, Kopittke PM (2018a) Using synchrotron-based approaches to examine the foliar application of $ZnSO_4$ and ZnO nanoparticles for field-grown winter wheat. J Agric Food Chem 66(11):2572–2579. https://doi.org/10.1021/acs.jafc.7b04153

Zhang GL, Zhou LL, Cai DQ, Wu ZY (2018b) Anion-responsive carbon nanosystem for controlling selenium fertilizer release and improving selenium utilization efficiency in vegetables. Carbon 129:711–719. https://doi.org/10.1016/j.carbon.2017.12.062

Zhou JM, Huang PM (2007) Kinetics of potassium release from illite as influenced by different phosphates. Geoderma 138:221–228

Zhu J, Dong CH, Zhu JK (2007) Interplay between cold-responsive gene regulation, metabolism and RNA processing during plant cold acclimation. Curr Opin Plant Biol 10:290–295. https://doi.org/10.1016/j.pbi.2007.04.010

Zhu ZJ, Wang HH, Yan B, Zheng H, Jiang Y, Miranda OR, Rotello VM, Xing BS, Vachet RW (2012) Effect of surface charge on the uptake and distribution of gold nanoparticles in four plant species. Environ Sci Technol 46(22):12391–12398. https://doi.org/10.1021/es301977w

Zlatev ZS, Lidon FJC, Kaimakanova M (2012) Plant physiological responses to UV-B radiation. Emir J Food Agric 24(6):481–501. https://doi.org/10.9755/ejfa.v24i6.14669

Zotikova AP, Astafurova TP, Burenina AA, Suchkova SA, Morgalev YN (2018) Morphophysiological features of wheat (*Triticum aestivum* L.) seedlings upon exposure to nickel nanoparticles. Sel'skokhozyaistvennaya Biologiya 53(3):578–586. https://doi.org/10.15389/agrobiology.2018.3.578eng

Zou XY, Li PH, Lou J, Zhang HW (2017) Surface coating-modulated toxic responses to silver nanoparticles in *Wolffia globos*a. Aquat Toxicol 189:150–158. https://doi.org/10.1016/j.aquatox.2017.06.010

Zhao L, Peralta-Videa JR, Varela-Ramirez A, Castillo-Michel H, Li C, Zhang J, Aguilera RJ, Keller AA, Gardea-Torresdey JL (2012) Effect of surface coating and organic matter on the uptake of CeO_2 NPs by corn plants grown in soil: insight into the uptake mechanism. J Hazard Mater 225–226:131–138. https://doi.org/10.1016/j.jhazmat.2012.05.008